LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT

Ashish Gulagi

SOUTH ASIA'S ENERGY [R]EVOLUTION – TRANSITION TOWARDS DEFOSSILISED POWER SYSTEMS BY 2050 WITH SPECIAL FOCUS ON INDIA

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 1067

Ashish Gulagi

SOUTH ASIA'S ENERGY [R]EVOLUTION – TRANSITION TOWARDS DEFOSSILISED POWER SYSTEMS BY 2050 WITH SPECIAL FOCUS ON INDIA

Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Room 1316 at Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland on the 9th of February, 2023 at 10:15.

Acta Universitatis
Lappeenrantaensis 1067

Supervisor Professor Christian Breyer
LUT School of Energy Systems
Lappeenranta-Lahti University of Technology LUT
Finland

Reviewers Professor Pao Yu Oei
Economics of Sustainable Energy System Transition
Industrial Engineering: Energy and Environmental Management
University of Flensburg
Germany

Dr. Jannik Haas
Civil and Natural Resources Engineering
University of Canterbury
New Zealand

Opponent Dr. Jannik Haas
Civil and Natural Resources Engineering
University of Canterbury
New Zealand

ISBN 978-952-335-916-1
ISBN 978-952-335-917-8 (PDF)
ISSN 1456-4491 (Print)
ISSN 2814-5518 (Online)

Lappeenranta-Lahti University of Technology LUT
LUT University Press 2023

Abstract

Ashish Gulagi
South Asia's Energy [R]evolution – Transition towards defossilised power systems by 2050 with special focus on India
Lappeenranta 2023
142 pages
Acta Universitatis Lappeenrantaensis 1067
Diss. Lappeenranta-Lahti University of Technology LUT
ISBN 978-952-335-916-1, ISBN 978-952-335-917-8 (PDF), ISSN 1456-4491 (Print), ISSN 2814-5518 (Online)

Current energy systems, with fossil fuels in the midst, are completely unsustainable on all accounts of environmental, social, and economic criteria. Consequently, global energy systems are undergoing transitions, primarily driven by climate change concerns, energy security fears, the cost competitiveness of renewable energy (RE), and Sustainable Development Goals (SDGs). Similarly, developing countries in the South Asian region, currently home to 24% of the world's population, are at the crossroads of such an energy transition, due to their high dependency on fossil fuels, especially coal. Thus, an energy transition towards integrating RE would address energy security, accessibility, and affordability, with the additional benefits of reducing air pollution and addressing the issue of water scarcity.

Against this background, the overall aim of this dissertation is to model, analyse and assess the techno-economic feasibility of the various energy transition pathways and scenarios integrating renewables for the South Asian region as well as for some of the individual countries within this region. First, the economic viability and technical feasibility of an overnight shift from the current fossil fuel dominated power system to a 100% RE-based system in 2030 is analysed on a macro level for the entire South Asian region. With scenario variations, the role of regional integration via power grids and sector coupling through integration of Power-to-Gas (PtG) and seawater reverse osmosis desalination is studied. Second, at a national level, the transition of current power systems is shown and analysed in 5-year time steps until 2050 for differences in transition pathways and to study each of the transition pathway in detail. Additionally, it is shown that each country in South Asia can transition towards a 100% RE-based system independently, utilising its own indigenous renewable resources. Furthermore, the transition of the entire energy sector (power, heat and transport) is analysed for Nepal and Bhutan, as these countries present an interesting case, due to their high dependency on hydropower, unsustainable biomass, and imported fossil fuels in the energy system. As the largest contributor to greenhouse gas (GHG) emissions in South Asia, the power system of India is analysed in more detail on a state-wide resolution, with the impact of the monsoon on a 100% RE-based power system. Third, with high shares of variable RE in the energy systems, various flexibility options are studied, such as storage technologies, transmission grids, and Power-to-X solutions. The LUT Energy System Transition Model is used in this dissertation to model the energy transition pathways for the South Asian region and the individual countries. The LUT-ESTM linearly optimises the target function i.e., to have a least annual cost of the power or energy system. The important features of the LUT-ESTM are high spatial and temporal resolution, a multi-nodal power transmission network and sector coupling.

The results of this dissertation show that the South Asian region is on the cusp of solar photovoltaics (PV) powered revolution. Thus, a cost optimised rapid transition from the current fossil fuel dominated power and energy systems towards 100% RE across the countries in South Asia is possible by integrating large shares of solar PV, complemented by wind power, hydropower, and modern uses of biomass. However, integrating large shares of VRE into the energy system calls for various new least cost portfolio of flexibility solutions. Batteries for temporal load shifting, transmission grids for spatial load shifting, and PtG provide the flexibility to a 100% RE-based system, even during the monsoon season. This transition not only decreases the cost of electricity but also enables other indirect economic benefits like reducing air pollution and the corresponding health costs, creating additional jobs, and reducing fossil fuel imports. As one of the most highly water stressed regions in the world that is entirely dependent on irrigation from fresh groundwater resources, seawater desalination using low cost RE provides an alternative source of freshwater, thus solving the existing and future water crises in the region. As one of the most important countries in the world to achieve climate change mitigation goals, India’s energy transition towards 100% RE could be a model to follow for other emerging and developing countries to demonstrate that robust economic growth is possible without an increase in GHG emissions while achieving SDGs.

The results of this dissertation contribute to the constructive discourse of the energy transition discussion currently taking place in the countries of this region. Consequently, this will help local as well as national governments, policymakers, and citizens better understand that such a transition from the current energy systems towards 100% RE is cost competitive and societally attractive. However, achieving a 100% RE-based system will require unwavering focus, political will, and coordination among all the stakeholders involved at the national and regional levels.

Keywords: energy transition, renewable energy, energy storage, cost optimisation, energy system flexibility, sector coupling, Power-to-X, monsoon, South Asia, SAARC, India, Himalayan countries, Bangladesh, Pakistan

Acknowledgements

This work was carried out in the LUT School of Energy Systems at Lappeenranta-Lahti University of Technology LUT, Finland, between 2015 and 2022.

Words cannot express my gratitude to my supervisor, Prof. Christian Breyer, for providing me the opportunity to work under your meticulous guidance. I could not have undertaken this journey without your vision, motivation, valuable feedback at every step, and continuous support over these years. I vividly remember our first interaction and your vision and excitement for this important research, which has remained the same over these years. Your relentless pursuit, dedication, and leadership have instilled in me a rigour for high quality research.

I am grateful to my fellow researchers from the ‘Solar Economy’ team. Without your discussions, questions, arguments, and most importantly, support, this would not have been possible. Thank you also to colleagues, whom I have met through projects and conferences and who have enriched my knowledge through fruitful conversations over these years. Lastly, a big thank you to all the reviewers of the articles for asking tough questions and giving helpful comments to improve each published article.

I wish to express my gratitude to the Fortum Foundation for their valuable scholarship, which helped to fund some of the research for this dissertation.

I would also like to acknowledge the time and efforts put in by the reviewers of this dissertation, Prof. Pao Yu Oei and Dr. Jannik Haas. I am honoured to receive positive feedback on my work. Additionally, many thanks to Dr. Jannik Haas for acting as the opponent in the public examination of the dissertation.

I would be remiss in not mentioning my friends and family for their constant support, encouragement, and the good times, back home as well as here in Finland. I am ever grateful for each one of them, especially my grandparents, parents, and brother Rohan. I would also like to mention a specific member of my family, my dog (Bhooma) for all the entertainment, especially in the last part when I was writing this dissertation.

Lastly, I could not have finished this journey without the support of my beautiful wife, Kalpita. You have been patient, understanding, and a supporting pillar, even in my bouts of disappointment, anger, and fits of pique. Thanks for keeping me sane throughout the whole process. I love you!

Ashish Gulagi
December 2022
Lappeenranta, Finland

This dissertation is dedicated to my family for the dream they envisioned for me and their endless love, support, and encouragement throughout my pursuit for education.

Contents

Publications

List of publications

This dissertation is based on the following publications. The rights have been granted by the publishers to include the publications in this dissertation.

I. **Gulagi, A.**, Choudhary, P., Bogdanov, D., & Breyer, C. (2017). Electricity system based on 100% renewable energy for India and SAARC. *PLoS ONE*, 12(7), e0180611. doi:10.1371/journal.pone.0180611

II. **Gulagi, A.**, Bogdanov, D., & Breyer, C. (2018). The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. *Journal of Energy Storage*, 17, 525-539. doi:10.1016/j.est.2017.11.012

III. **Gulagi, A.**, Ram, M., & Breyer, C. (2020). Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India. *IET Renewable Power Generation*, 14(2), 254-262. doi:10.1049/iet-rpg.2019.0603

IV. **Gulagi, A.**, Ram, M., Solomon, A. A., Khan, M., & Breyer, C. (2020). Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. *Renewable Energy*, 155, 899-920. doi:10.1016/j.renene.2020.03.119

V. Sadiqa, A., **Gulagi, A.**, & Breyer, C. (2018). Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. *Energy*, 147, 518-533. doi:10.1016/j.energy.2018.01.027

VI. **Gulagi, A.**, Pathak, S., Bogdanov, D., & Breyer C. (2021). Renewable energy transition for the Himalayan countries Nepal and Bhutan: Pathways towards reliable, affordable and sustainable energy for all. *IEEE Access*, vol. 9, pp. 84520-84544, 202. doi:10.1109/ACCESS.2021.3087204

VII. **Gulagi, A.**, Ram, M., Bogdanov, D., Sarin, S., Mensah, T.N.O., & Breyer C. (2022). The role of renewables for rapid transitioning of the power sector across states in India, *Nature Communications*, 13(1), 1-19. doi:10.1038/s41467-022-33048-8

The publications are numbered throughout the thesis using the Roman numerals. Reprints of each publication are included at the end of this thesis.

Author's contribution

Ashish Gulagi is the main author and investigator in **Publications I, II, III, IV, VI and VII**. In **Publications I, II, III, IV, VI and VII** Ashish Gulagi lead and assisted in conceptualising the research and identified unique and novel research questions in each of the above publications, as described in Section 1.5 of the dissertation. He collected and curated data in a high level of detail that is used as an input in the modelling. He performed the investigation and simulations, analysed the results and interpreted key discussions to answer the novel research questions framed and drew conclusions.

In **Publication V**, Ayesha Sadiqa carried out the input data analysis and paper writing, Ashish Gulagi carried out the simulations, result analysis and helped in paper writing and finding the key conclusions.

Lists of all publications

1. **Gulagi, A.**, Ram, M., Bogdanov, D., Sarin, S., Mensah, T.N.O., & Breyer, C. (2022). The role of renewables for rapid transitioning of the power sector across states in India, *Nature Communications*, 13(1), 1-19. doi:10.1038/s41467-022-33048-8
2. Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A. S., Aghahosseini, A., **Gulagi, A.**, Solomon, A. A., Keiner, D., Lopez, G., et al., (2022). On the History and Future of 100% Renewable Energy Systems Research. *IEEE Access*, 10, 78176-78218. doi:10.1109/ACCESS.2022.3193402
3. Ram, M., **Gulagi, A**., Aghahosseini, A., Bogdanov, D., & Breyer, C. (2022). Energy transition in megacities towards 100% renewable energy: A case for Delhi. *Renewable Energy*, 195, 578-589. doi:10.1016/j.renene.2022.06.073
4. Ram, M., Bogdanov, D., Aghahosseini, A., **Gulagi, A.**, Oyewo, A. S., Odai Mensah, T. N., Child, M., Caldera, U., Sadovskaia, K., De Souza Noel Simas Barbosa, L., Fasihi, M., Khalili, S., Traber, T., & Breyer, C. (2022). Global energy transition to 100% renewables by 2050: Not fiction, but much needed impetus for developing economies to leapfrog into a sustainable future. *Energy*, 246. doi:10.1016/j.energy.2022.123419
5. Keiner, D., Salcedo-Puerto, O., Immonen, E., van Sark, W. G. J. H. M., Nizam, Y., Shadiya, F., Duval, J., Delahaye, T., **Gulagi, A.**, & Breyer, C. (2022). Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives. *Applied Energy*, 308. doi:10.1016/j.apenergy.2021.118360
6. Sadiqa, A., **Gulagi, A.**, Bogdanov, D., Caldera, U., & Breyer, C. (2022). Renewable energy in Pakistan: Paving the way towards a fully renewables-based energy system across the power, heat, transport and desalination sectors by 2050. *IET Renewable Power Generation*, 16(1), 177-197. doi:10.1049/rpg2.12278
7. Caldera, U., Sadiqa, A., **Gulagi, A.**, & Breyer, C. (2021). Irrigation efficiency and renewable energy powered desalination as key components of Pakistan's water management strategy. *Smart Energy*, 4. doi:10.1016/j.segy.2021.100052
8. Bogdanov, D., Ram, M., Aghahosseini, A., **Gulagi, A.**, Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza Noel Simas Barbosa, L., Fasihi, M., & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, 227. doi:10.1016/j.energy.2021.120467
9. **Gulagi, A.**, Alcanzare, M., Bogdanov, D., Esparcia, E., Jr., Ocon, J., & Breyer, C. (2021). Transition pathway towards 100% renewable energy across the sectors of power, heat, transport, and desalination for the Philippines. *Renewable and Sustainable Energy Reviews*, 144. doi:10.1016/j.rser.2021.110934
10. Keiner, D., Barbosa, L. D. S. N. S., Bogdanov, D., Aghahosseini, A., **Gulagi, A.**, Oyewo, S., Child, M., Khalili, S., & Breyer, C. (2021). Global-local heat demand development for the energy transition time frame up to 2050. *Energies*, 14(13). doi:10.3390/en14133814

11. **Gulagi, A.**, Pathak, S., Bogdanov, D., & Breyer C. (2021). Renewable energy transition for the Himalayan countries Nepal and Bhutan: Pathways towards reliable, affordable and sustainable energy for all. *IEEE Access*, vol. 9, pp. 84520-84544, 202. doi:10.1109/ACCESS.2021.3087204
12. Bogdanov, D., **Gulagi, A.**, Fasihi, M. & Breyer, C. (2021), Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination, *Applied Energy*, 283. doi:10.1016/j.apenergy.2020.116273
13. **Gulagi, A.**, Ram, M., Solomon, A. A., Khan, M., & Breyer, C. (2020). Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. *Renewable Energy*, 155, 899-920. doi:10.1016/j.renene.2020.03.119
14. Breyer, C., Bogdanov, D., Aghahosseini, A., **Gulagi, A.**, & Fasihi, M. (2020), "On the techno-economic benefits of a global energy interconnection", *Economics of Energy and Environmental Policy*, vol. 9, no. 1, pp. 83-102. doi:10.5547/2160-5890.9.1.cbre
15. **Gulagi, A.**, Ram, M., & Breyer, C. (2020). Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India. *IET Renewable Power Generation*, 14(2), 254-262. doi:10.1049/iet-rpg.2019.0603
16. Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., **Gulagi, A.**, Oyewo, A.S., de Souza Noel Simas Barbosa, L. & Breyer, C. (2019), Radical transformation pathway towards sustainable electricity via evolutionary step, *Nature Communications*, vol. 10, no. 1. doi:10.1038/s41467-019-08855-1
17. Breyer, C., Bogdanov, D., Aghahosseini, A., **Gulagi, A.**, Child, M., Solomon, A.O., Farfan, J., Sadovskaia, K., Vainikka, P. (2018). Solar Photovoltaics Demand for the Global Energy Transition in the Power Sector, *Prog. Photovolt: Res. Appl.*, 26: 505 – 523. doi: 10.1002/pip.2950
18. **Gulagi, A.**, Bogdanov, D., & Breyer, C. (2018). The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. *Journal of Energy Storage*, 17, 525-539. doi:10.1016/j.est.2017.11.012
19. Sadiqa, A., **Gulagi, A.**, & Breyer, C. (2018). Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. *Energy*, 147, 518-533. doi:10.1016/j.energy.2018.01.027
20. **Gulagi, A.**, Bogdanov, D., & Breyer, C. (2017). The Demand for Storage Technologies in Energy Transition Pathways Towards 100% Renewable Energy for India, *Energy Procedia*, 135, 37 – 50. doi:10.1016/j.egypro.2017.09.485
21. Breyer, C., Bogdanov, D., **Gulagi, A.**, Aghahosseini, A., Barbosa, L. S. N. S., Koskinen, O., Barasa, M., Caldera, U., Afanasyeva, S., Child, M., Farfan, J., & Vainikka, P., (2017). On the role of solar photovoltaics in global energy transition scenarios. *Prog. Photovolt: Res. Appl.*, 25: 727 – 745. doi: 10.1002/pip.2885
22. **Gulagi, A.**, Choudhary, P., Bogdanov, D., & Breyer, C. (2017). Electricity system based on 100% renewable energy for India and SAARC. *PLoS ONE*, 12(7), e0180611. doi:10.1371/journal.pone.0180611

23. **Gulagi, A.**, Bogdanov, D., & Breyer, C. (2017). A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim, *Energies*, 10, 583. doi:10.3390/en10050583
24. **Gulagi, A.**, Bogdanov, D., Fasihi, M., & Breyer, C. (2017). Can Australia power the energy-hungry Asia with renewable energy? *Sustainability*, 9(2). doi:10.3390/su9020233

Nomenclature

Abbreviations

A-CAES	Adiabatic Compressed Air Energy Storage
BPS	Best Policy Scenario
Capex	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COP	Conference of the Parties
crf	Capital Recovery Factor
CPS	Current Policy Scenario
CSP	Concentrating Solar Power
DACCS	Direct Air Carbon Capture and Storage
FLH	Full Load hours
GHG	Greenhouse Gases
GWh	Giga Watt Hour
h	Hour
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Cost of Electricity
Li	Lithium
MWh	Mega Watt Hour
NDC	Nationally Determined Contribution
Opex	Operational Expenditures
OECD	Organisation for Economic Co-operation and Development
PtG	Power-to-Gas
PtX	Power-to-X
PV	Photovoltaic
PP	Power Plant
RE	Renewable Energy
TPEC	Total Primary Energy Consumption
TPES	Total Primary Energy Supply
SAARC	South Asian Association for Regional Cooperation
SDGs	Sustainable Development Goals
SNG	Synthetic Natural Gas
SoC	State of Charge
SWRO	Seawater Reverse Osmosis
UN	United Nations
USD	United States Dollar

VRE	Variable Renewable Energy
WACC	Weighted Average Cost of Capital

1 Introduction

1.1 Need for transition of the current energy systems

History tells that, transitions of the energy systems, are inevitable. An ‘Energy Transition’ *is a fundamental and systematic shift of a primary energy resource, technology, or prime mover (device that converts energy to useful services) from an existing model to a new paradigm* (Vaclav, 2010; Sovacool, 2016). Societies, in the last two centuries, have gone through these energy transitions. These transitions are often triggered by a combination of national policies and priorities, technological advancements, and the growth in energy requirements of people and industries. However, the most recent energy transition is governed not only by climate change concerns but also, energy security fears and the affordability of energy supply to boost the competitiveness of national economies (Mukherjee *et al.*, 2019; Hafner and Tagliapietra, 2020).

Energy is ingrained in all aspects of human life, powering technological advancement and economic progress throughout the history. Reflecting on the historical events, the transition of biomass to coal as an energy carrier as well as the invention of the steam engine, slingshot human societies into the modern era. Coal driven steam engines, and consequently coal powered electricity, heralded the advent of the first industrial revolution. This is followed by the second energy transition with the fast penetration of oil, as its share grew from 3% in 1915 to 45% by 1975 (Hafner and Tagliapietra, 2020). Due to its liquid state, oil was much easier to transport in pipelines and use in combustion engines. Further, it could be refined and re-synthesised to produce a large variety of liquid fuels and materials (Renn *et al.*, 2017). On the other hand, the last of the fossil fuel transition involved the partial replacement of both coal and oil by natural gas, whose share increased from 3% in 1930 to 23% in 2017 (Hafner and Tagliapietra, 2020). A common factor that led to these shifts was the higher economic efficiency of the new energy resource. Sovacool (2016) adds that these transitions are not only driven by efficiency but also by the availability and abundance of a particular energy resource.

Currently, we are at the beginning of the fourth energy transition (from fossil fuels to renewables), which, in contrast to the previous three, is driven by qualitative and quantitative new drivers. First, the most critical challenge humanity has ever faced: combating global climate change. Second, the cost competitiveness of the renewables and the energy sovereignty concerns of the countries, as highlighted by the recent Russian war. Despite the fact that fossil fuels are the foundation of global economic growth, societal development, and modern lifestyles, Grubler (2012), argues that current energy systems are completely unsustainable on all accounts of social, economic and environmental criteria. The need for a transition of the current energy systems towards long term sustainability is ever more pronounced, as large-scale greenhouse gas (GHG) emissions have caused environmental degradation, depletion of finite energy resources, and past energy transitions were unsuccessful in providing energy services to many people (Grubler, 2012).

Therefore, transitioning away from our current global energy system is of paramount importance (Sovacool, 2016). While reducing global GHG emissions is the critical driver of energy system transition, change in today's energy systems will also be due to the Sustainable Development Goals (SDG): energy security, affordable energy to power the global economy, an increase in the efficiency of the energy sector, and to change the traditional way that it functions. Thus, an energy transition should be able to satisfy all countries' desires, ensure the competitiveness of their national economies and boost development, but with a social prism of equitable and just transition, as no members of the society are left behind (Hafner and Tagliapietra, 2020; Diluiso *et al.*, 2021).

1.1.1 **Climate change driven transition**

Although the Intergovernmental Panel on Climate Change (IPCC) has been warning about the threats of global warming for three decades (Tollefson, 2021b), the latest climate report was the starkest reminder of the human impacts on climate change and stated that *'it is now unequivocal that human caused emissions from burning fossil fuels are responsible for recent warming'* (IPCC, 2021). Since the dawn of the industrial era, humans' continued dependence on fossil fuels has contributed to an increase in the Earth's global average temperature of around 1.1°C compared with the average in 1850-1900 (Tollefson, 2021b). On the other hand, it is estimated that the global temperature rise is currently accelerating by 0.2°C per decade (NASA, no date). The impact of this temperature rise is clearly visible with the recent extreme weather events like heatwaves in the northern hemisphere and extreme and abnormal rainfall in Europe and China (IPCC, 2021; Januta, 2021), with potential disruptions to entire human habitats. To give some perspective, even if the temperatures are held in check at 1.5°C, sea levels around the world are projected to rise by 2-3 metres and upto 6 metres with 2°C warming (Tollefson, 2021b). This would alter entirely the coastlines of the major cities currently inhabited by millions of people, a consequence of the melting of the Greenland ice sheet (King *et al.*, 2020). As Lenton et al. (2019) compellingly mention, 'we are in a climate emergency…this is an existential threat to civilisation'.

No country is immune to the impacts of climate change, but developing countries are more vulnerable, especially the region of South Asia, which is home to a quarter of the world's population (World Bank, 2021a). There are a growing number of studies showing that poor countries are more vulnerable and negatively affected by the impacts of climate change, mainly due to lack of resources for climate protection (Diffenbaugh and Burke, 2019) and the havoc additional warming could bring to these already warm regions, socially and economically (Burke *et al.*, 2015; Duffy *et al.*, 2019).

The issue of human impact on rising GHG levels in the atmosphere and climate change was acknowledged by the majority of the international community through the United Nations Framework Convention on Climate Change in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015 (Kompas *et al.*, 2018). The Paris Climate Agreement in 2015 was one of the most important recent conferences, where countries (developed and developing) submitted their voluntary emission targets (Nationally Determined Targets), aiming to limit global warming to well below 2°C and pursue efforts to limit to 1.5°C relative to the pre-industrial era by 2050 (UNFCC, 2015). For some years, this was the global policy makers target and the NDCs reflected this (Henderson and Sen, 2021). The latest IPCC report finds that there are high chances of global warming crossing 1.5°C in the next few decades unless there is an immediate, rapid, and large-scale reduction in GHG emissions. If large scale reduction is not achieved, limiting warming to 1.5°C or even close to 2°C will be beyond reach (IPCC, 2021). Therefore, the transition of the current energy systems to reach net-zero GHG emissions globally by 2050 would possibly avoid the worst impacts of climate change (IPCC, 2018, 2021).

In 2018, the total GHG emitted globally was 48.9 $GtCO_2e$. The energy sector was responsible for 76% of the total greenhouse gas (GHG) emissions, primarily generated from the burning of hydrocarbons in the power, industry, transport, and heat sectors (Climatewatch, 2021). Wherein electricity and heat are responsible for most of the GHG emissions with around 32%, followed by transportation, which emits about 14.2%, and manufacturing and construction activities, which contribute to 12.6% (Climatewatch, 2021). The other key sectors that produce GHG emissions are agriculture and livestock (12%), industrial processes (5.9%), waste, including landfills and wastewater emitting (3.3%), and land use, land-use change, and forestry including deforestation (2.8%) of total emissions in 2018 (Climatewatch, 2021). It is evident that human induced GHG emissions are responsible for most of the global emissions.

As a result, a rapid reduction in emissions in the energy sector is of the utmost priority. However, with a growing population in developing and least developed countries and widespread industrialisation, energy demand is projected to grow considerably in the future. Therefore, balancing the rising global energy demand with sustainable energy sources is of particular importance because at the current rate of GHG emissions, the world's remaining carbon budget to limit temperature rise to 1.5°C would be used up by the end of 2030 (IPCC, 2021).

1.1.2 **Sustainability driven transition**

An energy transition towards renewable and sustainable energy sources should not only be technical and address the climate change perspective but also encompass a broader spectrum of various sustainability constraints (Rockström *et al.*, 2009; Solomon and Krishna, 2011; Miller *et al.*, 2013). Together, the Paris Agreement in 2015 and the SDGs acknowledge the importance of developing sustainable energy transition pathways that also consider the environmental, social, and economic spheres of sustainability (Delafield *et al.*, 2021). Nerini et al. (2017) state that it is of the utmost importance that decarbonisation is not tackled independently, as energy systems are inherently associated with the natural environment and general human wellbeing.

Since the beginning of industrialisation around the 1800s, the current epoch, the Anthropocene started, a central feature of which has been the large scale use of fossil fuels (Crutzen, 2006; Steffen *et al.*, 2007). This resulted in a considerable rise in atmospheric carbon dioxide, from a preindustrial value of 270-275 ppm to around 414 ppm by 2020 (CO2 earth, 2020). Meadows *et al.* (2004) adds that, in addition to the increase in atmospheric CO_2 concentration, most of the other sustainability criteria are violated to some extent by the current energy systems using fossil fuels. The violation of sustainability criteria can be measured by the planetary boundaries (PBs) framework. It was first proposed by Rockström et al. (2009) and later updated by Steffen et al. (2015), and it provides a comprehensive and robust approach to evaluate the impacts of the Anthropocene on climate change and beyond on the stability and resilience of the Earth system (Bjorn *et al.*, 2020). Human perturbations have caused biosphere integrity, biogeochemical flows (nitrogen and phosphorus cycles), and land system change, in addition to climate change, to exceed the proposed PB of each of these earth systems. The finite resources on the planet are overexploited and consumed at rates faster than they are renewed (Rockström *et al.*, 2009; Steffen *et al.*, 2015).

Further, Child et al. (2018), adds, sustainability of energy systems should be viewed from a broader set of criteria to ensure societal risks are minimised beyond the issue of climate change. From this perspective, mitigation of climate change should not be only seen as a challenge to overcome and a target to achieve, but as a real struggle to prevent disproportionate impacts and damage associated with climate change to various sections of society, already disadvantaged by lack of economic and social wellbeing. Therefore, to avoid the unintended consequences of narrow policymaking and focusing only on GHG mitigation, it is imperative that decision-makers adopt a more holistic approach to sustainable energy transitions in the coming decades (Delafield *et al.*, 2021); otherwise, it will only reinforce the existing deep inequalities and structural injustices that in the first place caused climate change (O'Brien *et al.*, 2009).

1.1.3 Economics and accessibility driven transition

Affordability and accessibility are two of the important dimensions of the 'Energy Trilemma' and a central pillar of the SDGs. In particular, SDG 7 sets the target to 'ensure access to affordable, reliable, sustainable, and modern energy for all' (United Nations, 2017).

Currently, 759 million people have no access to electricity, while 2.6 billion depend on traditional polluting cookstoves and fuels (United Nations, 2021b). To compound the existing problems, the economic difficulties and risks from the Covid-19 pandemic are moving many people and areas further away from the goal of achieving universal access to electricity (World Bank, 2021e; Lazaro *et al.*, 2022). The lack of access to modern energy not only limits opportunities for income generation but also diminishes efforts to escape poverty for the poorest and most vulnerable populations. It also severely impacts women and children and contributes to global deforestation and climate change (United Nations, 2021b). Without access to basic energy, especially electricity, many households across the developing world must rely on primitive forms of lighting like candles, biomass, and kerosene lamps that burn fuel.

Globally, the affordability of energy is another significant challenge for households. A higher impact is observed for people living in energy poor countries, where 57% of the people spend more than 5% of their gross nominal income on energy needs (IEA *et al.*, 2018). As an example, in tropical and temperate climates, households are not expected to spend more than 5% and 10% of their monthly income on energy (Adenle *et al.*, 2020). Despite bearing huge costs, these households receive only 0.1% of the world's lighting energy services (Adenle *et al.*, 2020). For cooking, conventional or traditional open fire stoves cause household air pollution, a major source of premature deaths (WHO, 2021). In addition, traditional cooking fuels and stoves lead to numerous disabilities from burns, scalds, and poisoning. This leads to diminished income generation and educational and personal improvement opportunities due to the time spent or wasted on gathering fuel and using time-inefficient cooking practices. The impact is disproportionately distributed, with women and children bearing the heaviest burden (WHO and World Bank, 2014).

Thus, universal access to affordable, reliable, and modern energy services will benefit the households suffering from energy and economic poverty, improving the living and working conditions for the poorest and most vulnerable populations (United Nations, 2021b). For example, access to affordable clean energy can directly improve people's basic living standards and enhance their economic status, efficient agricultural methods, gender equality, and the quality of health and education services. An energy transition with the inclusion of SDG 7 targets is integral to the overall success of achieving a just and equitable transition (United Nations, 2021a).

1.1.4 Energy security driven transition

The International Energy Agency (2022a) defines 'energy security' as; uninterrupted availability of energy resources at an affordable price. Energy security is of critical importance to many energy importing countries, as either disruptions in energy supply or sudden price volatility could render supply unaffordable (Hoang *et al.*, 2021). Thus, energy insecurity creates barriers to human development and growth, especially in least developed and developing countries (Mayer, 2022). On the other hand, more than 80% of the population lives in countries that are net importers of fossil fuels (IRENA, 2019a).

Energy security has shaped various policies, international relations between countries, the formation of alliances, protection of national interests, and wellbeing of citizens (Kovacovska, 2010). This dependence has made countries vulnerable to the risks of supply chain disruptions; as observed recently due to Covid-19 and price volatility, and as observed in the case of the Russian invasion of Ukraine (Vaka et al., 2020; Chofreh et al., 2021; Liu et al., 2021; Bricout et al., 2022; Tollefson, 2022). On an economic front, countries dependent on large volumes of fossil fuel imports face currency fluctuations amid volatile fuel prices and trade deficits (IRENA, 2019a; Balli *et al.*, 2021). Thus, robbing developing countries of social and economic development, often plunging them into debt crises (Huntington, 2015; Balli *et al.*, 2021). Additionally, high fossil fuel prices cause stagnation in economic growth, resulting in rising inflation (Costantini and Gracceva, 2004; Edenhofer *et al.*, 2013; Kamber and Wong, 2020). As a result, energy security is critical in today's global geopolitics. In view of its importance, Azzuni and Breyer (2018, 2020) developed a comprehensive definition and dimensions to quantify and measure the energy security of individual countries.

To overcome the issue of energy security and decrease dependency on fossil fuel imports, countries should focus on developing indigenous renewable resources and transition towards integrating a large share of renewables in their energy systems (Azzuni *et al.*, 2020). This will change the dynamics of energy exporters and importers. Thus diminishing the role of oil and gas from the international politics (IRENA, 2019a). Increasing the share of renewables in the energy mix can help mitigate risks while also providing new bursts of economic growth. Thus, the current energy transition will also be driven by the ever changing geopolitics and energy autonomy concerns of individual countries around the world.

1.2 Trends in global energy systems

Fossil fuels' usage in global energy systems has grown rapidly in the last few decades (Jackson *et al.*, 2018). The bulk of this growth in energy consumption was largely driven by the ever growing population, industrialisation, strong economic growth, and increasing standard of living in emerging and developing countries, which is converging towards that of the developed countries. To put it into perspective, global fossil fuel consumption has grown by 69% from 1990 to 2019 (Ritchie *et al.*, 2020). This has resulted in a burgeoning of CO_2 emissions from the energy sector, growing by almost 61% during the same period (Ritchie *et al.*, 2020). Therefore, the global society is in a precarious position of meeting growing energy demand while averting the worst effects of climate change, the greatest challenge ever faced.

The growth in energy demand during the last century has been phenomenal across the world. First, driven by the current developed countries during their phase of industrial and economic development. Second, by the developing countries, especially China and India, during the last few decades. The growth in energy demand is projected to continue with new regions seeking access to modern energy services and growing aspirations for better standards of living (IEA, 2021b). The total primary energy consumption (TPEC) across the world increased from 43,075 TWh in 1965 to 153,593 TWh in 2020, an increase of almost 256% (Ritchie *et al.*, 2020). In the past, the growth in primary energy consumption was mainly covered by fossil fuels, and the situation is not much different today as well. As shown in Figure 1, fossil fuels usage is still growing, however, renewables are slowly gaining momentum in the primary energy consumption. The share of fossil fuels in TPEC was only six percentage points lower in 2020 than it was in 1965, as 88% of the total primary energy consumption was still covered by coal, oil, gas, and nuclear in 2020 (Ritchie *et al.*, 2020).

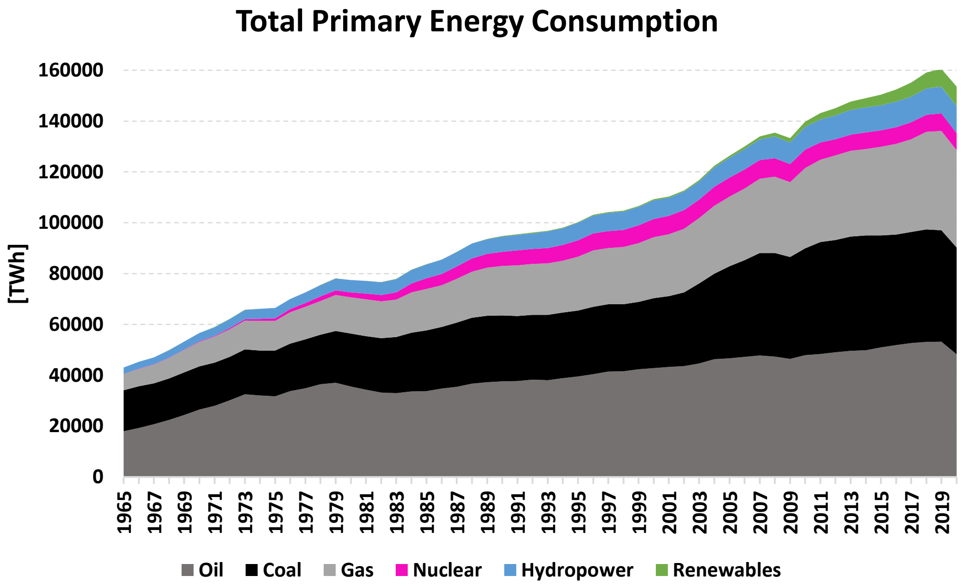


Figure 1: Global primary energy consumption from 1965 – 2020. Data adopted from (Ritchie *et al.*, 2020).

While TPEC may not be the right metric, especially when comparing fossil fuels with renewable generated electricity, as the inefficiency of fossil fuels is not reflected. Thus, the Total Final Energy Consumption (TFEC) is a better metric for reporting energy consumption. For instance, the inefficiency of fossil fuel use in road transport is still not considered well enough. On the final energy side, TFEC was 116.1 PWh in 2019 (IEA, 2020b). The transport and power sectors consumed 32% and 17% of the TFEC, while the heat sector had the largest share of 51% in 2018 (REN21, 2021). The share of modern renewables in TFEC increased from 8.7% in 2009 to 11.2% in 2019 (REN21, 2021). However, there has not been much change in the share of fossil fuels during this decade. This calls for a rapid transition towards renewables gather steam in all sectors. The global power sector has been a front runner, with a share of renewables growing rapidly from 20% in 2010 to 28% in 2021 (Ember, 2022b).

The critical events of the last couple of years have accentuated the need to accelerate the global energy transition away from fossil fuels (IRENA, 2022c). First, the Covid-19 pandemic had a major impact on the energy markets dependent on fossil fuels. The governments instituted lockdowns around the world, which resulted in energy demand and CO_2 emissions plummeting (Quitzow *et al.*, 2021). In a year, the primary energy demand fell by 4%, while the resulting CO_2 emissions from the energy system fell by

6.4%, the largest drop in history (REN21, 2021; Tollefson, 2021a). Second, the Russian war in Ukraine has bought new levels of concern and uncertainty across the world. Oil and gas prices have reached new highs, raising costs for the global economy, which is heavily dependent on fossil fuels and raising concerns about energy security (IRENA, 2022c). Therefore, acceleration of the energy transition towards renewables is necessary for long term energy security, price stability, and resilience.

Despite ongoing disruptions in the energy system, especially due to Covid-19, the renewable sector was quite robust during this period. The installed renewable power capacity reached a record high of almost 280 GW in 2020 (more than 80% of the newly installed capacity) (IEA, 2020d; IRENA, 2021b), whereas the installed fossil capacity decreased in comparison to 2019. By the end of 2021, the total installed renewable capacity reached 3064 GW, generating an estimated 8000 TWh of electricity (IRENA, 2022c). Among renewable technologies, solar photovoltaics (PV) and wind power have seen the fastest growth, with solar PV capacities growing by 25 times from 2011 to 2021 to reach added capacities of 904 GW, leading to a total cumulative installed capacity of 942 GW globally by the end of 2021 (IEA-PVPS, 2022). During the same period, wind power grew almost three times, reaching added capacities of 646 GW during this period and a total cumulative installed capacity of 837 GW (GWEC, 2022). In 2021, the global investment in energy transition towards low carbon technologies garnered an investment of 755 billion USD, an increase of almost 27% compared to 2020 (BloombergNEF, 2022). New renewable energy installations and small scale systems formed a major share of these investments, amounting to 366 billion USD (BloombergNEF, 2022). These large scale installations of renewables were spurred by lower investment costs and policy support. The average cost of electricity generation worldwide from utility-scale solar PV decreased dramatically by 85% between 2010 and 2020 (IRENA, 2021d). At the same time, the cost of electricity production from onshore wind decreased by 56% and offshore wind by 48% (IRENA, 2021d). Today, utility-scale solar and wind technologies typically fall in the range of, or are even the cheapest, compared to electricity generation from new fossil-fuel plants. In many regions, especially in developing countries that are dependent on coal like China and India, it has already become cheaper to build new wind power or solar PV plants than to operate existing coal-fired power plants (Mathis, 2021). Clearly, this has added financial stress to the existing coal power plants in many countries, which was amplified even further during the pandemic. Even when coal generation rebounded in 2021, the benefit of higher capacity factors in amortising coal plants' fixed operation and maintenance costs was not observed given the spike in coal prices (IRENA, 2022c). Despite all the progress made, there are still large gaps between the current growth of renewables and the deployment needed to achieve the 1.5°C target by 2050 (Papadis and Tsatsaronis, 2020). With the relative cost competitiveness of renewables and all their other advantages, governments should accelerate the energy transition towards renewables in all energy sectors.

1.3 South Asia – A key driver of global energy demands

The main region of focus in this dissertation is South Asia, also called as South Asian Association for Regional Cooperation (SAARC). This region comprises of the following countries Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. Due to its distance from the mainland, Maldives was not part of this research. However, the energy system of the Maldives was studied in detail by Keiner et al. (2022).

The South Asian region is home to more than 1.8 billion people, i.e., about 24% of the world's population lives in these countries. This results in countries from this region being among the most densely populated in the world (Rahman *et al.*, 2020). According to the United Nations (2019), the Maldives ranks 7th by population density, followed by Bangladesh (10th), India (29th), Sri Lanka (40th), Pakistan (49rd) and Nepal (72th). The population is projected to grow to 2.2 billion by 2050, with the highest CAGR observed in Afghanistan and Pakistan (Roser, 2013b). Additionally, the Gross Domestic Product (GDP) is also projected to grow for the major economies in the region: India, Bangladesh, and Pakistan by an average of 3.5% per annum (PwC, 2017). On the other hand, even with such a high population, all countries combined only account for 8% of the TFEC of the world in 2019 (IEA, 2020b).

With rapid growth in population, economic development, and growing urbanisation, the situation is changing, as energy consumption per capita has been rising in the region, and the trend is expected to continue (Shrestha *et al.*, 2007; IEA, 2021c; Zhang *et al.*, 2021). The TFEC grew by a CAGR of 1.7-4.2% between 2000-2019 for the countries in the region. India and Bangladesh recorded the highest growth, of 4.2% annually. Figure 2 shows the absolute growth in TFEC from 1990 to 2019 for selected South Asian countries.

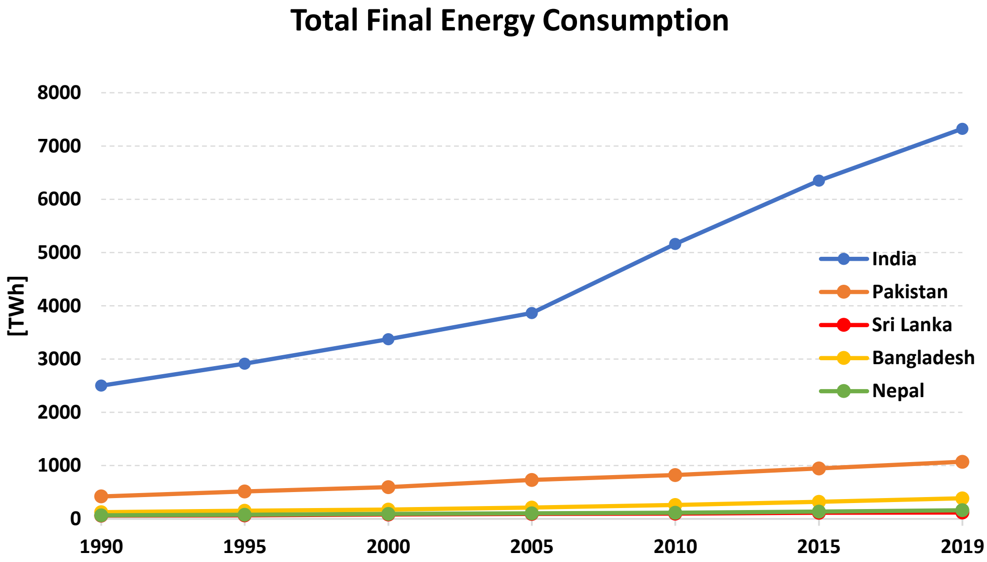


Figure 2: Total final energy consumption in selected South Asian countries from 1990 - 2019. Data from IEA (IEA, 2020b).

With an extended period of rapid economic and energy demand growth before the Covid-19 pandemic, the South Asian region has achieved impressive improvements in human development and providing energy access to millions of people (García-Escribano *et al.*, 2021; World Bank, 2021a). The onset of the Covid-19 pandemic had far reaching consequences in this region, as GDP and energy demand decreased drastically (United Nations, 2021c). However, due to fiscal and monetary stimulus, rapid economic recovery was possible, and in turn, energy demand and CO_2 emissions rebounded sharply (IEA, 2022b). As a major economy in the region and the world, India's long term energy demand is projected to grow at a CAGR of 2.6% (IEA, 2021a). In the coming decades, the expected economic growth combined with the current low per capita consumption levels, and growing aspirations of the rising population indicate that this will have a major impact on the future global energy demand (Song, 2019; World Bank, 2021d). More importantly, for satisfying the growth in energy demand, if the current dependence on fossil fuels is maintained, this will cause a considerable rise in GHG emissions as well as pose a growing challenge to the national energy security of the individual countries (World Bank, 2021d). Therefore, moving forward, South Asia's energy transition will need to be clean, sustainable, resilient, and inclusive of a developmental trajectory, away from fossil fuels and their imports.

1.3.1 Current energy landscape in South Asia

The South Asian countries have transitioned from predominantly rural and agriculture based economies to urban economies driven by services and manufacturing industries (IFAD, 2019). The service sector in the region accounts for an average of 52% of the GDP, while manufacturing and industry accounted for 33% in 2020 (World Bank, 2022b). Through the decades of rapid economic and population growth, urbanisation, and increased access to electricity, energy consumption has steadily increased across all the demand sectors and is expected to continue to grow, especially electricity demand. To fuel this rapid growth in TFEC and electricity demand, total primary energy supply has increased by a CAGR of 4.2% between 2000 – 2019. So far, the region's energy supply has come from fossil fuels, as seen in Figure 3. The use of fossil fuels has supported economic growth, helped millions of people gain access to energy, and improved standards of living, but it has also created major challenges.

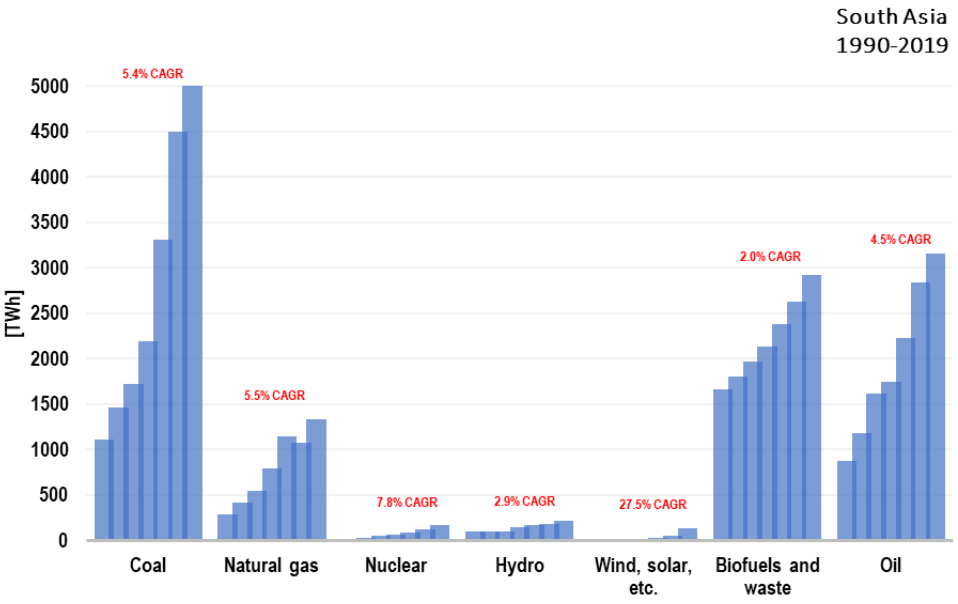


Figure 3: Total primary energy supply in selected South Asian countries from 1990 - 2019. Data adopted from IEA (IEA, 2020b).

In 2000, biomass was the major source of fuel in all the South Asian countries. However, its relative dependence has started decreasing since 2000, as coal, natural gas, and oil started gaining importance. The share of fossil fuels and nuclear power combined increased at a CAGR of 5.1% from 2000-2019, in the region to meet the incremental growth in demand (IEA, 2020b). In 2019, fossil fuels accounted for a 75% share of the

TPES in the region (IEA, 2020b). The largest share of fossil fuel usage was observed in Bangladesh, which accounted for 81% of the TPES, with natural gas accounting for a share of 59% (IEA, 2020b). In 2018, the lowest share was observed in Bhutan, with 18% of the TPES coming from coal and oil (IRENA, 2021e). The main sources of energy supply were coal in India, natural gas in Bangladesh and Pakistan, oil in Sri Lanka and the Maldives, and biomass in Nepal, Bhutan, and Afghanistan (IEA, 2020b). Hydropower supply has been relatively stable in most of the countries, except Nepal and Bhutan, where the shares have increased in the last decade. Solar PV and wind power shares have increased rapidly in the last few years, especially in the electricity sector, from an almost negligible share in 2000. However, currently they account for less than 1% of the TPES (IEA, 2020b).

The South Asian region is a net importer of energy, as domestic energy supply has not kept up with rising energy demand (World Bank, 2021b). Also, most of these countries do not have proven indigenous oil and gas reserves, or their domestic fuel reserves are insufficient to satisfy the growing demand (Rahman *et al.*, 2012). In 2019, about 40% of the TPES came from imported fuels, with India importing almost half its TPES (IEA, 2020b). As observed from the recent pandemic and Russian war in Ukraine, fuel imports are becoming increasingly risky due to high volatility in global energy markets (Fuentes and Chapman, 2021; World Bank, 2022a). Thus, energy security has the ability to shape various policies and the national behaviour of the countries in the South Asian region. Azzuni and Breyer developed and analysed energy security within the scope of 15 dimensions (Azzuni and Breyer, 2018, 2020). This is one of the most comprehensive and detailed approaches to quantifying the level of energy security with an ‘energy security index’ for each country. For the South Asian countries, the energy security index is between 34% and 53.7%, with the highest achieved by India and the lowest by Afghanistan. Germany, with an energy security index of 58.2%, has achieved the highest energy security performance. Therefore, energy security must be the top priority for the South Asian countries, and a transition towards large scale integration of renewables would help achieve that, as shown by Azzuni and Breyer (2020), for the case of Jordan, a country with a very low energy security index score.

South Asian electricity demand and generation have grown rapidly in the past decade. Its electricity demand has been among the world’s fastest growing with a 5.5% CAGR since 2000 (Ember, 2022a). However, the generation mix is dominated by fossil fuels, particularly coal and natural gas. Total generation across the region almost doubled between 2010–2020 (Ember, 2022a). In 2020, fossil fuels represented 77% of the total electricity generation mix in the region (Ember, 2022a), but renewable electricity generation, particularly from solar PV and wind power, is increasing rapidly, particularly in India, supported by ambitious targets, policy measures, and a rapid decline in costs. Figure 4 provides the electricity generation from 2000 to 2019.

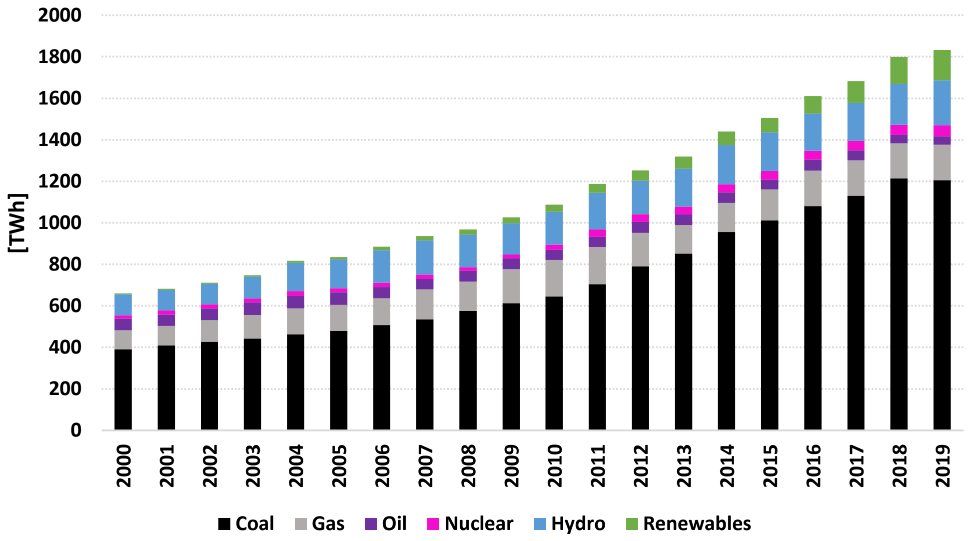


Figure 4: Total electricity generation in South Asia from 2000 - 2019. Data adopted from Ember (2022a).

1.3.2 Special focus on India

On the global stage, India has a major presence, given that it is the second most populous country in the world and the fifth largest economy (IEA, 2021a; World Bank, 2022b). It is responsible for 6.4% of the global total and accounts for 80% of the region's GHG emissions (World Bank, 2021a). According to the IEA (2021a), the TFEC is projected to double by 2050, while the CO_2 emissions are projected to increase by 1.5 times in the Stated Policies scenario of the IEA. Going forward, the potential for energy demand and the infrastructure needed remains enormous. Consequently, how the needs of what is soon to be the most populous country in the world are met will have a huge impact and influence on global trends, especially in the successful mitigation of climate change (Swamy *et al.*, 2021a).

On a per capita basis, India's CO_2 emissions are 60% lower than the global average of 4.76 tCO_{2eq}, but its emissions intensity from electricity generation is one of the highest in the world (IEA, 2021a). Over the past few decades, India's emissions have increased faster than the global average. In 2018, it was the world's third-largest emitter of GHG emissions with 3.3 billion tCO_2eq after China and the United States (Global Carbon

Project, 2021), with the energy system alone accounting for more than 70% of the total GHG emissions (Climate Watch, 2020). Despite the temporary reduction in GHG emissions due to the Covid-19 induced recession, CO_2 emissions jumped strongly in 2021, rising to 80 Mt above the 2019 levels as coal powered generation reached an all-time high (IEA, 2022b). Furthermore, as India continues to experience steady growth in its population and socio-economic development, its energy demand, and in particular its electricity consumption, is projected to rise considerably (IEA, 2021a). At the same time, India's urban population is projected to more than double by 2050, contributing to a significant increase in GHG emissions (He *et al.*, 2021).

Although India has made considerable progress in providing electricity access to the majority of its households, infrastructural challenges and reliability issues persists (Bali *et al.*, 2020). On the other hand, progress in adopting clean cooking fuels is slow, with 681 million people still relying on traditional biomass use (IEA, 2019c). Moreover, India has been consistently ranked among the top countries that are most vulnerable to the effects of climate change (Eckstein *et al.*, 2021). The country faces a trilemma of energy security, affordability, and sustainability, as its choices would impact the global fight against climate change. Therefore, the development of renewable energy pathways is crucial for achieving the goal of net zero emissions globally. Additionally, it would also mitigate the domestic effects of climate change over the coming decades.

While India has done its fair share of climate change mitigation efforts, as it is the only G20 country on the path to achieve its stated NDC, however, its efforts fall well short of limiting global warming to 1.5°C (Liu and Raftery, 2021). Recently, at the COP 26 conference in Glasgow, India pledged to achieve net zero carbon emissions by 2070 (Vaidyanathan, 2021). While this may be a significant shift, it is not ambitious enough to limit the global temperature rise to less than 1.5°C. With not enough ambitious targets from countries like India, the world would hit the 1.5°C target even if the developed countries set targets earlier than 2050 (Vaidyanathan, 2021). With renewables at cost parity or even lower in cost than the current fossil fuels, investing in them would transition the energy system at a faster pace than the pledged targets.

As most of the infrastructure of the future is yet to be built, India can leapfrog towards future low cost renewable technologies, especially solar power and batteries, for its energy needs. India is in a unique position to pioneer a new model for transition towards a low carbon energy system with inclusive growth, achieving the SDGs, and providing the foundation for long lasting prosperity and energy security. If this is possible, it will show a way for energy-hungry developing and growing economies around the world and in particular the Sunbelt, demonstrating that robust economic expansion is fully compatible with an increasing pace of emissions reductions and the achievement of other development goals (IEA, 2021a).

1.4 Implications of the current energy policies

The South Asian region is not a major source of historic GHG emissions (IEA, 2021a; World Bank, 2021a). However, as it has expanded its energy system and electricity generation has grown rapidly, dependency on fossil fuels has increased considerably, contributing to growing GHG emissions. Currently, it accounts for 7.8% of global GHG emissions (World Bank, 2022a). It is also expected to be one of the major sources of GHG emissions in the future, due to its dynamic economic growth and industrialisation. Apart from the climate change concerns, the use of fossil fuels causes considerable environmental degradation, particularly air pollution. This dependency on fossil fuels has resulted in 42 out of the top 50 most polluted cities in the world being in India, Pakistan and Bangladesh (Shetty, 2021). Thus, reliance on fossil fuels causes negative effects on the economy due to environmental damages caused by air pollution (World Bank, 2022a), as well as other issues like inefficient use of countries' financial resources (subsidies), health problems or even death, geopolitical risks and social risks, like pushing households into poverty.

The South Asian region is one of the most vulnerable to climate change (IPCC, 2022). According to the Global Climate Risk Index, 800 million people in South Asia live in extreme climate hotspots that are vulnerable to flash floods due to melting glaciers and landslides (Nepal and Bhutan), rising sea levels (Sri Lanka, Bangladesh, and the Maldives) and heatwaves (India and Pakistan) (Eckstein *et al.*, 2021). Globally, most of the countries in the region are ranked as the most vulnerable. The region's vulnerability is compounded by its large population, which is dependent on sectors like agriculture, fishing, and tourism, which are directly affected by climate change (Levin *et al.*, 2022). This will in turn decrease economic productivity, causing a decline in living standards. According to estimates from the Asian Development Bank, if climate change effects are neglected, the entire region's economy will lose an average of 1.8% of its annual GDP, rising further to 8.8% by 2100 (Ahmed and Suphachalasai, 2014).

Even with the decreasing role of agriculture in the region, it still accounts for an average of 19% of the total GDP in 2020, with some variations observed across the countries (World Bank, 2022b). Therefore, the sector holds significance for the local economies and the large population dependent on it. Fresh water, once abundant in the region, is under increasing stress due to population and socioeconomic growth, and urbanisation, while climate change is creating additional uncertainties (IFC, 2017; Hofste *et al.*, 2019).

Additionally, freshwater usage in fossil power plants is adding burden to an already water stressed region (Kressig *et al.*, 2018; Lohrmann *et al.*, 2019). On an average, fossil fuel based power plants require 200 times more water withdrawal than modern renewable based electricity generation (IRENA, 2015). Already, India has suffered huge losses due to the unavailability of cooling water for its thermal power plants, resulting in outages, with losses amounting to 14 TWh of electricity (enough to cover Sri Lanka's annual demand) and costing utilities 1.4 billion USD in revenues (Luo and Christianson, 2018; Gajardo *et al.*, 2021). Thus, vulnerabilities in water availability will pose serious risks to the energy supply and food production, affecting affordability, availability, and accessibility. Consequently, an increase in competition for water, energy, food, clean air, and other essential resources will create social and economic tensions between the countries and regions (IRENA, 2019a). On the other hand, renewable energy technologies have the potential to address the water-energy-food nexus, bringing substantial benefits in all the three sectors (IRENA, 2015) and contributing to achievement of the sustainable development goals.

1.5 Motivation and key research questions

The South Asian region is at the crossroads of a transition in the current energy system. While previous decades of transition towards the current energy system provided impetus to economic growth and improved the lives of millions of people by providing energy services, this has also created various challenges. These challenges are such that they are hard to ignore. With the changing geopolitical world, energy security will hold importance, as well as providing uninterrupted and reliable power to the growing population. Beyond the issue of energy security and supply reliability, the region is extremely vulnerable to the impacts of climate change like droughts, heatwaves, and floods. These effects are already visible at 1°C warming. Their intensity and frequency will continue to grow with further warming (Climate Analytics, 2019). Therefore, limiting the global temperature rise to 1.5°C or below by 2050, in line with the recent warning by the IPCC and the Paris Agreements, will reduce the impacts and risks in this region (Climate Analytics, 2019). Thus, a shift in the strategy away from coal and oil based energy systems towards renewable energy would help mitigate the above challenges. An energy transition towards a large share of renewables would address the trilemma of energy security, accessibility, and affordability, with additional benefits of reduction in air pollution and addressing the issue of water scarcity. The countries in the region need to investigate a least cost combination of renewable resources that can power the growing energy demand, enhancing energy security, limiting emissions, and improving the general wellbeing of the people.

Against this premise, the overall aim of this research is to model, analyse, and assess various pathways and scenarios towards integrating large shares of renewables in the power and energy system for the South Asian region and the individual countries within the region. The main emphasis of this dissertation is on studying the integration of variable renewable technologies and various flexibility solutions towards the transition from the current fossil fuel based energy systems to a fully sustainable energy system compatible with the 1.5°C target and the Paris Agreement. This dissertation focuses on the transition of the energy systems of the entire South Asian region and the individual countries within it; however, the findings are also applicable to the developing countries in the Global South with similar characteristics of the energy system. In addition, as Breyer et al. (2022) pointed out, there is a strong imbalance of 100% RE studies between the Global North and Global South. As one of the fastest growing and most populated regions, this dissertation will add to the transition studies in the Global South. Thus, for successful mitigation of climate change, 100% RE system studies in the Global South should not be neglected. Furthermore, this dissertation contributes to the existing knowledge and understanding of various studies on the energy transition pathways for the entire region and individual countries. After a critical literature review and reviewing the previous energy transition studies for the regions studied in **Publication I – VII** and from Table 2, some new and unique research gaps were identified and answered throughout this dissertation through the peer-reviewed publications.

1. ***Is a fast transition towards a large share of renewables in the power sector technically feasible and economically viable for a region home to 25% of the world's population and rapidly growing power demand? What is the role of regional and sector integration of the power systems in the region?***

Currently, the SAARC region is primarily dependent on coal, oil, and natural gas for its electricity production, with huge subsidies allocated for fossil fuels. There is a need to transition from the current unsustainable mix towards renewables due to energy security concerns, environmental consequences, and vulnerability to climate change. This region is rich and endowed with a vast potential of various renewable resources (refer to section 2.6). Furthermore, three different scenarios were studied for this region based on the interconnections between the sub-regions and an additional scenario showing the flexibility offered by seawater reverse osmosis (SWRO) desalination and Power-to-Gas (PtG).

Despite the importance of this region, there is no research on transition of the power sector towards large share of renewables or none have integrated all aspects of an energy system like the portfolio of technologies, flexibility options and transmission grids in a high spatial and temporal resolution, as it is done in this research.

For these reasons, **Publication I** answers to the primary research question and other sub questions.

2. *Based on energy independency concerns, how countries within the South Asian region transition towards an energy system based entirely on renewables by 2050?*

A deeper view on individual country level analyses was conducted based on detailed analysis of the regional power system transition, and the results are presented in **Publications II, IV, V, VI and VII.** Transition of the current power system for individual countries in the region is undertaken to highlight the differences and the possibility to study each country in detail. Additionally, it is also shown that each country in South Asia can transition towards a 100% RE-based system independently, utilising its own indigenous renewable resources. A transition pathway clearly shows the investments needed during each of the transition steps. This is particularly important to avoid technology lock-ins (stranded assets) and show that the hourly demand for an entire year can be satisfied with the indigenous RE sources with a least cost portfolio of technologies.

This analysis was carried out for India on a 10-node resolution and the results are presented in **Publication II**, while a more detailed view of a state-level transition applying a unique and newly developed methodology is shown in **Publication VII**. The overall results of these two publications show that the transition from a primarily dispatchable coal-based generation to a fully RE-based generation dominated by solar PV and Li-ion battery hybrid is lower in cost than the current fossil-based system. Wind and hydropower provide the required complementarity to a solar based generation.

In **Publication IV**, various transition scenarios are analysed for Bangladesh after studying the local energy policies and future energy planning. The transition from a natural gas-based power system to a solar PV based, fully RE-based system is lower in cost than the current policy approach by the government.

In **Publication V**, a transition from the current gas and oil dominated electricity generation system, with a very high fuel cost for Pakistan is modelled and analysed. The results show that Pakistan can reduce its power generation costs by more than half by installing solar PV and batteries.

The Himalayan countries, Nepal and Bhutan, present an interesting case, as the current power generation is entirely based on hydropower, while other sectors, such as heating and transport, are completely based on unsustainable biomass and imported fossil fuels, respectively. **Publication VI** shows that an energy transition towards a sustainable and secure energy system for all sectors is possible for Nepal and Bhutan by utilising primarily solar PV and complementing it with hydropower and dispatchable biomass. A fully RE-based system is both, technically feasible and economically viable despite having substantial limitations in infrastructure and economic development currently.

The common denominator of the transition towards a large share of renewable energy in each of these countries is the role of solar PV and batteries.

3. *How a power system based on high shares of variable renewable energy, especially solar PV, operates in the monsoon season? What are the flexibility and complementarity options available to the power system?*

The monsoon season presents a unique challenge to a fully renewable, solar dominated power system in South Asia. The monsoon of South Asia, also called the Southwest monsoon, is a phenomenon that largely affects the entire South Asian region; however, its pattern is defined by the arrival of strong south-westerly winds at the South-west coast of India and then travelling through the entire sub-continent. The arrival of the monsoon causes an increase in wind availability across southern and western parts of India. On the other hand, there is a decrease in solar resource availability due to cloudy and rainy weather.

The effect of monsoon on a solar PV-dominated power system in India is studied in detail for 2050 and the role of wind energy, transmission grids and storage technologies in mitigating the monsoon effect is analysed in **Publication III and Publication IV.**

4. *A high VRE share in the power system needs various flexibility options. Based on this, what is the role of storage technologies, transmission grids, and Power-to-X in energy transition pathways?*

Large scale integration of renewables requires various flexibility options to balance the intermittency and variability and create a reliable electricity distribution system. Storage technologies such as batteries and PtX balance the temporal variability, while transmission grids balance the spatial variability of renewable resources. Sector coupling with non-industrial gas demand and other additional demand sectors like heat and transport add further flexibility to the power and energy system.

Detailed analyses on the demand and role of storage technologies, transmission grids, PtX and sector coupling in the transition of the power system of India is given in **Publication II and VII.** While for other countries in the region, the role of these flexibility options is analysed in **Publication I, IV, V and VI.**

5. *Air pollution is a major issue in most of the cities in South Asia. Will a transition towards large share of renewables in the energy sector reduce GHG emissions and achieve the net zero target by 2050?*

The energy system is responsible for the majority of the GHG emissions in the South Asian region. Dependence on coal, oil, and natural gas for power generation has created huge issues with air pollution, resulting in a large number of mortalities. On the other hand, integrating renewables in the transition has resulted in reduced GHG emissions and cleaner air in cities around the world.

Publications I, II, IV, V, VI and VII highlight the trajectory of GHG emissions during the transition towards 100% RE-based systems by 2050.

The main aim of this dissertation is to frame these novel research questions and answer them using the complex LUT-ESTM model, rather than actively develop the model itself.

1.6 Scope of the research

This dissertation contributes to the constructive discourse of energy transition towards renewable and sustainable energy systems in the South Asian region and countries within it. It provides an open, techno-economic, and analytical approach towards creating transition pathways for cost optimal, 100% renewable-based energy systems. While the transition pathway varies for each country within the region, the overall structural outcome would be relevant to the countries in the Global South with similar characteristics. However, careful analysis should be done before interpreting results for regions and countries that were not part of this research.

Specific research questions are asked in each publication included in this dissertation. However, the central theme of the research was to show from a large region such as South Asia to a small sub-region or a country like Nepal and Bhutan, that a transition towards 100% RE is technically feasible and economically viable, except for **Publication III,** which shows a detailed analysis of the monsoon phenomenon on a 100% renewables-based power system**.** This research was guided by an important research question: '*How will a 100% RE based power system with a large share of solar PV in its electricity supply operate in the 3-4 months of the monsoon season*?'

1.7 Scientific impact of this research

This research has comprehensively and extensively analysed the techno-economics of energy transition pathways towards long term sustainability for the South Asian region as a whole and for India, Pakistan, Bangladesh, Nepal, and Bhutan as individual countries. This dissertation further adds to the existing knowledge on energy transition pathways at high temporal and spatial resolution with a large portfolio of generation, storage, transmission, and flexibility providing technologies. Furthermore, first of their kind research insights are presented and highlighted across **Publications I to VII**. The transition pathways shown for the region and individual countries could cater to the policy decisions for decarbonizing the region and the countries and complying with the 1.5°C target by 2050.

Some of the key novelties are:

- **Publication I** is a first-of-its kind study aimed at modelling a cost optimal, 100% RE based power sector for the South Asian region in 2030. Various transmission grid development and sector integration scenarios were analysed on an hourly scale for an entire year. Furthermore, the LCOE of different scenarios was compared, and detailed analyses were presented.

- **Publication II** is the first study to show a transition pathway based on an hourly resolved model for a 10-node Indian power sector towards 100% RE by 2050, which is compatible with the Paris Agreement and the 1.5°C target. Furthermore, it also quantitatively shows the demand and role of storage technologies during this transition. Further, detailed research was presented on a state-level analysis of the transition towards a 100% RE-based power system by 2050 in **Publication VII.**

- **Publication III** is the first study to analyse the complementarity of solar PV and wind power and the role of transmission grids and storage technologies in mitigating the monsoon effect in a 100% RE-based power system that is highly dependent on solar PV in 2050.

- **Publication IV** is the first study for Bangladesh that compares various energy transition scenarios, mainly the Current Policy Scenario – a transition pathway based on the government’s future policy direction, and the Best Policy scenario – a transition pathway to achieve a 100% RE-based power system by 2050. Various comparisons between the results of the scenarios are analysed and presented. **Publication V** presents for the first time a scenario comparison between the power only scenario and an integrated scenario where demand for seawater reverse osmosis and non-energetic industrial gas are added to the power demand, for the case of Pakistan.

- **Publication VI** is a first-of-its kind study for the Himalayan countries Nepal and Bhutan, showing an energy transition for the sectors coupled: power, heat and transport sector towards 100% RE by 2050. Further, this study quantitively and qualitatively compares two scenarios based on the cost associated with GHG mitigation, i.e., the carbon cost. This study explores the importance of sector coupling in an energy system.

1.8 Structure of this dissertation

The dissertation is structured as follows:

Chapter 1 contextualises the need for an energy transition, gives important background information of the energy situation in South Asia and the relevancy of this region and India in the global energy context. It also states the motivation and key research questions, and further elaborates the scope and the scientific impact of this research.

Chapter 2 gives further information on the current and future trends in the energy system, the potential of renewable energy and the role of India driving the renewable energy transition in South Asia.

Chapter 3 presents the applied methodology, introduces the modelling tool for the simulation, the LUT Energy System Transition Model, the input data used, and the technologies used in the modelling.

Chapter 4 presents the key findings and results from the publications that comprise this dissertation.

Chapter 5 discusses the results and the broader implications of this entire dissertation.

Chapter 6 draws the final conclusions.

References and the original publications that comprise this dissertation are included at the end of this dissertation.

2 South Asia energy outlook

Fundamental changes are taking place in the global energy systems, and any assessment of the global energy outlook must have South Asia as its centre. The South Asian region is home to a quarter of the world's population, and its rapidly growing economies will shape various aspects of any global economic and energy outlook. According to the IEA (2021a), India will see the largest rise in energy demand of all countries in the world by 2040. This is enabled by the growing economy, industrialisation, population, and increase in urbanisation, which will see a rapid surge in infrastructure needs, resulting in energy demand growth of almost three times the global average (IEA, 2021a). Consequently, rapid decarbonisation of the energy system, holds the key to net zero ambitions, as it is responsible for the majority of the emissions (Matthews and Caldeira, 2008; Rogelj *et al.*, 2016; Bogdanov *et al.*, 2021b; Teske *et al.*, 2021).

The countries in the South Asian region are unique and diverse in terms of their current energy systems, but the policymakers have one common goal to ensure an affordable, secure, and sustainable pathway for the energy systems (UNESCAP, 2018). The potential benefits of sustainable, secure, and affordable energy systems across countries are huge, as observed by increased welfare and quality of life. These countries have traditionally relied on fossil fuels to bring millions of people out of poverty, provide basic energy services, and have a large pipeline of future fossil fuel based power plants; if unmitigated, will have severe effects on local and global climate change (Climate Analytics, 2019).

However, there are encouraging signs in the energy sector, but the progress has been slow. This is further compounded by the effects of Covid-19 induced recession and the Russian war in Ukraine (IEA, 2021c). These effects are trickling down to the current energy system, burdened by the record high prices of coal, oil, and natural gas (IEA, 2021c). Consequently, the region will face challenges ahead with rising inflation and commodity prices (World Bank, 2022a). More than ever, urgent climate action is needed to pave the way for a resilient energy system in the medium to long term (Schafer and Roome, 2021).

There is vast renewable energy potential in South Asian countries, especially solar and wind energy (Shukla *et al.*, 2017). With rapid technological advances and increasing cost competitiveness, the cost of generating electricity from renewables has declined sharply over the last decade, with power from newly built renewables cheaper than fossil fuel based power plants in most of the regions (Mathis, 2021). Utilising renewables and the clean energy transition towards complete defossilisation will deliver on primarily threefold objectives: first, ensuring universal access to affordable and reliable energy; second, reducing dependence on fossil fuel imports; third, avoiding air pollution and environmental degradation; plus a plethora of other benefits (IRENA, 2018). According to the IPCC, delaying the transition towards sustainability will only increase the mitigation cost by as much as 50% (IPCC, 2014). Going forward, the transition of the energy systems will be governed by various factors. In the following sections, the key factors are presented which will shape the South Asia energy outlook towards the future.

2.1 Rising income and urbanisation

In South Asia, the GDP per capita has increased considerably over the last two decades. While the fastest growth was observed in India, with GDP per capita growing by 160% between 2000-2019, with a CAGR of 5.2% (Roser, 2013a). Similarly, the South Asia region has been able to maintain a consistent CAGR of around 4.7% during the same period (Roser, 2013a). The rising income has resulted in a dramatic increase in consumer spending across all sections of society. As a result, demand for materialistic conveniences and technologies has gone up. This has resulted in a rapid increase in energy demand across all countries. Currently, the average per capita final energy consumption is about 4.8 MWh, which is considerably lower than the world average of about 15 MWh and much less than that of Organisation for Economic Co-operation and Development (OECD) countries, which is about 32.3 MWh, while about 700-800 million people live below the 3.2 USD/day poverty threshold (United Nations, 2019; IEA, 2020b; World Bank, 2022a). According to the World Bank, a poverty line of 3.2 USD is typical of lower-middle income countries, and almost all of South Asia’s population lives in lower-middle-income economies. The World Bank (2022a) forecasts that poverty in this region will continue to decline in the coming years, consequently increasing demand for goods and energy services.

The link between economic growth and urbanisation is well documented (Henderson, 2003; Bloom *et al.*, 2008). Economic growth encourages expansion of modern industries and services, a result of an increase in the urban population; vice versa, urbanisation also promotes economic growth to some extent (Chen *et al.*, 2014). As a result of rising income levels and economic growth, urbanisation is projected to grow considerably in the future. It is projected that in the South Asian region, over 580 million people will move to urban areas by 2050, making it the second-fastest urbanising region in the world following the region of sub-Saharan Africa (World Bank, 2021a). This will increase the urbanisation rate from 34% in 2018 to more than 50% by 2050, almost doubling the current urban population in the next three decades (World Bank, 2021a). As a result, the region is expected to have 10 megacities with around 200 million people by 2030 (United Nations, 2019), led by Delhi, the capital of India, as the most populous city on the planet by 2028 (United Nations, no date; Ram *et al.*, 2022a). The growth in population living in cities will increase the requirement for energy intensive building materials, especially steel and cement. Additionally, urbanisation will result in a transition from using solid biofuels to electricity in households. With increasing income, rising temperatures and heatwaves, demand for air conditioners will increase considerably, which is a strong driver of an increase in overall and peak electricity demand (Toktarova *et al.*, 2019). IEA projects that the demand for cooling in India will reach 650 TWh by 2040 (IEA, 2021a), equivalent to the current electricity demand of Brazil (Ritchie *et al.*, 2020). Thus, in the coming decades, economic growth and urbanisation trends will push the growth in energy demand, particularly for electricity (Nepal and Paija, 2019). Given that most of the infrastructure needed for the year 2050 is yet to be built, this represents a significant opportunity to develop more sustainable, efficient, and low-carbon infrastructure (IFC, 2017; World Bank, 2021a).

The GHG emissions in South Asia are comparatively low with respect to the world average but are rising rapidly with urbanisation and the growing middle class (Climate Watch, 2020). On the other hand, India is the third largest GHG emitter in the world and accounts for 80% of the region's emissions (Climate Watch, 2020). To power the growth, South Asia needs to avoid locking in high-emitting fossil fuel-based investments that will be stranded assets (Seto *et al.*, 2016). Decarbonising economic growth will be key to reducing emissions in the region and South Asia's share of global emissions.

2.2 Role of the power sector

South Asia's electricity generation has increased with a CAGR of 5.5% between 2000-2019 (Ritchie *et al.*, 2020). In 2019, the total generation in the region was 1839 TWh. About 77% of the total generation in the region is from fossil fuels; hydropower has a share of 12%; nuclear power contributes 3%; and renewables account for 8%. Coal, natural gas, and oil are the main fossil fuels used for electricity generation in South Asia (Ritchie *et al.*, 2020).

India, as the largest country in terms of area and population and one of the biggest economies in the world, has a share of 87% of the region's total electricity generation (Ritchie *et al.*, 2020). During the last decade, the government focused on providing access to electricity to millions of people, resulting in a strong growth in electricity demand (CEA, 2019). This resulted in electricity consumption growing by a CAGR of 6.5% between 2000-2019 (IEA, 2020b). Figure 5 gives the electricity generation share according to sources for all the South Asian countries in 2000 and 2019.

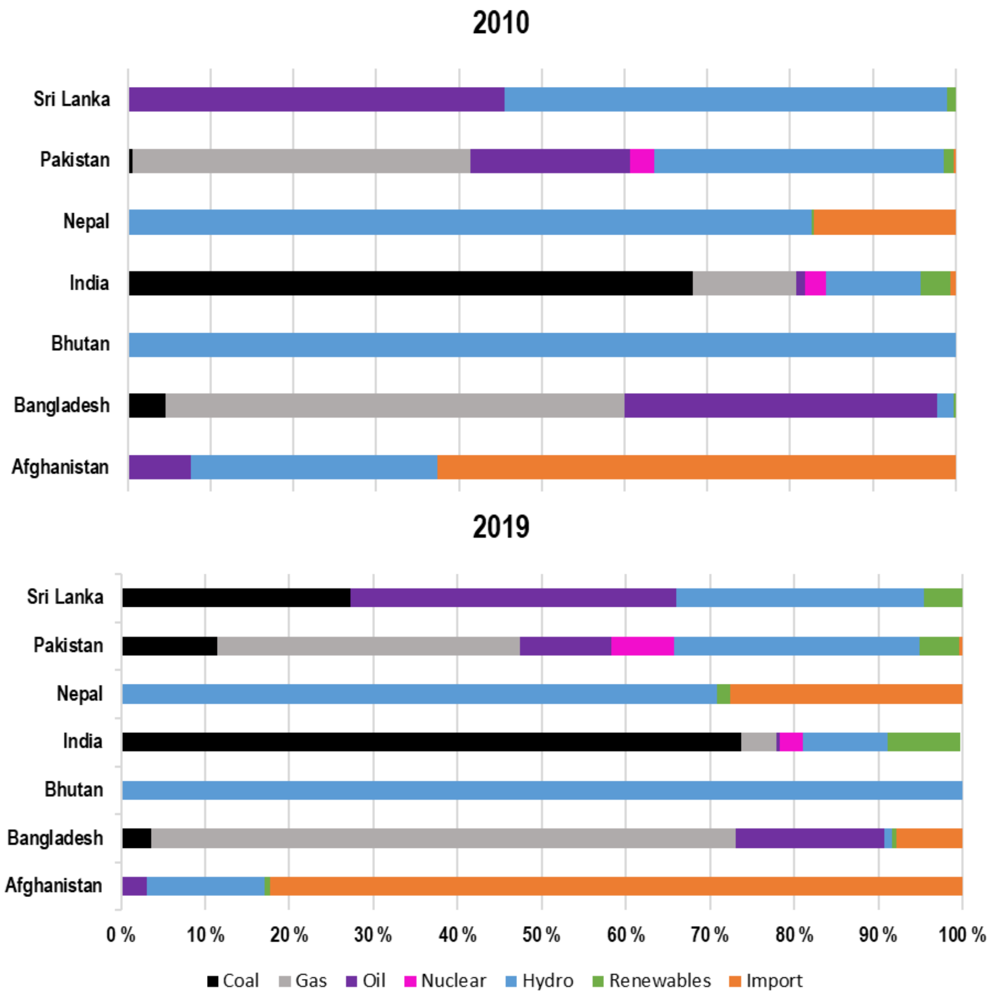


Figure 5: Total electricity generation shares in the South Asian for 2010 and 2019. Data adopted from Ember (2022a).

To power this electricity growth, coal has been the dominant source, with a share of 74% in 2019. India has one of the highest coal shares in its electricity generation in the world. Between 2010 and 2019, electricity generation from coal almost doubled. While there was a slight dip in the share due to the Covid-19 induced lockdown and a decline in electricity demand, the share rose rapidly to reach the pre-pandemic level of 74% in 2021. The second largest share of electricity generation comes from hydropower, with a share of 10%, while solar PV, wind power, and other renewables have a share of 9%. The role of nuclear power has stayed almost the same for India, while Pakistan has increased its share to 8% of the total generation in 2019.

Globally, the power sector accounts for approximately 40% of the energy-related CO_2 emissions, and the situation is similar in larger South Asian economies (Climate Analytics, 2019). India's power sector emissions contribute almost 50% to the total energy-related emissions, the result of a large share of coal in the power generation, while Pakistan has a share of 25% (Climate Watch, 2020; IEA, 2021a). Bangladesh and Sri Lanka's power sectors contribute 44% and 43%, respectively, to their total energy related emissions (Climate Watch, 2020). Therefore, the role of power sector decarbonisation will be crucial going forward for the decarbonisation of the entire energy system, as electricity will be a key vector to decarbonise heat, transport, and industry sectors (Climate Analytics, 2019; Palchak and Chernyakhovskiy, 2022). The share of electricity in total final energy consumption globally has increased steadily over the last few decades and contributed 19.4% in 2018 (IEA, 2019a). According to the IEA, the share of electricity might grow upto 50% of the total final energy consumption by 2050 (IEA, 2021c). However, as electricity delivers useful energy with much higher efficiency than fossil fuels, the contribution of electricity might be even higher than 50% (Pursiheimo *et al.*, 2019; Ram *et al.*, 2019; Bogdanov *et al.*, 2021b).

The growth in electricity generation without increase in emissions is possible as this region has abundant renewable energy potential, with solar PV and wind power being cost competitive with current fossil fuel technologies. With the cost of storage technologies, especially batteries, decreasing rapidly (Ziegler and Trancik, 2021), flexibility and system reliability can be achieved. In order to align energy plans with the Paris Agreement and the SDGs and to limit the risk of stranded fossil-fuel assets (Mercure *et al.*, 2021), countries in South Asia will need to reverse the current trend of expanding coal-fired generation capacity and instead urgently implement policies to enable fast decarbonisation of the electricity mix.

2.3 Electricity access, affordability and security

The South Asian region has achieved considerable progress in electrifying and providing energy access to its population (World Bank, 2021c). About 490 million people were able to access electricity for the first time between 2000 and 2019, primarily provided by fossil fuels (Ritchie *et al.*, 2020). As the GDP per capita has grown considerably in these countries, the positive effect has trickled down in terms of access to electricity and vice versa (Rao, 2013). According to the World Bank, an increase in income does have a positive effect on access to electricity, and if poor people do not have access to electricity, they stay poor (Indrawati, 2015). However, still, this region is troubled by intermittent electricity access, with widespread blackouts observed in all countries and average per capita final energy and electricity consumption of 4.8 MWh and 0.9 MWh, which is considerably lower than the world average of 15 MWh and 3.2 MWh, respectively, and much less than the OECD standards of 32.3 MWh and 7.5 MWh, respectively (IEA, 2020b; Ritchie *et al.*, 2020). Consequently, the unreliability of energy supply has created a hindrance for economic growth and underpinned the region's global competitiveness (Zhang, 2019). The current energy crisis faced by the South Asian countries will be detrimental to their ambitions of universal electrification and achieving the SDG (Murshed, 2021).

To achieve SDG 7.1 (United Nations, 2021b), i.e., universal access to affordable, reliable, and sustainable energy services by 2030, it is required that 9 million people gain access to electricity every year in the South Asian region. Before 2019, electrification increased at a rate of 18% per year, between 2010-2019 (Ritchie *et al.*, 2020). The high growth rate in electrification was possible due to India making great progress through different policies (Palit, 2019). According to the government statistics, almost 100% of the households in the country were connected to electricity in 2019. However, the problem of reliability and quality of grid connected electricity still exists (REC, 2018; Sreekumar *et al.*, 2018; Hou and Urpelainen, 2020; Sharma *et al.*, 2020). On the other hand, access to clean cooking has been slow, and still a large number of people rely on polluting fuels, mostly the traditional use of biomass and kerosene (IEA, 2020a). This causes a negative impact on human health, productivity, and the environment. Thus, there is an urgent need to accelerate the transition to modern and efficient cooking methods (IEA, 2020c).

The recent Covid-19 pandemic and its economic impact could push about 40 million people connected to the grid back into energy poverty, unable to pay for the grid connected electricity. According to the World Bank (2021a), grid extension might be the preferred option to supply electricity to the unelectrified population, but it is not necessarily the most reliable or sustainable. According to the IEA, renewable energy will provide access to electricity to 80% of people by 2030, as solar PV (mini-grids or off grid) can provide reliable and low cost electricity (IEA, 2021b). The decreasing cost of solar PV and the growing range and flexibility offered by the off-grid solar PV technologies provide the fastest and a low cost path for achieving last mile connectivity (Kumar *et al.*, 2019; United Nations, 2021b). Bertheau et al. (2017) provided analysis for various off-grid electrification options for sub-Saharan Africa, with results indicating that solar home systems (SHS) are the fastest way to provide electricity to non-electrified households. This is also observed in the successful implementation of solar home systems (SHS) for electrification in Bangladesh (Khan, 2019). This can provide basic electricity services to households that have access to electricity for the first time. However, as the demand increases, households will shift towards larger systems of mini-grids and macro grids with connections to the national power grid (Aziz and Chowdhury, 2021).

The basic goal of energy security is to ensure the uninterrupted availability of energy resources at an affordable price (IEA, 2017). The energy security concerns in South Asia originate from the mismatch of domestic energy demand and supply, resulting in increasing energy imports (Ul-Haq *et al.*, 2020). Consequently, by providing energy access to a growing population and energy services to a large number of people, these South Asian countries are facing huge and growing volumes of imported fossil fuels. The continued reliance on imported fossil fuels creates vulnerabilities due to price volatility and possible supply chain disruptions. Thus, emphasising the importance of developing indigenous renewable resources to ensure energy supply affordability and reduce import bills, which would otherwise grow dramatically and stagnate economies (Parikh *et al.*, 2013).

The South Asian region has made progress in improving electricity and energy access and has started to develop its indigenous renewable resources. Going forward, with energy demand projected to increase manyfold, numerous challenges will arise. How these challenges are met will have major consequences for the future energy system. The governments in these countries should make priority policies for energy accessibility at affordable prices with improved energy independence and greater sustainability.

2.4 Regional power trading

Globally, focus has increased on developing cross-border electricity interconnections and trading between countries and regions, as governments in many countries around the world have realised the benefits of regional power interconnections (UNESCAP, 2018). There are many successful examples globally of such interconnections, like the Southern African Power Pool (SAPP), Western African Power Pool (WAPP), Greater Mekong Sub-Region (GMS), Nord Pool, and the European Network of Transmission System Operators (ENTSO-E) (IRENA, 2013, 2021c; Parikh *et al.*, 2013; ENTSO-E, 2017; UNESCAP, 2018; Oyewo *et al.*, 2020). Many more are in the development stages, especially in developing countries like the ASEAN Power Grid and the Energy Super Ring in Northeast Asia (UNESCAP, 2018). These interconnected power grids are seen as a supporting instrument for the uptake of renewable energy while bringing various other benefits such as an increase in operational efficiency, greater system reliability, energy security, and economic as well as environmental benefits (Parikh *et al.*, 2013; IRENA, 2021c).

The concept of a SAARC interconnected electricity system covering the countries in the South Asian region was first announced in 2004 (UNESCAP, 2018). Since then, there has been some progress in developing bilateral electricity interconnections in some of the

South Asian countries (Singh *et al.*, 2018). Finally, in 2014, a framework agreement for regional electricity cooperation was signed (Singh *et al.*, 2018). However, there has not been much progress since, except for the bilateral agreements, and it remains to be seen how the provisions signed in the agreement will help develop the SAARC market for electricity (Singh *et al.*, 2018). Interconnecting the power grids of different countries is not an easy process and has political challenges as it requires building of trust between countries and institutional reforms over several decades (UNESCAP, 2018; Ul-Haq *et al.*, 2019).

The cross-border electricity trading in the South Asian region is mainly concentrated on the eastern side (Bhutan, Bangladesh, India and Nepal). There are power flow interconnections outside the region as well, between Central Asia, Pakistan, and Afghanistan. The amount of electricity traded in 2019 within the region reached a maximum of 15.6 TWh, at a capacity of more than 3500 MW (IRADe, 2021). The amount of electricity traded between the South Asian countries is shown in Figure 6.

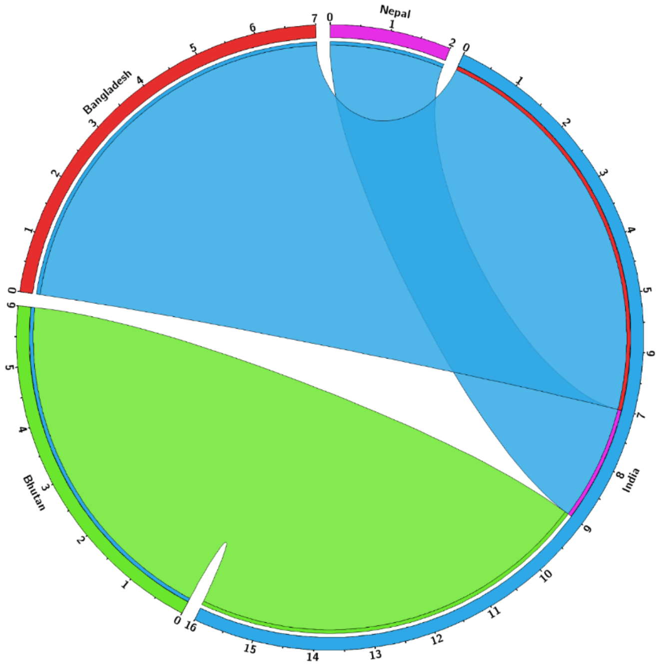


Figure 6: Electricity trade in 2019 between some countries in South Asia. Data adopted from IRADe (2021). The thickness of the flow indicates the amount of electricity exchanged between the countries in TWh. The colour of the flow indicates import or

export with respect to its outer ribbon colour. For example, Bhutan is an exporting country, its outer ribbon and its flow has green colour.

The region has a vast potential for renewable energy sources such as hydropower, wind power, and solar PV (IRADe, 2021). Thus, regional cooperation in terms of electricity trading provides an ideal opportunity to enable sustainable growth in the entire region by utilising the abundant renewable energy potential (Hurlbut *et al.*, 2020). However, creating a regional grid does not automatically guarantee an increase in renewable energy usage in the region, but it will create a conducive atmosphere for low cost electricity trade. With the right policies in place, regional power trading in South Asia will facilitate a transition towards low cost, sustainable energy systems across the entire region. Additionally, it will strengthen regional energy security and provide affordable power supply, helping to achieve the SDGs.

2.5 The energy-water-food nexus

Growing population, economic growth, industrialisation, and urbanisation particularly in developing countries will significantly increase the demand for freshwater, energy, and food. It is projected that by 2050, energy and food demand will grow by 80% and 60%, respectively, while freshwater withdrawals will increase by 50% (Lu *et al.*, 2021a). Consequently, this poses a serious stress on these limited resources, which are already constrained by competing needs and further compounded by climate change (IRENA, 2015; Zhang *et al.*, 2018). Moreover, in South Asia, where a quarter of the world’s population lives on less than 5% of the earth’s land area, the situation appears to be more severe (Rasul, 2016). The extreme droughts in the region have had consequences for energy and food security, intensified by the water stress (Luo *et al.*, 2018; Walker, 2020). Thus, food, water, and energy are inextricably linked in a nexus; action or inaction in one sector influences the others and the country’s SDGs.

Climate change can put stress on the infrastructure that depends on water and adequate water supplies. Water is required in every step of the fossil fuel value chain, with the energy system accounting for 10-15% of the global freshwater withdrawals annually (Terrapon-Pfaff *et al.*, 2020). Thermal power plants generating electricity consume about 88% of this water for cooling purposes (IEA, 2016).

Thus, any water shortages due to droughts reduce the output from thermal power plants using freshwater cooling (Gajardo *et al.*, 2021), especially in regions where freshwater flows are dependent on seasonal rainfall (Loo *et al.*, 2015). India is among the most water stressed countries in the world, and most of its states are facing depleting freshwater resources (NITI Aayog, 2018). By the end of 2030, about 66% of the country’s power plants will face high levels of water stress (Gajardo *et al.*, 2021). India's majority of coal power plants are situated in highly water stressed regions, and cooling for thermal power plants uses half of the domestic water demand (CSE, 2015; IEEFA, 2019). Consequently, between 2013 and 2016, water shortages resulted in thermal power plant shutdowns in various regions, resulting in a loss of 1.4 billion USD (1.3 b€), due to lack of freshwater available for cooling (Luo *et al.*, 2018). On the other hand, Pakistan is also under extreme water stress, as its freshwater resources are dwindling faster (Caldera *et al.*, 2021). This is a result of poor management of existing water resources, highly inefficient irrigation systems, and climate change (Parry *et al.*, 2017). With the population expected to grow in the region, there will be an increase in irrigation requirements, which will put tremendous pressure on already scarce water resources (Srinivasan *et al.*, 2018). Competing uses of freshwater for vital irrigation and electricity generation in thermal power plants cause immense challenges for decision makers.

According to IRENA (2015), energy systems with large shares of renewable energy require considerably less water. Because there is no need for cooling, solar PV and wind power use very little water during the electricity generation process. On the other hand, thermal power production requires about 200 times more water than solar PV and wind power (IRENA, 2015). Thus, solar PV and wind power provide a potential solution to increase water security in the region, and completely phase out the energy-water nexus (Lohrmann *et al.*, 2019).

2.6 Potential of renewable resources

Knowing the potential of RE resources is important to anticipate the potential role of each of these resources in the energy mix. The South Asian region is endowed with a large potential for different renewable resources. These resources are spread across different countries, which is sufficient to fulfil the future energy demand. Table 1 shows the potential of different resources in the region

Table 1: Potential of different renewable resources in the South Asian countries.

	Solar PV potential	**Reference**	**Wind potential**	**Reference**	**Hydropower potential**	**Reference**	**Sustainable biomass potential**	**Reference**
	TWh		**TWh**		**TWh**		**TWh**	
Afghanistan	141	(Anwarzai and	342	(Anwarzai and	268		25	

		Nagasaka, 2017)		Nagasaka, 2017)		(Gernaat *et al.*, 2017)		(Mensah *et al.*, 2021)
Bangladesh	217	(UTS, 2019)	580	(UTS, 2019)	3.5		187	
Bhutan	81	(Gilman *et al.*, 2009)	10	(Gilman *et al.*, 2009)	395		4.8	
India	8900	(Deshmukh *et al.*, 2019)	4000	(Lu *et al.*, 2009)	1737		1760	
Nepal	57	(Neupane *et al.*, 2022)	4	(Neupane *et al.*, 2022)	245		56	
Pakistan	3500	(Harijan *et al.*, 2008)	212	(Harijan *et al.*, 2011)	449		398	
Sri Lanka	44	(SSEA, 2020)	39	(SSEA, 2020)	5.5		22	

The South Asian region is located in the Sunbelt with the average yearly global horizontal irradiation (GHI) ranges between 1438 – 2003 kWh/(m^{2}·a). Afghanistan has the best resource availability due to its location, with a GHI of 2003 kWh/(m^{2}·a), while India, Pakistan, and Bangladesh have average GHI of 1861 kWh/(m^{2}·a), 1949 kWh/(m^{2}·a) and 1677 kWh/(m^{2}·a), respectively. The availability of solar resource is almost constant throughout the year in Pakistan, while there are variations observed due to the monsoon in Bangladesh and India. Comparatively, the best wind resources in South Asia are limited to the southwestern part of Pakistan, the western region of Afghanistan and the southern and western parts of India (ESMAP, 2022). Pakistan has a technical potential of about 212 TWh, mainly concentrated in the coastal areas of Baluchistan and Sindh, with FLH between 1000-1500 and 2000-3000, respectively (Harijan *et al.*, 2011). In India, wind resources are mainly concentrated in the southern states of Tamil Nadu and Karnataka and the western states of Maharashtra and Gujarat (MNRE, 2022c). According to Lu et al. (2009), the technical potential of wind power in India is about 4000 TWh. According to Gernaat et al. (2017), Nepal and Bhutan have 245 TWh and 395 TWh, respectively, of exploitable hydropower potential, representing a large potential for the small countries. On the other hand, large countries like India and Pakistan have a potential of 1737 and 449 TWh, respectively. Hydropower has long been the main source of RE in the region. The traditional use of biomass in heating and cooking is huge in the South Asian region, especially in Nepal (Gurung *et al.*, 2011). In 2014, biomass had a share of 80% in Nepal's primary energy supply. As majority of the population is dependent on agriculture, South Asian countries produce large amounts of waste and residue. Furthermore, growing population will result in large production of municipal waste. The biomass potential for the South Asian countries is presented in Table 1.

The share of renewables in the South Asian energy system is projected to grow substantially in the coming decades, based on the availability of vast potential and climate change targets. The countries are realising the benefits of integrating renewables into their energy mix in terms of improved energy security and access, socio-economic development and climate change mitigation (IRENA, 2015).

2.7 Role of India in driving the renewable energy transition in South Asia

During the last decade, India has taken giant strides in providing electricity access to millions of people and promoting the rapid expansion of renewable energy (IEA, 2021a). The citizens have benefited in terms of improved quality of life and more economic opportunities. However, some lingering issues remain, aggravated by the recent Covid-19 pandemic (IEA, 2021a). Water scarcity and air pollution are major issues in many parts of the country, mainly caused by the use of coal in the energy system. As India aims for a trillion dollar economy, climate change and inclusive growth are the priorities of the government (World Bank, 2021a).

India is one of the countries that has been aggressively pursuing electricity generated by renewables, particularly solar PV. The solar PV capacity has grown by more than 13 times during the last six years, reaching 53.9 GW by the end of March 2022 (MNRE, 2022a). This growth rightly follows the path of the ambitious target of 500 GW of installed renewable capacity by 2030 (The Economic Times, 2021). The ambitious target reflects the government’s policy to ride the wave of declining costs and abundant renewable energy potential, especially solar PV, and possibly reduce fossil fuel imports (Wood, 2021; Modi, 2022). With the launch of the International Solar Alliance (ISA) at COP21 in Paris, India aims to be a global leader in promoting solar electricity in the Sunbelt countries (ISA, 2019). Thus, ISA aims to make a positive contribution to the goal of increasing solar utilisation globally.

Also, India has ambitious policies for electric vehicle penetration in the transport sector to reduce its dependence on oil imports (Ghosh, 2022). A study by CEEW (2020) found out that if 30% of the newly sold vehicles are electric vehicles by 2030, India would save on crude oil imports worth 14 billion USD annually.

The trend of growing renewable capacity installations will continue amid sharply falling costs and supportive policies from the central and state governments. However, the challenge for India going forward will be to align its renewable growth trajectory with its development imperatives: energy affordability and accessibility, mitigating air pollution, and maintaining rapid economic growth (Mathur and Shekhar, 2020).

Therefore, it is important to set long term goals and envision a net zero emission energy system across the country, which will not only ensure economic benefits but also place India in a leadership position, both globally and in South Asia. Thus, the benefits of integrating renewables go beyond the energy sector, with solar and wind technologies being foremost in achieving sustainability goals (Child *et al.*, 2018).

With India being the largest contributor of GHG emissions in South Asia and its growth in energy use expected to be the largest in the world, the steps India takes will have long lasting consequences in the region as well as globally. As the IEA said in its recent India Energy Outlook, ’All roads to a successful global clean energy transition go via India’ (IEA, 2021a).

3 Modelling energy systems in South Asia

Very few studies have shown future energy transition pathways for the entire South Asian region, integrating each country's power systems and incorporating a wide range of assumptions for various generation, storage, and transmission technologies, with the target of net zero CO_2 emission energy systems by 2050. A few of the scenario studies for the South Asian region are listed in **Publication I,** along with their key findings**.** Most of the studies cover an individual country or state, which are also listed in **Publication I, IV, V, VI and VII.** Most of these studies show future energy system pathways with a phase down of fossil fuels rather than a phase out, while integrating some shares of renewable energy to satisfy the increasing demand. Furthermore, these studies fail to acknowledge the role of different storage technologies and other flexibility options such as PtG and seawater desalination. Recent research has shown that achieving 100% renewable energy and zero emissions is possible by 2050, even in developing regions (Jacobson *et al.*, 2017; Löffler *et al.*, 2017; Hansen *et al.*, 2019; Teske, 2019; Breyer *et al.*, 2022).

3.1 Overview on 100% renewable energy studies in South Asia

A global review and perspective on studies related to 100% renewable energy systems are given by Breyer et al. (2022). Most of these 100% RE studies mainly focus on the Global North; thus, countries from the Global South that represent 5 billion people, such as South Asia, Southeast Asia, Africa, and Central Asia, are not yet well researched (Hansen *et al.*, 2019; Breyer *et al.*, 2022). Typically, countries from these regions are in the Sunbelt, which receives a large amount of solar energy annually without much seasonal variation. Thus, transitioning to 100% RE-based systems is both technically feasible and economically viable for these countries. As Breyer et al. (2022) rightly point out, a successful global transition towards 100% renewables requires all countries, especially those from the Global South, to be in sync with global efforts and avoid investing in fossil infrastructure to avoid stranded assets in the future.

Table 2 presents a brief overview on the peer reviewed studies for the South Asian region and the individual countries. The studies are selected based on a minimum 95% renewables share criteria in the electricity generation.

Table 2: 100% RE system studies for the South Asian region and the countries within it. Abbreviation: simulation (Sim), optimisation (Opt), transition (T), overnight (O).

	Model	Model type	Temporal resolution	Sectors	Path	Scope	Remark
Gulagi et al. (2020b) **Publication IV**	LUT-ESTM	Opt	hourly	power	T	Bangladesh	Transition of Bangladesh's power system was analysed from 2015 to 2050 with four different scenarios: Current policy scenario and Best policy scenario with and without GHG emissions costs. The results show that a least cost 100% RE-based power system is possible for Bangladesh by 2050, with a share of almost 95% of solar PV in the electricity generation and a battery output share of almost 50% of the total electricity demand in the best policy scenario with GHG emissions costs. On the other hand, the levelised cost of electricity for the current policy scenarios increases from 82.4 €/MWh in 2015 to 139.4 €/MWh in 2050.
Gulagi et al. (2022) **Publication VII**	LUT-ESTM	Opt	hourly	power	T	India/states	The transition modelling for the power sector is performed in two steps for the 22 states/regions in India First, the power system is modelled at a lower regional resolution (4 regional grids). Second, the modelling of each of the regional grids in full state resolution, considering the power flows between the regional grids simulated in the first step. The results indicate that solar PV installed capacity reaches 3000 GW by 2050, contributing almost 73% to the total power generation of India, while wind power share reaches 19% in 2050. This system is ably supported by batteries, power-to-gas, and transmission grids.
Ram, Gulagi et al. (2022a)	LUT-ESTM	Opt	hourly	all	T	India/Delhi	A pathway towards a 100% renewable based energy system is explored for the megacity of New Delhi within the Northern grid of the Indian power system. The results indicate that a cost optimal energy transition pathway is possible even for a megacity like Delhi, integrating large shares of solar PV (96% of the total electricity generation) and utilising strong power transmission line networks with the Northern grid.
Jain et al. (2021)	Own model	Sim	hourly	power	T	India	The role of solar, wind, and storage is estimated for a 30-year period from 2019-2048. The results show that integrating 2-3 TW of solar PV and wind power is possible; however, it would require multiple complementary strategies for balancing the power system.
Lugovoy et al. (2021)	IDEEA	Opt	hourly	power	T	India	A pathway towards a 100% RE-based power system was studied using only solar PV and wind power. The result shows that a 100% RE-based power system is possible with only solar PV and wind power, with intraday balancing or demand-side flexibility, and a power transmission grid. The complementarity of solar PV and wind power reduces the requirement of energy storage.
Gulagi et al. (2020a) **Publication III**	LUT-ESTM	Opt	hourly	power	T	India	The results from Gulagi et al. (2018) of a 100% RE-based power sector in 2050 were used to analyse the power system during the monsoon season. The results indicate that a fully renewable electricity system for India in 2050 can effectively handle the decreased solar power generation during the monsoon season by effectively utilising transmission grids and increased wind power availability, along with additional flexibility provided by the increased hydropower generation and storage technologies.
Lawrenz et al. (2018)	GENeSYS-MOD	Opt	time slices	all	T	India	Different pathways were explored based on the integration of renewable energy for the 10 Indian regions. A limited emissions scenario is based on a solar share of 67%, wind power with a share of 23%, and hydropower complements with a share of 6%.
Gulagi et al. (2018) **Publication II**	LUT-ESTM	Opt	hourly	power	T	India	The transition pathways of two scenarios from 2015 to 2050 were analysed for India at a spatial resolution of 10 regions. The results show that a 100% RE-based power system is lower in cost than the current system based on coal power generation. In an integrated scenario, the levelized cost of electricity decreases from 58 €/MWh to 46 €/MWh. The storage demand in the power scenario will be covered by batteries, which provide a share of 41.6%, while PHES and gas storage cover 0.2% and 3.2% of the total electricity demand, respectively.
Gulagi et al. (2017a)	LUT-ESTM	Opt	hourly	power	T	India	The demand for storage technologies is explored in a transition pathway towards a 100% RE-based power system by 2050. Batteries provide 2596 TWh, PHES provides 12 TWh, and gas storage provides 197 TWh for electricity to the total electricity demand. Most of the storage demand will be based on batteries, which provide as much as 42% of the total electricity demand.

Keiner, …, Gulagi et al. (2022)	EnergyPLAN	Sim	hourly	all	O	Maldives	The potential of offshore floating technologies is investigated using two 100% renewable scenarios. Offshore floating PV and wave power with batteries and e-hydrogen power a least cost 100% renewable based energy system. Offshore floating PV provides a share between 56-60%, while wave power provides a share between 28-31%.
Liu et al. (2018)	unspecified	unspecified	unspecified	power/water		Maldives	Feasibility analysis of a 100% RE-based power and water supply in the Maldives. The authors conclude that a 'zero import of energy and water' is feasible utilising indigenous solar PV, wind power, biomass, and desalination technologies.
Van Alphen et al. (2007)	HOMER	unspecified	unspecified	power	O	Maldives	Techno-economic analysis for the future energy system in the Maldives. The authors conclude that RE-diesel hybrid systems are more financially viable than a fully RE-based power system.
Lohani et al. (2021)	unspecified	unspecified	unspecified	all	O	Nepal	According to the article, Nepal can achieve energy self-sufficiency with renewables, especially solar PV, without depending on hydropower. Nepal has 100 times more solar potential, even with an energy system completely dependent on 100% solar PV, in which each citizen has a per capita consumption similar to that of a developed country.
Gulagi et al. (2021) **Publication VI**	LUT-ESTM	Opt	hourly	all	T	Nepal and Bhutan	An integrated all sector (power, heat, and transport) transition pathway for Nepal and Bhutan was analysed for the two scenarios based on the GHG emissions costs from 2015 to 2050. The results show that Nepal and Bhutan can transition from the current energy system towards 100% RE by utilising their solar potential rather than depending on hydropower. The levelised cost of energy decreases from 90 €/MWh to 49 €/MWh in a 100% RE-based energy system.
Rizvi et al. (2022)	unspecified	unspecified	unspecified	unspecified	unspecified	Pakistan	A sustainability assessment of different electricity generation technologies in Pakistan is presented. The results indicate that hydro at 0.59 has the highest sustainability impact score. Gas, solar PV, wind power, and coal have sustainability scores of 0.54, 0.52, 0.52 and 0.42, while oil has the lowest sustainability score of 0.39.
Caldera, …, Gulagi et al. (2021)	LUT-ESTM	Opt	hourly	desalination/power	T	Pakistan	A pathway is explored to solve Pakistan's water crises using desalination technologies powered by 100% RE by 2050. Additionally, the role of improving irrigation efficiency in reducing the total water demand by 2050 is studied. The results show that due to the vast availability of solar resources in the country, solar PV-battery hybrid systems power the SWRO desalination technologies to overcome the water scarcity issue in Pakistan. In 2050, the levelised cost of water (LCOW) was 0.6 €/m3.
Sadiqa, Gulagi et al. (2022)	LUT-ESTM	Opt	hourly	all	T	Pakistan	A transition pathway towards 100% RE by 2050 is explored for the power, heat, and transport sectors, with desalination included as an additional demand. The share of solar PV reaches 92% of the total primary energy demand by 2050, with a levelised cost of energy of about 56.1 €/MWh.
Hussain et al. (2021)	LEAP	Opt	annual	Power	T	Pakistan	Various scenarios are presented based on the share of renewable energy penetration. The 100% RE-based Demand Side Management - Optimisation (DSM-Opt) scenario relies on a large share of hydropower (large and mini) in supplying the total electricity demand for the region
Sadiqa, Gulagi et al. (2018) **Publication V**	LUT-ESTM	Opt	hourly	power	T	Pakistan	For Pakistan, the transition pathways of two scenarios from 2015 to 2050 in a spatial resolution of two regions were examined. The results show that the levelised cost of electricity decreases from 106 €/MWh in 2015 to 46 €/MWh in the Power scenario, while in the integrated scenario, which also includes the additional cost of SWRO desalination and synthetic gas production, the LCOE decreases to 47 €/MWh in 2050. Solar PV provides a share of 86% of the total electricity demand, with a corresponding share of Li-ion batteries to power the night time demand. The levelised cost of water decreases from 0.84 €/m^3 in 2015 to 0.62 €/m^3 in 2050, exploiting the low cost potential of solar PV generation.
Gyanwali et al. (2021)	unspecified	Opt	hourly	power	T	Eastern South Asia*	Various decarbonisation pathways exists for grid connected hydrogen storage and CCS, including a 100% RE scenario. The authors conclude that solar PV, wind power, hydropower, and power trading within the countries are important for decarbonising the power sector. Complete decarbonisation requires solar PV installed capacity of 2806 GW, while wind power capacity would reach 125 GW.
Gulagi et al. (2017c) **Publication I**	LUT-ESTM	Opt	hourly	power	O	South Asia	An overnight shift for the entire South Asian region from the current system to a fully renewable energy based power system by 2030 for four different scenarios based on the level of grid integration desalination, and non-energetic industrial gas demand. The results

							show that the levelised cost of electricity decreases from 71.6 €/MWh in a region-wide scenario to 67.2 €/MWh in an area-wide centralised grid connected scenario. The solar PV and wind power installed capacity reaches a maximum of 2218 GW and 694 GW, respectively, for the integrated scenario, with a generation share of 51% and 35%, respectively, of the total electricity generated in 2030.
Luderer et al. (2021)	REMIND-MAgPIE	Opt	annual	all	T	Global	Various scenarios were analysed for the transition of the energy system towards integrating renewables. The world is divided into 12 regions, with India as an independent region. The results indicate that globally, the generation share of solar PV and wind power in total electricity generation reaches 63% and 26%, respectively.
Bogdanov, …, Gulagi et al. (2021)	LUT-ESTM	Opt	hourly	all	T	Global/ South Asia	Presents a least cost scenario compatible to the 1.5°C target for the entire world divided into 145 regions. The South Asian region was divided into 16 regions. The total solar PV installed capacity in 2050 for the South Asian region is 11,910 GW (21,290 TWh of generation), while wind power capacity is 344 GW (810 TWh of generation). Other technologies, such as hydropower and biomass, complement solar PV and wind power.
Jacobson et al. (2019)	LOADMATCH, GATOR-GCMOM	Sim	hourly	all	O	Global	Simulation of a 100% RE-based energy system utilising wind, water, and solar (WWS) based in Pakistan (grouped with the Central Asia region), Bangladesh (grouped with the Southeast Asia region) and India (including Nepal and Sri Lanka). For India, the installed capacity of wind power is 1078 GW, solar PV is 4385 GW, and hydropower is 47 GW, with minor contributions from other technologies.
Bogdanov, …, Gulagi et al.(2019)	LUT-ESTM	Opt	hourly	power	T	Global/ South Asia	Presents a least cost scenario compatible to the 1.5°C target for the entire world divided into 145 regions for the power sector. The South Asian region was divided into 16 regions. The total solar PV installed capacity in 2050 for the South Asian region is 3730 GW (7005 TWh of generation), while wind power capacity is 200 GW (456 TWh of generation). Other technologies, such as hydropower, biomass, and geothermal, complement solar PV and wind power.
Pursiheimo et al. (2019)	VTT-TIMES	Opt	time slices	all	T	Global	Four high share renewable energy scenarios were compared with a BAU scenario. The authors conclude that large shares of solar PV and wind power with storage technologies and power-to-X would be required. High share of electrification in all sectors. India is modelled as a single region, while other countries in the South Asian region are combined into ‘Other Developing Asia’. In the high renewable and low biomass scenarios, installed solar PV capacity reaches 6152 GW, while installed wind power capacity reaches 161 GW.
Jacobson et al. (2018)	LOADMATCH, GATOR-GCMOM	Sim	hourly	all	O	Global	Simulation of a 100% RE-based energy system utilising wind, water, and solar (WWS) based in Pakistan (grouped with the Central Asia region), Bangladesh (grouped with the Southeast Asia region) and India (including Nepal and Sri Lanka). For India, the installed capacity of wind power is 1423 GW, solar PV is 2102 GW, and hydropower is 49 GW, with minor contributions from other technologies.
Löffler et al. (2017)	GENeSYS-MOD	Opt	time slices	all	T	Global	A pathway is modelled for the global energy system till 2050. The world is divided into 10 regions, with India as an independent region. Other South Asian countries are combined into one region. The overview results show that a 100% RE-based energy system is feasible globally with an average cost of electricity generation of 40 €/MWh.

*Bangladesh, Bhutan, India and Nepal

In this context, this research presents an energy transition pathway for South Asia in an overnight modelling approach by 2030 and transition of the individual countries in the region by 2050 using the LUT Energy System Transition Model towards 100% RE and zero GHG emissions, in an hourly resolution. The high temporal resolution captures the variability and intermittency of renewable resources and resolves them through various storage, transmission, and flexibility options, in a cost optimised manner.

3.2 Overview on the LUT Energy System model: Overnight and Transition

The entire research for this dissertation was conducted using the LUT Energy System Transition Model, henceforth LUT-ESTM. The LUT-ESTM linearly optimises the required energy system on an hourly resolution for an entire year under a set of applied constraints, with the assumption of perfect foresight of power generation and demand within the considered year but a myopic optimisation across the transition period. The main constraint for the optimisation is matching of generation from all technologies with the power demand for every hour of the applied year, and the optimisation criteria is to have the least annual cost of the power or energy system. A general constraint for the entire energy system modelling will be matching the generation from all technologies with the demand from all sectors. The hourly resolution of the model significantly increases the computation time; however, it guarantees that for every hour of the year, the total supply within a region covers the local demand and enables a more precise system description, including synergy effects of different system components.

The optimisation is performed using a third-party solver. In this research, MOSEK ver.8 (Mosek, 2017) is used as an optimiser, but optimisation using other solvers (Gurobi, CPLEX, etc.) is also possible. The model is compiled in Matlab in the linear programming (LP) file format so that it can be read by most of the available solvers. After the simulation, results are parsed back to the Matlab data structure and post-processed with an output in spreadsheet form (MS Excel is used) and also graphical results. The LUT-ESTM can be used on a single node as well as on a multi-node design in different sectors; either individual or integrated, different scenarios with a portfolio of different generation, storage, and transmission technologies. The overall modelling algorithm is shown in Figure 7.

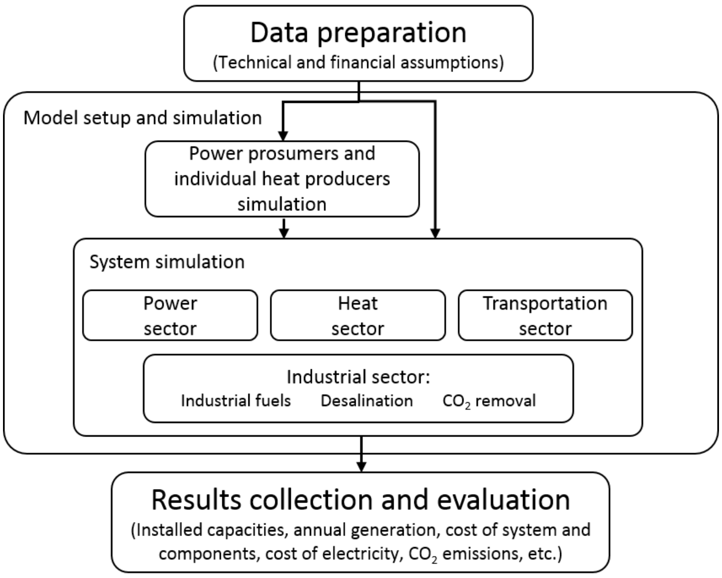


Figure 7: Modelling algorithm of the LUT-ESTM, with inputs, optimisation and results (Bogdanov *et al.*, 2019).

The LUT-ESTM was first developed as a tool to model an overnight scenario approach for the power sector, shifting from a fossil-based power system to a 100% renewable-based electricity generation by 2030 (Bogdanov and Breyer, 2016). In that case, the year chosen for a fully renewable power system was 2030; however, any year in the future could be assigned to show the overnight approach. Further, the model could be used for an interconnected transmission grid (multi-node) among the different regions and countries. Limited flexibility in the model was provided by the seawater reverse osmosis (SWRO) desalination and the PtG system, which was also used to cover the non-energetic gas demand. **Publication I** present an analysis using this version of the model for the entire South Asian region to determine the least cost fully RE-based power system for the year 2030. The main aim of **Publication I** was to show a fully RE-based power system for a particular year, rather than a transition (which was applied in the next development step of the model). Therefore, decommissioning based on the lifetime of the existing plants was not applied in the case of **Publication I**.

The next step in the development of the model involved describing a power system transition from the selected reference year to any future year (Bogdanov *et al.*, 2019). In this step, the LUT-ESTM was used to simulate a transition in every 5-year interval until 2050. For each of these 5-year time steps, the model defines a cost optimal energy system structure and operation mode for the given set of constraints. As this model was built on the previous version of the model, it has all the functionalities of the previous model version. **Publication II – V** uses the transition model with a detailed description for modelling the transition of the power sector. In addition to the transition, **Publication VII** uses a novel hierarchical modelling approach (Bogdanov *et al.*, 2022). The hierarchical approach employs two modelling steps to reduce simulation time while simultaneously optimising a large number of nodes.

The model was next developed to integrate all the demand sectors: power, heat, transport, and industry (Bogdanov *et al.*, 2021a). In addition to these end-use sectors, seawater desalination could be added wherever required (Caldera and Breyer, 2020). The model describes the transition of the entire energy system in every 5-year time step, covers most of the future energy demand, and shows a pathway for a decrease in future anthropogenic GHG emissions. The model also defines the cost optimal structure and operation of the energy system in order to satisfy the given hourly profiles of power demand, heat demand (space heating, domestic hot water and biomass for cooking), transport sector energy demand (modes for road, rail, marine and aviation for passenger and freight transportation), and industrial demand (cement, steel, chemicals, aluminium, pulp and paper, other industry, plus desalination). **Publication VI** uses this version of the all-sector transition model but without the industrial sector integration, which was simplified as industrial process heat which is part of the heat sector.

3.3 Why LUT-ESTM was chosen for this research

The primary aim of energy planning and scenarios is to provide future energy system pathways for discussion among the policy and decision makers in developing short and long term strategies, in a way that is transparent on important assumptions, input parameters, approach and output results (Cao *et al.*, 2016; Prina *et al.*, 2020). Over the last couple of decades, a wide variety of energy system models (ESMs) have been developed that can simulate and optimise 100% RE systems. Prina et al. (2020) have identified four main challenges related to ESMs: resolution in time and space, techno-economic details, and sector coupling.

The LUT-ESTM can optimise on a high resolution in time, i.e. hourly resolution for an entire year, similar to EnergyPLAN (Lund *et al.*, 2021), unlike the other ESMs, such as the Long-range Energy Alternatives Planning model (LEAP) (Heaps, 2022), Makral/TIMES (Pursiheimo *et al.*, 2019) and OSeMOSYS (Howells *et al.*, 2011), which are based on the time slices approach. The hourly resolution allows to capture the short term and long term seasonal variation of the VRE (Haydt *et al.*, 2011; Deane *et al.*, 2012), as seen by the effect of monsoon on a fully renewable Indian power system which is explained in detail in **Publication III.** The hourly temporal resolution increases the computation time substantially; but it also guarantees a power or energy system that is close to reality and describes the synergy between various components in the system. This is the preferred way to document a stable energy system for all hours of a defined year.

Additionally, the spatial resolution of the potential of VRE is an important factor, as the cost and generation are dependent on the potential at different locations (Prina *et al.*, 2020). The LUT-ESTM uses publicly available datasets for solar irradiation and wind speed in a 0.45° X 0.45° (50km X 50km) spatial resolution for real historic weather conditions. The LUT-ESTM is also capable of simulating a multi-nodal approach. The multi-nodal approach allows several different regions within a country, as in **Publications II, IV, V and VII**, different countries within a larger region, as in **Publication I**, and continents (Gulagi *et al.*, 2017b; Aghahosseini *et al.*, 2019; Breyer *et al.*, 2020), to be interconnected to form a power transmission network.

A wide range of techno-economic details and assumptions are associated with the LUT-ESTM and are listed in the publications, or the supplementary material associated with the publications. Optimal dispatch of generation technologies with cold starts, storage, and utilisation of transmission grids in the power and energy systems is possible with the LUT-ESTM. The capacity expansion during the transition can be optimised and a cost optimal energy system capacity can be obtained.

Furthermore, the LUT-ESTM can integrate the main energy end use sectors: power, heat, transport, and industry, based on the level of detail required in each of the simulations. It is critical to investigate different levels of flexibility and synergies between various sectors of an energy system in order to reduce overall costs.

For this dissertation, the LUT-ESTM is used for modelling energy transition pathways for the South Asian countries and region, based on its identified main requirements for an ESM. The model is considered robust and suitable to evaluate the integration of high shares of VRE resources in power or energy systems.

3.4 Model target function and constraints

3.4.1 Target function

The main target of system optimisation is to minimise the total annual cost of an integrated energy system or any one of the sectors. This cost is calculated as the sum of the annual costs of the installed capacities of different technologies, the costs of power generation, and ramping technologies. The target function includes the annual costs of the power, heat, transport, and industry (desalination if included) sectors. The target function of the applied energy model for minimising annual costs is presented in Eq. (1) (Bogdanov *et al.*, 2019) using the abbreviations: states/regions (*r*, *reg*), generation, storage and transmission technologies (*t*, *tech*), capital expenditures for technology *t* in region *r* ($CAPEX_{r,t}$), capital recovery factor for technology *t* in region *r* ($crf_{r,t}$), fixed operational expenditures for technology *t* in region *r* ($OPEXfix_{r,t}$), variable operational expenditures technology *t* in region *r* ($OPEXvar_{r,t}$), installed capacity in the region *r* of technology *t* ($instCap_{r,t}$), annual generation by technology *t* in region *r* ($E_{gen,t,r}$), cost of ramping of technology *t* ($rampCost_t$) and sum of power ramping values during the year for the technology *t* in the region *r* ($totRamp_{r,t}$).

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}\left(CAPEX_{r,t}\cdot crf_{r,t}+OPEXfix_{r,t}\right)\cdot instCap_{r,t}+OPEXvar_{r,t}\cdot E_{gen,r,t} + rampCost_t\cdot totRamp_{r,t}\right) \quad (1)$$

The target function only considers the cost assumptions for the given step of transition, as the previously built capacity is defined as a lower limit for the total capacity ($instCap_{t,r}$), and thus these previously built capacity costs do not affect the optimisation, even though they are part of the total system cost and older existing capacities may differ in operational expenditures.

The rooftop prosumer system (solar PV and Li-ion batteries) and heating technologies are realised in an independent sub model with a slightly different target function. These heating technologies are based on electricity or fuels and satisfy the demand for hot water and space heating (if required). The prosumer system is optimised for each region and each demand segment (residential, commercial and industrial) independently, even if the states/regions are interconnected with each other. Minimisation of the cost of consumed electricity and heat is the target function of prosumers. This cost is calculated by adding the annual costs of power, heat and storage capacity, the cost of consumed fuels for heating, cost of electricity purchased from the grid minus the income generated by selling excess electricity to the grid. The target function of the applied prosumer model for minimising annual costs is presented in Eq. (2) (Bogdanov *et al.*, 2019) using the abbreviations: generation and storage technologies (*t*, *tech*), capital expenditures for technology *t* ($CAPEX_t$), capital recovery factor for technology *t* (crf_t), fixed operational expenditures for technology *t* ($OPEXfix_t$), variable operational expenditures technology *t* ($OPEXvar_t$), installed capacity of technology *t* ($instCap_t$), annual generation by technology *t* ($E_{gen,t}$), retail price of electricity (*elCost*), feed-in price of electricity (*elFeedIn*), annual amount of electricity bought from the grid (E_{grid}), annual amount of electricity sold to the grid (E_{curt}).

$$\min\left(\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t) \cdot instCap_t + OPEXvar_t \cdot E_{gen,t} + elCost \cdot E_{grid} + elFeedIn \cdot E_{curt}\right) \tag{2}$$

3.4.2 Energy balance constraints

The main constraint for the power sector optimisation is the matching of the power generation and demand for every hour of the applied year. For every hour of the year, the total generation within a region and the electricity imported should cover the local electricity demand.

$$\forall \mathrm{h} \in [1{,}8760]\ \sum_t^{tech} E_{gen,t} + \sum_r^{reg} E_{imp,r} + \sum_t^{stor} E_{stor,disch} = E_{demand} + \sum_r^{reg} E_{exp,r} + \sum_t^{stor} E_{stor,ch} + E_{curt} \tag{3}$$

Eq. (3) describes the constraint for the energy flows of a region. Abbreviations: hours (*h*), technology (*t*), all modelled power generation technologies (*tech*), sub-region (*r*), all sub-regions (*reg*), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies (*stor*), electricity from discharging storage ($E_{stor,disch}$), electricity demand (E_{demand}), electricity exported (E_{exp}), electricity for charging storage ($E_{stor,ch}$), curtailed excess energy (E_{curt}). The energy loss in the high voltage direct current (HVDC) and alternating current (HVAC) transmission grids and energy storage technologies are considered in storage discharge and grid import value calculations.

The heat sector energy balance is defined by three equations: for industrial high temperature heat demand, for industrial high and medium temperature heat demand, and all centralised heat demand. High temperature heat can only be generated by fuel-based boilers as given in Eq. (4). Medium temperature heat can also be generated by electrical heating and can be stored in high temperature heat storage and used to produce electricity with steam turbines as given in Eq. (5). Low temperature heat can also be provided by heat pumps, electric heating rods and waste heat from other technologies as given in Eq. (6).

$$\forall h \in [1{,}8760]\ \sum_t^{techHH} E_{gen,t} \geq E_{demandHH} \tag{4}$$

$$\forall h \in [1{,}8760] \sum_{t}^{techHH} E_{gen,t} + \sum_{t}^{techMH} E_{gen,t} + E_{stor,disch} \geq E_{demandHH} + E_{demandMH} + E_{stor,ch} \quad (5)$$

$$\forall h \in [1{,}8760] \sum_{t}^{tech} \mathrm{E_{gen,t}} + \sum_{t}^{stor} E_{stor,disch} = E_{demand} + \sum_{t}^{stor} E_{stor,ch} + E_{curt} + E_{other} \quad (6)$$

Abbreviations: hours (h), technology (t), high temperature heat generation technologies ($techHH$), medium temperature heat generation technologies ($techMH$), all heat generation technologies ($tech$), industrial high temperature heat demand ($E_{demandHH}$), industrial medium temperature heat demand ($E_{demandMH}$), total centralised heat demand, including industrial, and space heating and water heating demand (E_{demand}).

The important constraints applied in the modelling of the best policy scenario (BPS) and other scenarios namely current policy scenario (CPS) are given below:

- **Best Policy Scenario**

1. No new power and heat boiler capacity will be installed after 2015 for coal, nuclear, and conventional fossil oil-based power plants, mainly due to their inability to fulfil the high sustainability criteria set in the model. Exception here being capacities commissioned and grid connected between 2015-2019. It is assumed that coal and oil-based power plants under construction and with planned capacities are scrapped and not commissioned. All fossil fuel-based power plant capacities are fully amortised until the end of their technical lifetimes to facilitate a gradual phase out. Their utilisation is cost-optimised, so that full load hours or capacity factors fall to zero in later periods due to their higher per unit cost of electricity production. Even though these capacities do not produce electricity, they have to be amortised due to political reasons, a procedure known as ‘cold reserve’ (also called security reserve). Because of lower carbon emissions and the ability to incorporate renewable electricity-based methane (e-methane), bio-methane, and green e-hydrogen into the system, gas turbines and multi-fuel ICE can be installed after 2015. Gas-fired power plants are more flexible, not only in their ramping rates, but also in utilising different e-fuels, with high efficiency and lower GHG emission factors. This is a default constraint for BPS; however, changes can be made based on a particular scenario.

2. In a specific year, growth in the shares of installed capacities of renewable energy technologies cannot exceed more than 4% per annum from 2020 onwards in congruence with empirical data (Farfan and Breyer, 2017).

3. Hydropower plants are often refurbished at the end of their technical lifetime and not decommissioned. To reflect this in the modelling these plants are refurbished after every 35 years, and refurbishment costs are applied (Farfan and Breyer, 2017).

4. If profitable, share of prosumers can progressively increase from 3% in 2015 to 20% in 2050.

- **Current Policy Scenario**

1. All constraints used for the Best Policy Scenario are also applicable to the Current Policy Scenario, except for a major difference that new fossil fuel based power and heat boiler capacities can be installed during the transition until 2050. This is the default for the CPS; however, changes can be made as required based on a particular scenario.

2. Additionally, in **Publication IV**, to account for the potential electricity imports in future government policy, a ‘Deflated demand’ approach was used to integrate electricity imports in the modelling of CPS scenarios. In this, the imported electricity is subtracted from the total demand, and the new residual demand is used as the input for the simulation. This logic uses the prosumer approach to optimise the domestic residual system demand. As the government of Bangladesh wants to use the imported electricity to meet the base load, this methodology may be a better way to represent the role of imported electricity in the power system. As Bangladesh will have power purchase agreements with the respective neighbouring countries for imported electricity, assuming a constant hourly import is a simplified way to capture the hourly distribution.

3.5 Portfolio of modelled technologies

The model is integrated with various technologies, which can be classified into five main categories: electricity generation (renewables, fossil, and nuclear), heat generation (renewables and fossil), energy and heat storage, power transmission, and sector coupling technologies to provide additional flexibility to the energy system. The entire portfolio of technologies in an aggregated overview is shown in Figure 8.

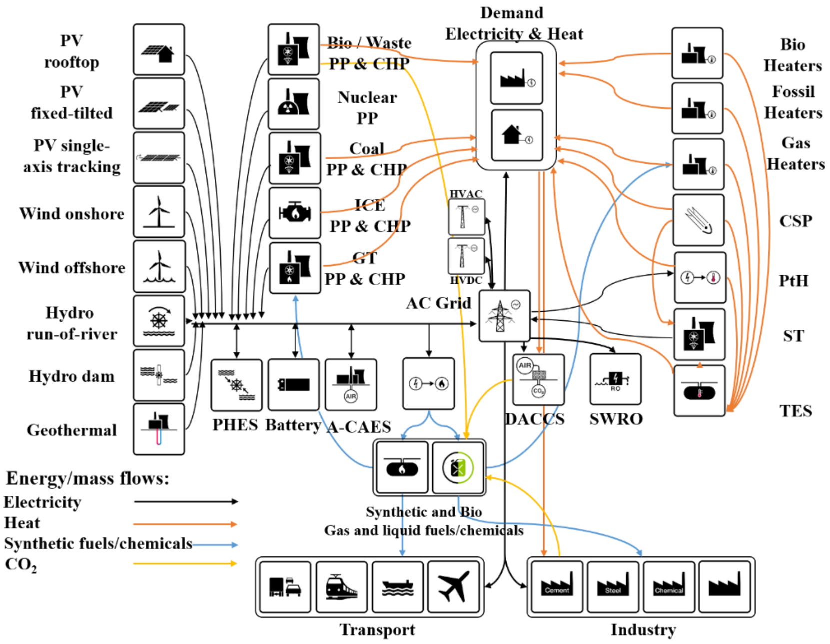


Figure 8: Portfolio of technologies that are possible to be used in the LUT-ESTM (Bogdanov *et al.*, 2021a). In **Publication VI**, the industrial demand of the feedstock for the industrial processes was not part of the modelling. Industrial process heat was part of the total heat demand.

- **Technologies for electricity generation**: solar PV fixed tilted, solar PV single-axis north-south tracking, solar PV rooftop, concentrating solar thermal power (CSP), wind onshore and offshore, hydropower run-of-river, hydropower reservoirs, geothermal, bioenergy (solid biomass, biogas, and waste-to-energy). The existing fossil fuels-based generation technologies considered are coal and conventional oil based power plants, open cycle gas turbines (OCGT), combined cycle gas turbines (CCGT) and nuclear technologies. In addition, new technologies like multi-fuel reciprocating ICE (gas) and heavy-duty open cycle gas turbines (OCGT HD) make up the electricity generation technologies.

- **Technologies for heat generation**: RE-based heat generation technologies are concentrated solar thermal power (CSP) parabolic fields, individual solar thermal water heaters, geothermal district heaters, and bioenergy (solid biomass, biogas district heat, and individual boilers). The existing fossil fuels-based heat generation technologies are coal-based district heating, oil-based district and individual scale boilers, and gas-based district and individual scale boilers.

- **Energy storage technologies**: Li-ion batteries and pumped hydro energy storage (PHES) for short-term storage. Adiabatic compressed air energy storage (A-CAES) (Aghahosseini and Breyer, 2018) and thermal energy storage (TES) for high and medium temperature heat. Gas storage including PtG technology, which allows production of e-methane and e-hydrogen for the energy system for seasonal storage requirement.

- **Electricity transmission technologies**: The existing power grid, its future development, and impact on overall electricity transmission and distribution losses (Sadovskaia *et al.*, 2019) are considered in the transition. The states are interconnected with high voltage direct current (HVDC) or high voltage alternating current (HVAC) power lines. These transmission lines provide required flexibility through the spatial distribution of renewable based electricity, especially in the monsoon season, while reducing overall national system costs. This is explained in **Publication III**

- **Sector coupling technologies**: The bridging technologies are electrolysers, methanation, Fisher Tropsch (FT) units, SWRO desalination plants, steam turbines, direct electrical heaters, heat pumps for district heating, and individual use. These technologies convert energy from one sector into valuable products for the other sector, thus increasing total system flexibility, efficiency and decreasing the overall costs of the energy system. A detailed overview of the sector coupling technologies can be found in (Bogdanov *et al.*, 2021a).

3.6 Main assumptions and input data for modelling

3.6.1 Technical and financial assumptions

The financial assumptions related to Capex, Opex (fixed and variable), and technical parameters for all technologies applied during the modelling of the South Asian region are available in the main manuscript or the supplementary material of each publication included in this dissertation. All assumptions are based on literature, with references provided in each case. In cases where country specific cost projection data was not available, financial projections were assumed based on a global average for all the technologies. The weighted average cost of capital (WACC) is typically set at 7% for all RE technologies, whereas a WACC of 4% is considered for residential PV rooftop prosumers due to lower risk and hence lower financial return expectations. However, in **Publication VII**, a different WACC assumption during the transition period is used, starting at 11% in 2015 and later converging to the standard assumption of 7% in 2030. After 2030, a constant WACC of 7% is assumed until 2050.

Electricity prices for the three prosumer categories, i.e., residential, commercial, and industrial, for the year 2015 were mainly assumed from (Breyer and Gerlach, 2013; Gerlach *et al.*, 2014), except in cases where individual country level data was available. These references are provided in the publications included in this dissertation. Future electricity prices are estimated based on the approach of Gerlach et al. (2014), which assumes that grid electricity prices will increase by 5% per annum for prices less than 0.15 €/kWh, 3% per annum for prices in a range of 0.15-0.30 €/kWh and 1% per annum for prices greater than 0.30 €/kWh.

3.6.2 **Renewable potential and feed-in profiles**

The maximum installable potential (upper limit) for solar PV and wind power is based on land use limitations and is set at 6% and 4% of the total region's land area, respectively. The average specific capacity density of solar PV is assumed to be 75 MW/km^2 during the transition. This is based on 15% module efficiency and a 50% ground coverage ratio (Bogdanov and Breyer, 2016) and is confirmed by empiric data (Bolinger and Bolinger, 2022). However, an increase in the efficiency of the PV modules that would impact the specific capacity density is not considered. For onshore wind power plants, the average specific capacity density is assumed to be 8.4 MW/km^2 (Bogdanov and Breyer, 2016). With this calculation, the total installable potential for utility-scale solar PV in India is 14,223 GW, and for onshore wind power, it is 1062 GW. Existing capacities are mainly taken from (Farfan and Breyer, 2017), while other sources for existing capacities, if used, are given in individual publications used in this dissertation.

For the hydropower plants and PHES, the potential was set at 150% and 200% of the already installed capacity in 2015. The geothermal energy potential was calculated according to the methods described in Aghahosseini and Breyer (2020). The biomass potentials were calculated based on the methodology described in Mensah et al. (2021).

The hourly capacity factor profiles for an entire year of solar PV, wind power, and hydropower were used as inputs for the modelling. Solar PV was divided into optimally tilted PV, single-axis tracking PV, and solar CSP. As for wind power, only onshore wind is considered for the countries in the South Asian region due to the unavailability of offshore wind profile data. The raw data is for the year 2005 from NASA databases (Stackhouse and Whitlock, 2008; 2009), reprocessed by the German Aerospace Center (Stetter, 2012) and has a resolution of 0.45°×0.45°. This data is further processed to calculate hourly capacity factor profiles as described in Bogdanov and Breyer (2016) and Afanasyeva et al. (2018). The increasing efficiency of solar PV systems and their impact on land area requirements during the transition are not considered in this research. However, it would have a positive effect in the densely populated South Asian countries.

Monthly resolved river flow data for 2005 is used to prepare hydropower capacity factor profiles as a normalised sum of the river flow throughout the country.

3.6.3 Demand projections

The electricity demand is taken from different local sources and is described in the respective publications used in this dissertation. The electricity demand is divided into residential, commercial, and industrial. The hourly load profile for each sub-region is calculated as a fraction of the total demand in the country based on synthetic load data, according to Toktarova et al. (2019), weighted by the sub-region's population. The hourly electricity demand projection is based on the method described by Toktarova et al. (2019).

4 Results

The summary of the main objectives, applied methodology and results for each of the publication included in this dissertation is presented in this chapter.

4.1 Publication I: A 100% renewable energy based cost optimal electricity system for the SAARC region

Aim

The main objective of **Publication I** was to simulate a cost optimal, 100% RE-based power system in an overnight approach for the year 2030, based on an hourly temporal and multi-nodal spatial resolution. Additionally, this publication aimed at providing a comparison between different levels of transmission grid development between the regions in a techno-economic analysis. Finally, the role of integrating PtG for non-energetic industrial gas demand and SWRO desalination into the power system was explored.

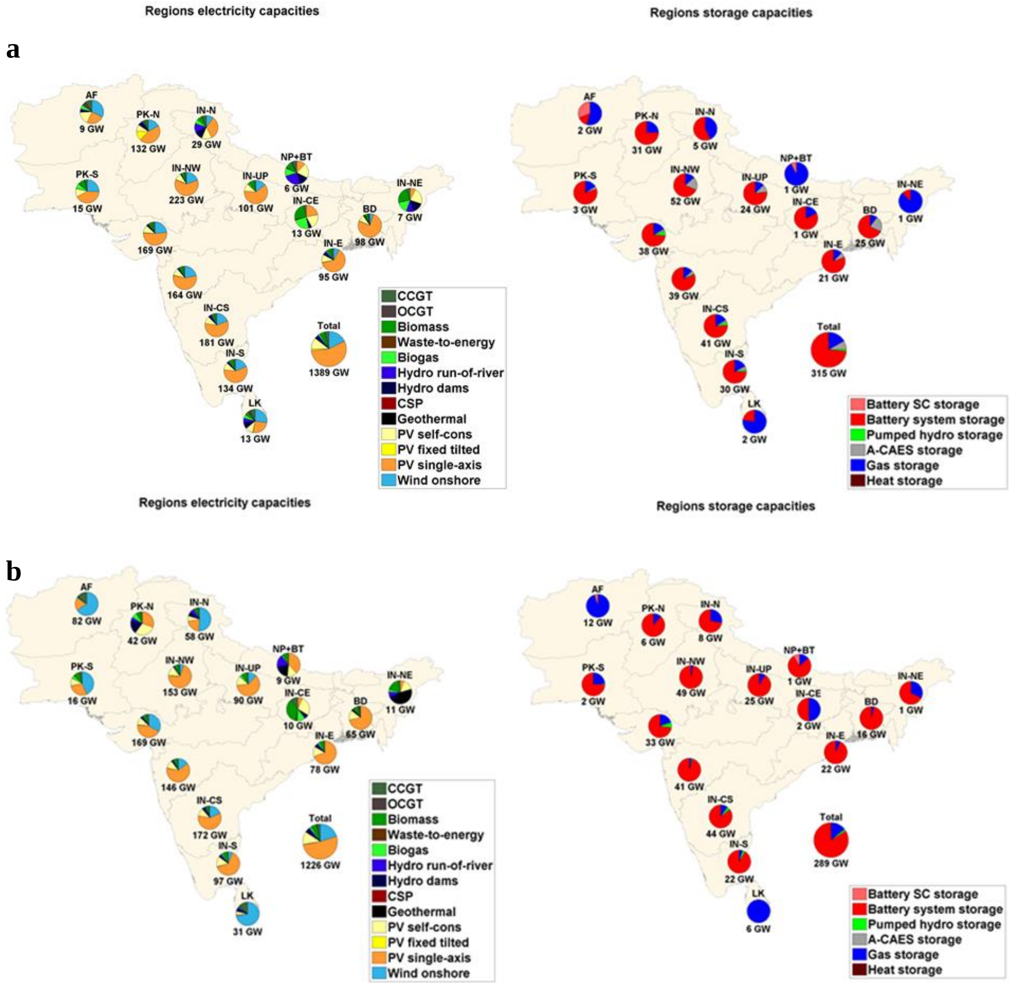
Methods

To show the multi-nodal approach, the SAARC region was divided into 16 sub-regions: 10 sub-regions in India; 2 sub-regions in Pakistan; Bhutan and Nepal are combined as one region, while Afghanistan, Bangladesh, and Sri Lanka are individual regions. The distribution of sub-regions was based on the population distribution, electricity demand, and grid structure. Four different scenarios were considered for the analysis of the power system in the SAARC region:

- **Region-wide scenario:** The 16 sub-regions are independent and have no transmission line connections. The region’s demand for electricity is covered by its own generation capacity.
- **Country-wide scenario:** Regions of the same country are interconnected via HVDC lines.
- **Area-wide scenario:** Highest level of transmission grid connection between the power systems of the different countries in the SAARC region.
- **Integrated scenario:** Area-wide scenario plus SWRO desalination and industrial gas demand to provide flexibility to the system where PtG technology also covers non-energetic industrial gas demand.

Results

The results of this research show that a 100% RE-based electricity system is technically feasible, economically viable, and a real policy option for the entire SAARC region, based on the cost assumptions used in this research. This option might be more cost competitive than nuclear power and fossil fuel-based CCS alternatives. The indigenous renewable energy resources, especially solar PV and wind power, with support from Li-ion batteries, can cover the total electricity demand in 2030 for the entire power sector, including the demand for SWRO desalination and non-energetic e-methane demand by the industry using PtG technology. Figure 9 shows the installed generation and storage capacities for the region-wide, area-wide, and integrated scenarios.



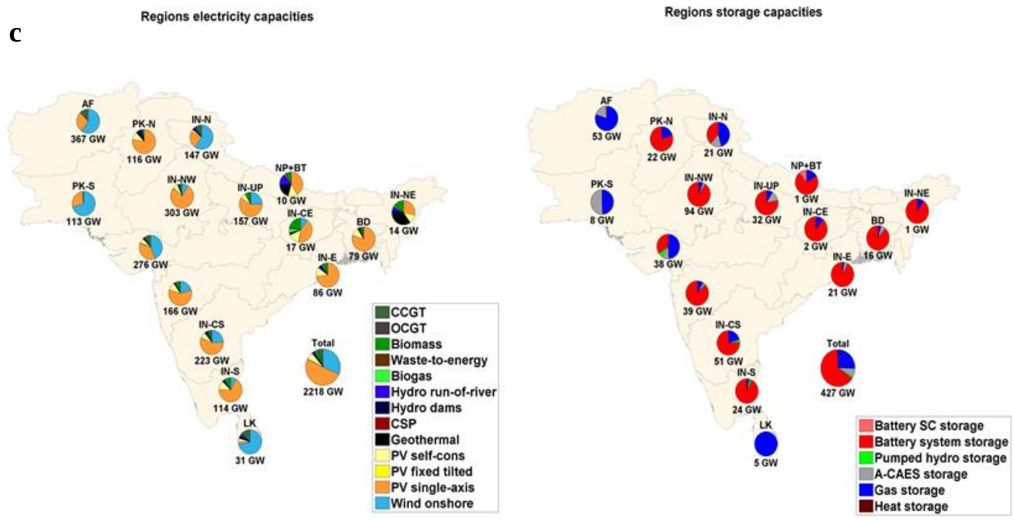


Figure 9: Installed capacities of power generation and storage technologies for; a) region-wide scenario, b) area-wide scenario and c) integrated scenario.

The results for a total system levelised cost of electricity (LCOE) showed a decrease from 71.6 €/MWh in a region-wide scenario to 67.2 €/MWh in an area-wide centralised grid connected scenario. The benefits of integrating e-methane production for industry and SWRO for desalination demand showed that the system cost decreased by 5% and total electricity generation decreased by 1% in the region. Furthermore, the proposed energy system configuration can manage the hurdle due to the monsoon season quite effectively.

4.2 Publication II: Pathways towards 100% renewable electricity for India and the role of storage technologies

Aim

The role of India, as one of the world's fastest-growing economies, and its rapidly expanding electricity demand, is critical for the global goal of limiting temperature rise to 1.5°C or below. To show a transition pathway for the Indian power sector, this study models a 100% RE-based power sector by 2050. The main objective of **Publication II** was to show a transition pathway towards a cost optimal, 100% RE-based power system by 2050, covering the demand of the power, desalination, and non-energetic industrial gas sectors at an hourly temporal and multi-nodal spatial resolution. Furthermore, this study explores the demand for and role of various storage technologies during the transition. Finally, the role of integrating PtG for non-energetic industrial gas demand and SWRO desalination into the power system was analysed.

Methods

The LUT-ESTM was used to optimise the transition scenarios to determine the optimal generation mix, storage demand, and investment required during the transition to satisfy the growing electricity demand until 2050. The simulation of the power demand was performed in 5-year time steps from 2015 to 2050 with an hourly temporal resolution. The optimisation of the model was carried out based on an assumed cost basis and the state of technology from 2015 to 2050. The financial and technical assumptions for all the components of the energy system are given in the supplementary material of this publication. For the energy transition of India, two scenarios were studied for the power system analysis:

- **Power scenario**: In this scenario the power systems of the 10 sub-regions are interconnected.
- **Integrated scenario**: The power scenario plus SWRO desalination and industrial gas demand, where PtG technology is used not only as a storage option but also for covering non-energetic industrial gas demand.

Results

The results of this study indicate that a 100% RE-based power system can be achieved by 2050 with a levelised cost of electricity decreasing from a level of 58 €/MWh in 2015 to 52 €/MWh in 2050 in the power scenario, while it decreases to 46 €/MWh in the integrated scenario. With a large influx of variable renewable energy sources in the system, the demand for storage technologies increases from the current level to 2050. Batteries, PHES, and gas storage provide 2596 TWh, 12 TWh, and 197 TWh of electricity output, respectively, to the total electricity demand. Majority of the storage demand in the power scenario will be covered by batteries, which provide a share of 41.6%, while PHES and gas storage cover 0.2% and 3.2% of the total electricity demand, respectively. Figure 10 shows the electricity generation and storage output during the transition in the power and integrated scenario.

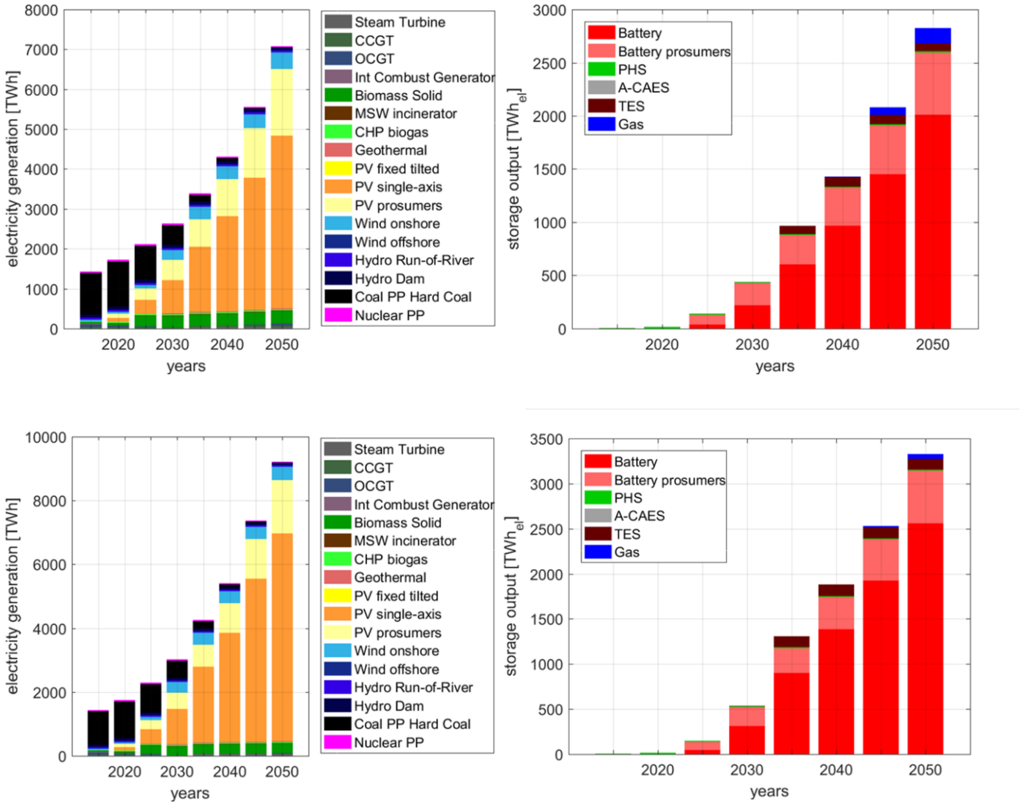


Figure 10: Electricity generation and storage output during the transition for power scenario (top) and integrated scenario (bottom).

The synchronised discharging of batteries at night and charging of power-to-gas in the early summer and summer months reduces curtailment on the following day and thus is part of a least cost solution. The combination of solar PV and battery storage evolves as the low cost backbone of the Indian power supply, resulting in 3.2–4.3 TWp of installed PV capacities, depending on the applied scenario in 2050. During the monsoon period, complementarity between storage technologies and the transmission grid helps to achieve uninterrupted power supply. The results of this study clearly prove that renewable energy options are the most competitive and least-cost solution for achieving a net zero emission power system.

4.3 Publication III: Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India

Aim

Various assessments have shown the potential and the huge role of solar PV in the transition towards the long term sustainability of the Indian power system. Results from **Publication II** show that about 3.2–4.3 TWp of installed solar PV capacity is required in a fully RE-based power system in 2050. With a large share of solar PV in the power system, the monsoon presents a challenge, resulting in a decrease in the availability of solar resources for the power system's uninterrupted operation. This publication answers the following research questions: ‘How will a solar PV dominated power system operate during the 3-4 months of the monsoon season?’, and ‘What are the various complementarity, storage technologies, and flexibility options available to the power system?’

Methods

The results of the Power scenario from **Publication II** were used for the analysis of the Indian power system during the monsoon season. The average monsoon period for entire India was taken from June – September, while the other months are taken as non-monsoon months.

Results

A fully renewable electricity system for India in 2050 can effectively handle the decreased solar power generation during the monsoon season by effectively utilising transmission grids and increased wind power availability, along with the additional flexibility provided by the increased hydropower generation and storage technologies.

The reduced power generation from solar PV in the monsoon period can be effectively complemented by an increase in power generation from wind power, in some regions. Total power generation from wind power in the monsoon period is 62% of the total wind power generated in India.

The interconnection of regions via transmission grids helps to balance the power demand in regions that are most affected by the monsoon in a cost effective way. The share of imports needed to satisfy the respective electricity demand during the monsoon period increases by 1.3% in comparison to the share of imports needed to satisfy the respective electricity demand during the non-monsoon period. It is observed that during the monsoon period, which represents only one-third of a year, the net electricity transfer in the grids is 38% of the annual net electricity transfer. Figure 11 shows the role of wind power in India Central West (top), a region affected by the monsoon, and the role of electricity exports in India South (bottom), a region least affected by the monsoon.

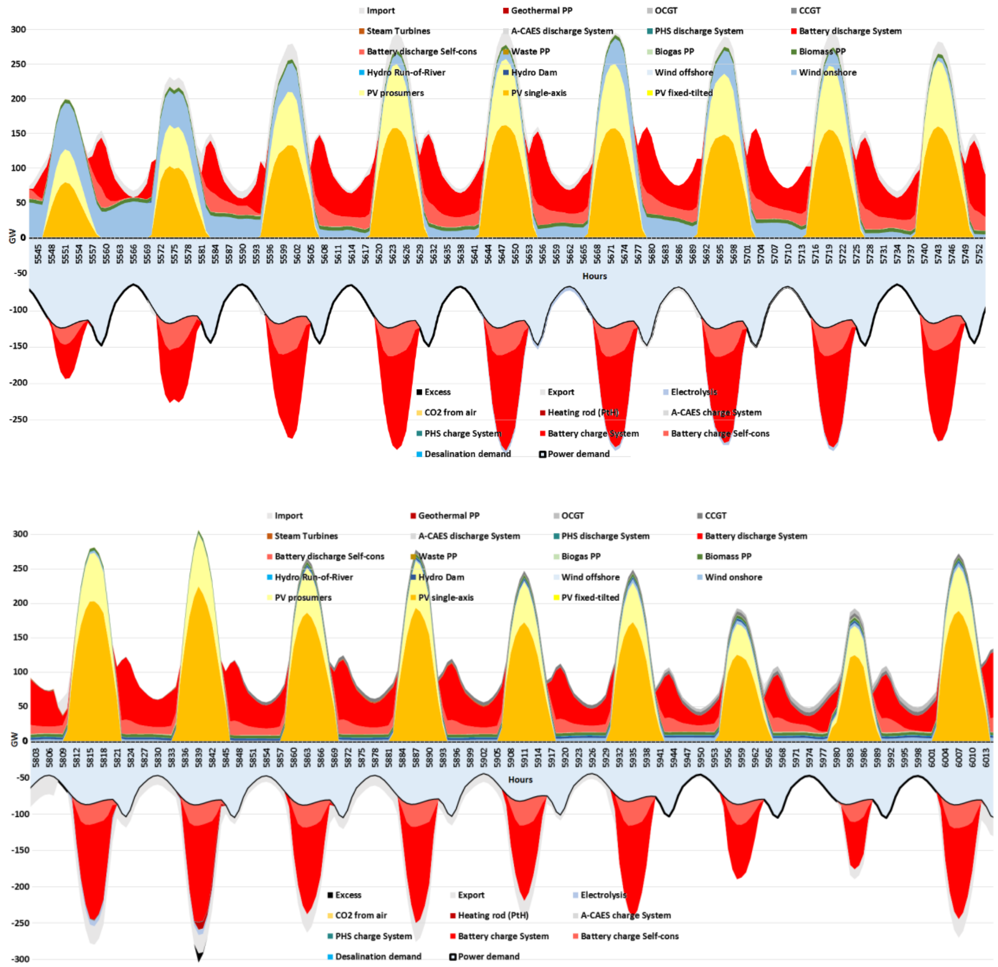


Figure 11: Electricity dispatch for the region India Central West (top) and India South (bottom) in a monsoon week in 2050.

These results clearly prove that RE options are the most competitive and least-cost solution for achieving a zero GHG emission based electricity system, even in the monsoon season without utilising backup power based on fossil fuels.

4.4 Publication IV: Current energy policies and possible transition scenarios towards 100% renewable energy for Bangladesh

Aim

Bangladesh presents a case for developing countries that are highly dependent on fossil fuels, and future energy policy is to increase fossil fuel imports as these countries do not have indigenous fossil fuel reserves. Most of these developing countries lie within the Sunbelt region. The aim of **Publication IV** was to demonstrate various power sector transition pathways by comparing a Current Policy Scenario (CPS) and a Best Policy Scenario (BPS), with an emphasis on the impact of GHG emissions costs on both scenarios. Further, this publication discusses the risks associated with future energy policies of the Government of Bangladesh, like energy security, increasing GHG emissions, climate change, and high electricity costs, as well as the potential opportunities in embracing renewables. **Publication IV** shows how RE could solve the energy security challenges of Bangladesh as well as meet the climate change goal of reducing its GHG emissions.

Methods

The various energy transition pathways were analysed using the LUT-ESTM for 2015 to 2050 period in 5-year time steps. For this research, four scenarios were developed: First, a CPS based on government policies and future energy planning. Second, a BPS to focus on the policy options leading to a transition towards a 100% RE system, taking into account the GHG emissions reduction and the overall system cost. Additionally, the impact of removing GHG emissions cost is explored in these two scenarios.

Results

The results show that a 100% RE-based power system is possible for Bangladesh by 2050, with the cost of electricity lower than in 2015 for the BPSs. Adding GHG emissions costs accelerates the transition towards a fully renewable energy system; however, removing emissions costs does not significantly affect the transition, as renewables would still contribute 94% of the electricity generation by 2050. Solar PV and batteries dominate the installed RE technologies due to their low costs and excellent solar resource conditions in Bangladesh. The huge share of solar PV in the electricity generation system corresponds to the huge share of batteries as storage technology, which serves as the least cost option for the power mix in Bangladesh. However, during the monsoon, batteries are not charged to their full capacity due to low solar resource availability. e-Methane generated from the excess electricity in the summer months is stored in a gas storage and used during the monsoon months, when batteries cannot completely satisfy the night time demand.

On the other hand, the CPSs increase the LCOE and the GHG emissions costs significantly after 2025. The LCOE for the CPSs increases from 82.4 €/MWh in 2015 to 139.4 €/MWh in 2050. This indicates a serious and complicated national risk that leads to several vulnerabilities like high electricity costs, an increase in GHG emissions, energy insecurity, and poor political trust if the present energy policy is continued. However, focusing on indigenous renewable resources could help mitigate this vulnerability. Figure 12 shows the increase in GHG emissions from the CPSs compared to the BPSs.

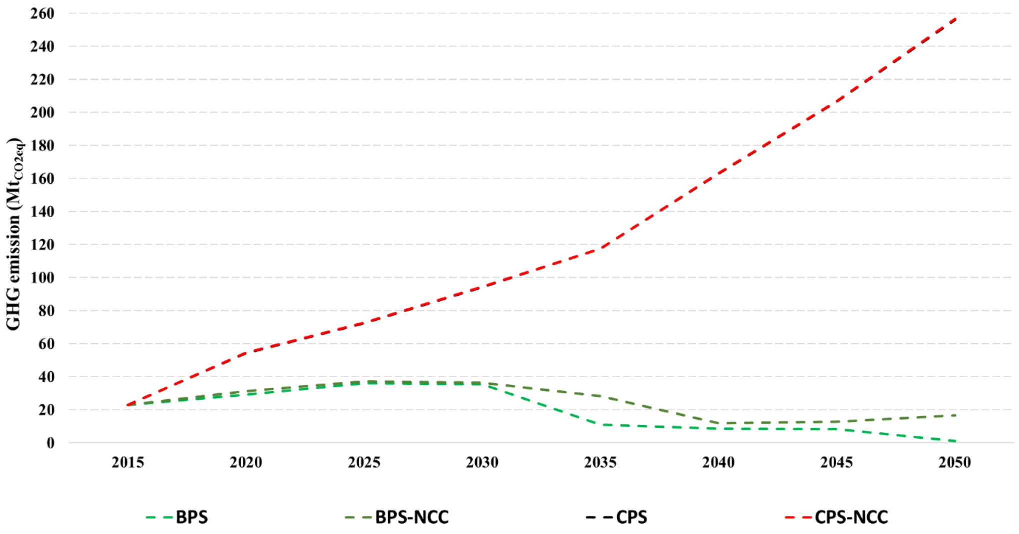


Figure 12: GHG emissions during the transition from 2015 to 2050, for the BPSs and CPSs.

Additionally, land availability is not a constraint if all the available wastelands are used properly for PV installations. New technologies, such as floating PV and efficiency improvements in PV technology, would help to maximise resource potential while requiring less land.

4.5 Publication V: Renewable energy transition roadmap in the power sector towards sustainability for Pakistan

Aim

Pakistan is on the verge of a severe water shortage and is turning into a highly water scarce country (Mustafa *et al.*, 2013). It is projected that there will be a demand and supply gap for water resources (Mustafa *et al.*, 2013). As majority of the water is used for irrigation purposes, this will have a huge consequence on the food production in the country. The main aim of this study is to show a transition of the current fossil fuel-based electricity system of Pakistan towards a least cost, 100% RE-based system, incorporating the desalination technologies into transition to satisfy the growing freshwater demand. The study also analyses the investment cost requirement, capacity mix, and demand for storage technologies.

Methods

The hourly resolved LUT-ESTM was used to simulate a 100% RE-based power sector from 2015 to 2050, covering the demands of the power, desalination, and non-energetic industrial gas sectors. The optimisation is done on the basis of assumed costs and technological status for every 5-years from 2015 to 2050 for all energy technologies involved.

For this study, Pakistan was subdivided into two regions: Pakistan-North and Pakistan-South, based on the population distribution, electricity demand, and existing grid structure. Two scenarios were studied for the energy system analysis:

- **Power scenario**: Only the power demand is covered, and the power systems of the two regions are interconnected for electricity trading.
- **Integrated scenario**: In addition to the Power scenario a SWRO desalination and non-energetic industrial gas demand is added, where PtG technology is also used to cover the non-energetic industrial gas demand in addition to the storage option.

Results

The results of this study show that the LCOE decreases from 106 €/MWh in 2015 to 46 €/MWh in 2050 in the power scenario. In an integrated scenario, which also includes the additional cost of SWRO desalination and synthetic gas production, the LCOE decreases to 47 €/MWh in 2050. Figure 13 shows the LCOE during the transition for the power sector (top) and the integrated scenario (bottom) from 2015 to 2050. Even with the huge demand from the desalination sector, the LCOE in the integrated scenario is comparable to the power only scenario.

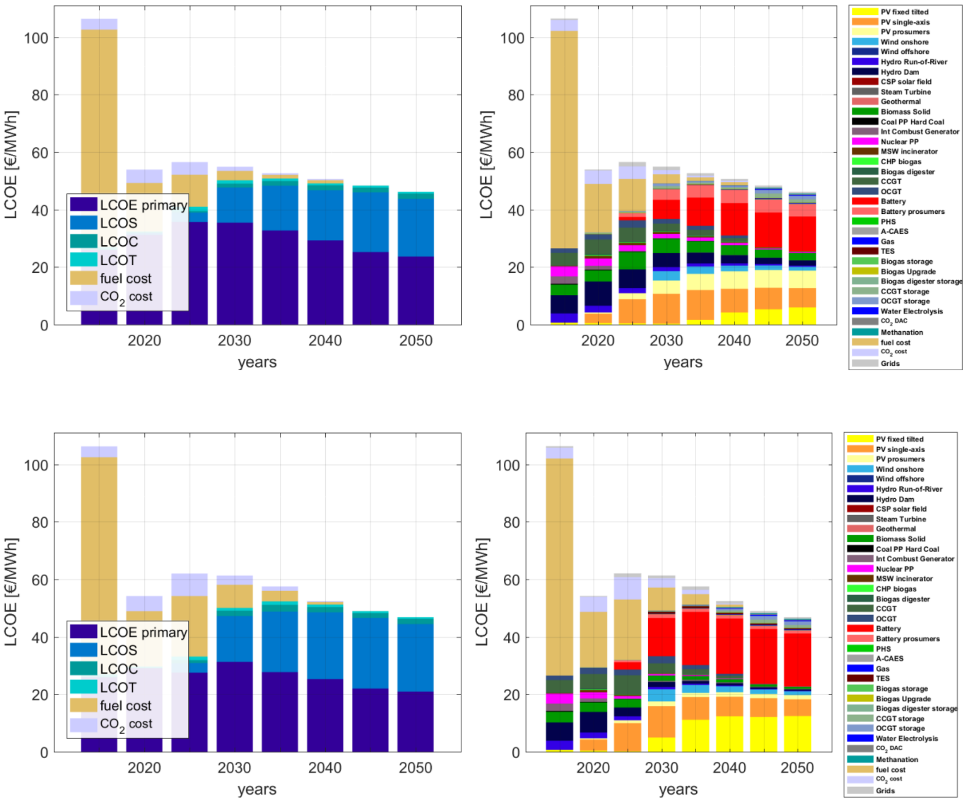


Figure 13: LCOE during the transition from 2015 to 2050 for the power sector (top) and integrated scenario (bottom).

The demand for water grows to 1.3·10^9 m^3/day in 2050. To satisfy the growing water demand, the main desalination technology used is SWRO because of its higher efficiency and cost competitiveness as compared to other desalination technologies. The levelised cost of water (LCOW) decreases from 0.84 €/m^3 in 2015 to 0.62 €/m^3 in 2050, exploiting the low cost potential of solar PV generation.

Solar PV and batteries dominate the installed RE capacity due to their cost competitiveness and excellent solar resource availability. Solar PV provides almost 86% of the total electricity demand and is complimented by wind power and biogas in low solar irradiation areas. Major share of solar PV in electricity generation corresponds to the huge share of batteries as storage technology as the least cost and sustainable option.

The results of **Publication V** show that a least cost electricity transition pathway for Pakistan is possible and compatible to the Paris Agreement.

4.6 Publication VI: Renewable energy transition pathways for the Himalayan countries Nepal and Bhutan

Aim

The Himalayan countries, Nepal and Bhutan, face similar but unique challenges related to climate change. The power system is completely dependent on hydropower, while the other sectors are dependent either on fossil fuel imports or the unsustainable use of biomass. Governments in these countries promote hydropower as a source of uninterrupted power and economic development, but there are various social, financial, environmental, and technical concerns associated with building new hydropower plants. Therefore, the main aim of his study is to show an energy transition pathway for the power, heat, and transport sectors towards a 100% renewables-based energy system, incorporating large shares of solar PV and limited hydropower development. The role of GHG emission costs is explored through scenario comparisons.

Methods

All sector LUT-ESTM was used to show a transition pathway for an integrated power, heat, and transport sectors for Nepal and Bhutan on an hourly resolution for every 5-year time step from 2015 to 2050.

For the simulation, Nepal was sub-divided into 7 regions based on the provincial state structure. Bhutan was considered an individual region due to its smaller area, population, and energy demand. The sub-regions in Nepal are interconnected with each other, with Kathmandu as the main consumption centre. Dividing a larger country into sub-regions enables higher spatial resolution of each sub-region’s RE generation potential, consumption pattern, transmission, and storage requirements.

Two scenarios for analysing energy transition pathways toward a higher share of renewable energy were considered in this study. A Best Policy Scenario (BPS-1) with GHG emission cost and a Best Policy Scenario (BPS-2) without GHG emission cost. Based on the overall system cost and GHG emissions reduction, these scenarios focus on two policy options leading to an energy transition in Nepal and Bhutan.

Results

The results in **Publication VI** show that an energy transition towards a 100% RE-based system is technically feasible and economically viable by 2050 for Nepal and Bhutan, utilising the abundant renewable resources apart from hydropower. Due to the shift from fossil fuel-based primary power generation to renewables and a comprehensive electrification of the end-use demand, in particular for heat supply and road transportation, the energy system in 2050 will be substantially more efficient than the current system. Figure 14 shows efficiency gains in primary energy demand due to direct and indirect use of electricity in different energy sectors.

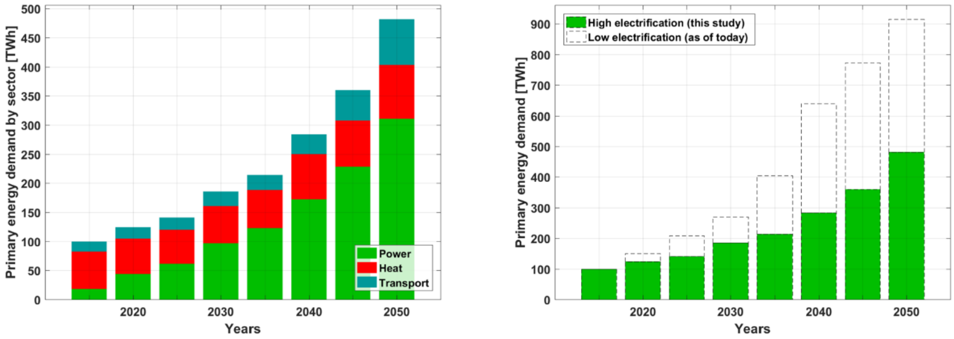


Figure 14: Growth in primary energy demand and efficiency gains during the transition.

The levelised cost of energy for Nepal and Bhutan decreases from 90 €/MWh in the present non sustainable energy system to 49 €/MWh and 47 €/MWh by 2050 in BPS-1 and BPS-2, respectively, documenting an increase in levels of sustainability and overall economics. Despite having large snowmelt, high river currents, and sloping terrain, which are excellent for hydropower generation, solar PV emerges as the backbone of electricity generation supported by batteries.

4.7 Publication VII: Renewables for rapid transition of the power sector in India on a state-wide resolution

Aim

The role of renewables in electricity generation is highly variable across the states in India. The share of renewables in electricity generation in renewable energy rich states like Andhra Pradesh, Gujarat, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Punjab, Rajasthan, Tamil Nadu, and Telangana is considerably higher than the national average of 8.2% (IEA and NITI Aayog, 2021). The states of Karnataka, Tamil Nadu, and Rajasthan have considerable generation from solar PV and wind power, while other states are still lagging in capacity and generation. To achieve the goal of a transition to net zero GHG emissions by 2050 for India, there needs to be synergy between the state and central government policies.

The power sector assumes an important role, as direct and indirect electrification, in particular electricity-derived e-fuels, will form the backbone of an entire energy system. Thus, decarbonisation of the power sector is key to reducing CO_2 emissions by the mid-century. As a result, failure to deeply decarbonize the power sector before mid of this century will seriously jeopardise the ongoing climate mitigation efforts (Jenkins *et al.*, 2018).

Methods

The modelling of a transition of the Indian power sector is performed using the LUT-ESTM. A multi-node approach is used to describe any desired configuration of interconnections between the states. A novel hierarchical modelling approach is applied to decrease the simulation time (Bogdanov *et al.*, 2022). The modelling is performed in two steps. First, modelling of the system in reduced regional resolution (4 regional grids). Second, modelling of each of the regional grids in full state resolution, considering the power flows between the regional grids simulated in the first step. The results represent the operations of the integrated power system in full resolution, where power can flow between all the states.

Results

The results in **Publication VII** show that a rapid transition away from coal and towards 100% renewables-based electricity generation across the different states of India can be achieved in a cost optimal way, by integrating large shares of solar PV, batteries, wind power and ably supported by a strong transmission and distribution infrastructure. This transition not only decreases the cost of electricity generation by phasing out fossil fuels but also enables a rapid decrease in CO_2 emissions and losses in the power sector. Figure 15 shows the transition from coal-based electricity generation in 2020 towards a solar PV dominated electricity generation in 2050.

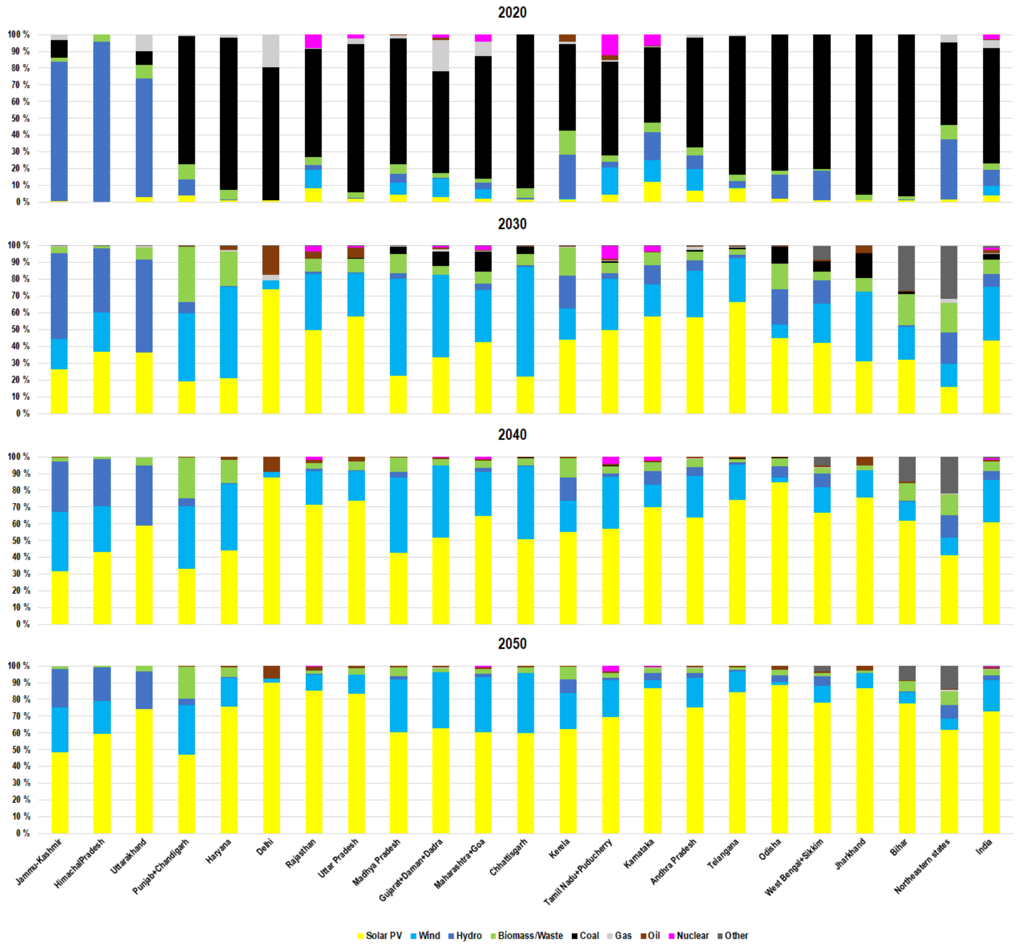


Figure 15: Share of solar PV and other technologies in electricity generation during the transition in a state-wide resolution.

Solar PV installed capacity reaches 3000 GW by 2050, contributing almost 73% to the total power generation in India. During the monsoon season, wind power plays a supporting role that complements solar PV perfectly. The contribution of wind power to total power generation reaches 19% in 2050. Solar PV and wind power are already low cost options in India. With costs of batteries continuously decreasing, a rapid transition of the power sector towards utilising 100% renewables is a possibility.

5 Discussion

The primary objective of this dissertation was to show least cost energy transition pathways for the entire South Asian region and the individual countries. The transition pathways show that the South Asian region can achieve its NDCs and even go further to achieve the ambitious target set in the Paris Agreement of achieving net zero GHG emissions by 2050. An energy transition towards 100% RE is technically feasible and economically viable. However, large policy shifts, strong political will, and long term national, regional, and state policies around integrating renewable technologies will be needed.

The previous section provided insights and implications of the transition towards 100% RE in the South Asian countries. Generally, without a proper context, future energy policies from governments typically show that pursuing large-scale RE integration would raise electricity costs (Greenstone *et al.*, 2021; Toh, 2021). However, further discussion based on the results of this dissertation shows that the transition itself not only yields a lower cost of electricity for the end consumers but also lowers GHG emissions and the corresponding air pollution issue, leads to higher energy security, and provides clean water.

5.1 General discussion of the presented results

5.1.1 Costs and investments of the energy transition

Transition pathways towards integrating large shares of renewable energy and achieving net zero energy systems across South Asian countries hinge on large expansion in investments and a big shift in capital flows towards renewable technologies rather than fossil fuels. The pathways shown in this dissertation provide an outlook for investments required in each of the technologies in every 5-year time step, based on the assumed Capex and Opex for each of the technologies. Further, annual investments will not provide the entire picture of costs, especially for supplying a kWh or MWh of electricity or energy. Thus, LCOE was used as one of the metrics for cost normalisation and comparison across technologies, scenarios, and during the transition (Ram *et al.*, 2018). LCOE as a tool for cost comparisons remains robust (Kuckshinrichs and Juelich, 2021) and widely used despite various sceptics (Loewen, 2019; 2020).

The growth in installed capacities of RE, especially solar PV and wind onshore in the South Asian region, observed from the results of the publications included in this dissertation, point to the growing cost competitiveness of these technologies. Thus, a large decrease in the LCOE during the transition is in line with the expected cost decline of RE technologies. For the interconnected South Asian region (**Publication I**), with the additional demand from SWRO desalination and e-methane demand, the LCOE is 67.9 €/MWh in 2030. Globally, the cost of renewables, especially solar PV and wind onshore, has declined dramatically by 85% and 56%, respectively, while the cost of Li-ion batteries has reduced by 89% between 2010-2020 (BloombergNEF, 2020; IRENA, 2021f). These technologies will have a major impact in the region based on the results of this dissertation. Nowadays, renewables are the most cost competitive source of electricity generation in many countries, and the same is true for the countries in South Asia (IEA, 2021c; IRENA, 2022b). The average LCOE of constructing a new utility-scale solar PV plant in India is 23 €/MWh, as compared to the average cost of existing coal-fired power plants at 24 €/MWh (Shumkov, 2021). In the South Asian countries, the LCOE for solar PV and wind onshore ranged between 32–85 €/MWh in 2020 (Chauhan *et al.*, 2021), while that of conventional technologies, including nuclear power, ranged between 38–165 €/MWh (Chauhan *et al.*, 2021). Ram et al. (2018) calculated the LCOE of electricity generation technologies for India, with internalising the external and CO_2 emissions costs of power production. The median LCOE for coal is 59 €/MWh, for combined cycle gas turbines is 71 €/MWh, for open cycle gas turbines is 97 €/MWh and for nuclear power it is 64 €/MWh.

Publication IV compared the CPS - an increased emphasis on fossil fuel-based power plants build-up and BPS - aim of achieving 100% RE by 2050 for a least cost transition scenarios for the case of Bangladesh. The LCOE of the CPSs are 25% and 58% higher than the BPSs, depending on the GHG emissions costs implementation. The higher cost in 2050 for the CPS is a result of the expansion of oil, gas, and coal-based power plants during the transition, resulting in higher fuel costs and GHG emissions. Comparatively, BPS utilise renewables and take advantage of the rapidly falling costs, especially of solar PV, and thus provide cost competitiveness against the fossil fuel options. The LCOE of the BPS could have been even lower if the Indian government's benchmark costs for solar PV were considered (CERC, 2016). New investments in fossil fuels create a lock-in for several years, with an extremely high likelihood of the investment being stranded. Furthermore, fossil fuel and nuclear power investments are often embroiled in legal disputes, making them liable for cost and schedule overruns (Sovacool *et al.*, 2014). As seen from the CPS, investments in fossil fuels lead to a higher annualised cost, plus they violate the sustainability criteria and lead to a higher cost of electricity.

Similar cost trends are also observed in **Publications II, V, and VI,** during the transition to 2050. The slight increase in LCOE observed between 2020–2035 in Pakistan, Bangladesh, and India is a result of the combination of utilising fossil fuels to power the growing electricity demand and the associated fuel and GHG emissions costs. In the case of India, coal power generation as a primary source during the initial years has a higher emission intensity, thus resulting in higher emissions and the associated cost. Additionally, phasing out power generation from fossil fuels creates additional investment needs. Sadiqa et al. (2022) modelled an all sector energy transition for Pakistan, including the desalination demand, using the LUT-ESTM, showing a similar decreasing cost trend by 2050. The total levelised cost of energy for a 100% RE-based energy system in 2050 is 56.1 €/MWh, down from 70 €/MWh in 2015. Thus, showing the cost competitiveness of renewables during the transition.

For the Indian Ocean islands in the South Asian region, Keiner et al. (2022) simulated the energy transition for the Maldives, while Meschede et al. (2022) reviewed the key results of an energy transition study for Sri Lanka. The results for Sri Lanka show that it can achieve a least cost, 100% RE-based energy system in 2050, with a total levelised cost of energy of 33 €/MWh. On the other hand, the Maldives can transition from a fossil fuel importing country with a very high levelised cost of energy of 105.7 €/MWh in 2017 to a self-sufficient and energy independent country in 2050, with a levelised cost of energy of 92.6 €/MWh. Thus, this shows that transition even on islands is cost competitive with several other advantages.

Solar resource availability is excellent in the South Asian region, and with the declining cost of Li-ion batteries, hybrid PV-battery systems form the backbone of the power sector. Wind onshore in the region is not cost competitive with hybrid PV-battery systems, especially after 2030. First, the region lacks excellent large scale wind resource availability all year around, and in addition, it lacks land availability in resource rich regions, especially in India. Second, the cost decline for wind onshore technology is not as fast as for solar PV. Therefore, low-cost solar PV has a maximum share in the region and the individual countries' electricity generation in a 100% RE system in 2050.

The total annualised costs of the power system in 2030 for the entire South Asian region ranges between 181-299 b€ depending on the scenario. On the other hand, the total annualised cost for India in 2050 ranges between 232 and 330 billion euros, depending on the scenario. Similarly for Bangladesh in 2050, it ranges between 34-36 b€ for the BPSs, while for the CPSs, it is between 40-78 b€. Pakistan has total annualised cost in 2050 ranging between, 29-122 b€, depending on the applied scenario. For a fully integrated energy transition of all the sectors in Nepal and Bhutan, the cost for a 100% RE system is 27 b€. The total annualised cost is calculated as the sum of the annual costs of all the power generation capacities, energy generation, generation ramping of the technologies, storage technologies, and transmission costs of the generated electricity for each of the transition years. As expensive fossil fuels are replaced by cost-competitive renewables, the fuel cost and the variable Opex decrease, and are replaced by fixed Capex and Opex during the transition. The cost savings significantly outweigh the initial investment required during the transition, while air pollution declines, leading to lower health costs and environmental damage (IRENA, 2018).

Very few studies have estimated the cost of 100% RE systems for the entire South Asian region, and very few country level analyses exist. Jacobson et al. (2019) conclude that India can achieve a 100% RE (wind, water, solar) system at a LCOE of 91 €/MWh, including all end-use demand. According to Teske et al. (2019) India can generate 100% of its electricity using RE at a cost of 45 €/MWh. However, this does not include the cost of transmission, storage, and curtailment. These studies and others support the results of this dissertation that a 100% RE-based power system is technically possible (Brown *et al.*, 2018; Diesendorf and Elliston, 2018). However, the cost might differ due to different technical and financial assumptions (Matsuo *et al.*, 2020).

5.1.2 **Electricity generation mix**

The electricity generation mix changes from a fossil fuel dominated to an energy system completely dependent on RE in the South Asian region. By 2050, 100% of the electricity generated in the region is projected to come from renewable technologies, with the majority from solar PV, complemented by wind power and hydropower. The continuous cost decline of solar PV generated electricity, supported by its abundant potential, results in an increasing share in total electricity generation. Wind power complements solar PV in regions where good wind resources are available. This is observed from the results in **Publications I-VII**, as growing share of electricity generation from renewable sources substitutes for the present and future reliance on fossil fuel-based electricity. Solar PV, due to its cost decline, is ably supported by Li-ion batteries to form a new kind of base supply of electricity (Miemois and Zhang, 2018) in 100% RE-based systems. As part of a least cost power dispatch, a solar PV generation share of 51% and a wind power share of 35% is possible across the entire South Asian region, as shown in **Publication I.** Generation from utility-scale solar PV has already achieved grid parity in many parts of the world, faster than projected (Breyer and Gerlach, 2013) undercutting the existing and cheapest electricity generation based on fossil fuels (IRENA, 2021a). The same is observed in the South Asian countries, which are dependent on coal, oil, and gas. On the other hand, wind onshore plays an important role in regions where wind resources are cost competitive with solar PV, for example in Afghanistan and Sri Lanka. The northern part of Sri Lanka has one of the best wind resources in the South Asian region, with a capacity factor of over 41% (ESMAP, 2022). This results in the export of wind power-based electricity to the high electricity demand centres in South India. However, if the modelling had been done for the year 2050, the share of wind onshore electricity generation would be different.

For the case of individual countries, Bangladesh, Bhutan, India, Nepal, and Pakistan, as seen in **Publication II, IV, V, VI and VII,** the solar PV share in electricity generation ranges between 67-95%, while the wind power share ranges between 0-18.5%, depending on the scenarios. The lowest share of solar PV is observed in Nepal and Bhutan, as these countries have extremely good hydropower resources; therefore, some hydropower capacities were built during the transition. However, the dependency on hydropower is reduced from more than 80% in 2015, as decentralised, modular, and low cost solar PV replaces large hydropower plants during the transition. The share of hydropower in total electricity generation in 2050 will be between 3-31% depending on the scenario. Similarly, for Sri Lanka, solar PV has a maximum generation share of 85%, wind power has a share of 11% and hydropower has a share of 4% (Meschede *et al.*, 2022). The role of electricity as a primary energy carrier results in a share of 98% of the total primary energy supply, indicating its huge role in the heat and transport sectors (Meschede *et al.*, 2022). For a land constrained archipelago such as the Maldives, floating offshore PV technology has a generation share of 62%, while wave power and wind offshore have a generation share of 28.2% and 9%, respectively, in a 100% RE-based self-sufficient energy system (Keiner *et al.*, 2022). For a fully renewable energy system in Pakistan in 2050, solar PV technologies will provide more than 90% of the total electricity generation (Sadiqa *et al.*, 2022).

India has a solar PV share between 86-89% and a wind power share of 5-18.5% in the total electricity generated in 2050, depending on the pathway. Low cost solar PV forms the backbone of the electricity generation mix across all the states in India, as can be seen from the results of **Publication VII**. Especially, during the first decade of the transition, large scale expansion of solar PV capacities is observed primarily in the states dependent on hydropower and coal-based electricity, such as the northern and eastern states. Building new hydropower plants is comparatively expensive and time consuming, and the states cannot invest in building new coal power plants, as per the assumption. Building solar PV capacities is thus the cheapest source of new electricity generation, saving these states carbon emission costs and corresponding GHG emissions. The high share of solar PV in the total electricity generation is ably supported by low cost Li-ion batteries, which support the night-time peak load. Additionally, prosumers with their installed batteries play an important role in reducing the peak load on the system and also contribute to power generation. These prosumers benefit greatly by maximising their roof space and reducing their annual electricity costs and dependency on grid-based supply (Keiner *et* *al.*, 2019). Thus, PV prosumers will have a crucial role in enabling energy transitions and shaping future energy markets (Ram *et al.*, 2017; Kotilainen, 2020; Steadman, 2021).

The highest growth in wind power capacity installations is observed during the first decade of the transition, particularly in the wind resource rich states of Gujarat and Maharashtra. During this period, batteries are not cost competitive, and the dependence of solar PV on batteries to supply night-time demand enables wind power to see the highest growth. In the future, newer turbines with higher hub heights will increase the capacity factors at these locations to make wind power cost competitive with other fossil and renewable sources of electricity generation. Therefore, wind power and hydropower complement each other in regions with good wind and hydro resource availability, especially in the western, southern, and northern parts of India. The overall wind conditions in India are not the best to maximise its utilisation annually, however during the monsoon, installed wind capacities are utilised in periods of low solar radiation, when in some parts of India, wind resources are excellent. **Publication III** visualises in detail the effect of the monsoon season on a 100% RE-based power system for the year 2050.

The growth in solar PV and wind power installed capacity during the last 5 years has been phenomenal in India, as solar PV has grown at an CAGR of 38%, while wind power grew at a CAGR of 7%, outpacing the overall growth in total installed capacities (IRENA, 2022a). The share of solar PV and wind power in total electricity generation has increased from 3% in 2014 to 8% by the end of 2021 (Ember, 2022a). While some states like Karnataka, Rajasthan, Tamil Nadu, Gujarat, etc. are leaders in installed capacity and generation share, contributing 29%, 20%, 18%, and 14% respectively to the state's annual electricity generation in 2020, others like Uttar Pradesh, Punjab, etc. are laggards with generation shares lower than the national average of 8.2% (IEA and NITI Aayog, 2021). During the peak Covid-19 crisis in 2020, electricity generation from solar PV and wind power was resilient, even when the total electricity demand decreased, affecting coal generation, which was reduced (IEA, 2021a). However, many challenges exist for renewable capacity installation, especially land acquisition and the requirement for large scale expansion of solar PV and wind power. Based on **Publication II** and **Publication VII**, total utility-scale solar PV installed capacities would require 5.2-7.8% of the total wasteland area, while onshore wind power would require 3.9-8.7% in a fully RE-based electricity generation. The government of India has introduced measures to overcome the issue of land acquisition by working with the state and local governments and creating solar parks (MNRE, 2022b) by leasing barren agricultural lands from farmers (The Economic Times, 2022).

Similar land availability issues are of concern in other South Asian countries, particularly in land constrained Bangladesh. Based on the installed capacities of utility-scale solar PV in **Publication IV,** a 100% RE-based power system in the BPS would require 10% of the land area. This land area excludes land suitable for agriculture and forests (Trading Economics, 2015). Additionally, water bodies and hydro reservoirs could provide a potential area for installing floating solar PV systems (Abid *et al.*, 2019; IRENA, 2019b; Lohrmann *et al.*, 2019; Cazzaniga and Rosa-Clot, 2021; Charles Rajesh Kumar and Majid, 2021; Muhammad *et al.*, 2021). Other co-allocation of solar PV would be ‘Agri-PV’, allowing agricultural production in co-existence to electricity generation (Malu *et al.*, 2017; Adeh *et al.*, 2019; Schindele *et al.*, 2020; Worringham, 2021). Thus, these options could be explored in the future to reduce land availability stress.

With abundant low cost solar PV potential available in the region, fossil fuel plants are on the verge of becoming stranded assets. For the case of India, 33.1 GW of coal power plants are under construction, while 29 GW are in the preconstruction phase (Global Energy Monitor, 2022). Majority of the under construction plants are owned by the central or state government entities. With the cost of renewables between 25–28 €/MWh compared to the domestic coal power plant’s tariff of 44–63 €/MWh, any increase in power demand will be supplied by renewables (Shah, 2021). Thus, these inflexible base load generation will add to the distribution companies’ fixed capacity charges and financially burden an already troubled power sector (Shah, 2021). There seems to be no economic rationale for new coal power plants operating in India (Chakravarty and Somanathan, 2021).

5.1.3 System flexibility, storage technologies and transmission grids

The rapid growth in VRE integration into the power sector, puts a huge emphasis on the need for system flexibility measures, such as short and long term storage and the expansion of transmission grids. Therefore, it is apparent that greater focus is required on these mechanisms in energy transitions to promote and facilitate more affordable, sustainable, reliable, and resilient energy systems (IEA, 2019b). This will enable a smooth and secure power supply from VRE to meet the increasing power demand across the South Asian region, as observed from the results in **Publications I-VII.**

Currently, PHES provides the required balancing of the power supply in countries where there are already installed capacities, for example, India. The growth in PHES capacities in India has largely been tepid due to environmental, social, economic, and regulatory constraints (Buckley and Shah, 2019; IEA, 2021a). On the other hand, recently, the focus has been shifted on modular Li-ion battery energy storage systems (BESS), due to their considerable cost decline in the last decade and their ability to provide the required balancing as the share of VRE grows in the total electricity generation. It is observed from the results, except for **Publication I,** that the role of batteries grows after 2025. As a result, large-scale, cost optimal investments in utility-scale and rooftop BESS are made during the transition, while synthetic gas storage provides the required seasonal storage flexibility. In a 100% RE-based power system in South Asia (**Publication I**), batteries provide a share of 13-19% of the total electricity demand, depending on the scenario, a consequence of the high share of solar PV in the total electricity generation. Similarly, for India (**Publication II and VII**), Bangladesh (**Publication IV**), Pakistan (**Publication V**) and Nepal and Bhutan (**Publication VI**), batteries provide the required balancing of supply and demand with an output share of 35-42%, 50-55%, 39-47% and 30%, respectively, depending on the scenario. With solar PV accounting for more than 90% of electricity generation in Pakistan, batteries provide the majority of storage output to meet total demand (Sadiqa *et al.*, 2022). The same is observed in the cases of the Maldives and Sri Lanka (Keiner *et al.*, 2022; Meschede *et al.*, 2022). This is a typical characteristic of power systems in Sunbelt countries highly dependent on solar PV, where variation in solar resources' output is low during the year (Solomon *et al.*, 2018; Blakers *et al.*, 2019). As a result, rather than long-term seasonal (months) balancing, short-term (hours) power shifting is required to balance the night time load. Recent studies highlight the importance and influence of hybrid PV-battery systems on future power systems (Creutzig *et al.*, 2017; Haegel *et al.*, 2019; Breyer, 2021; Lu *et al.*, 2021b). Thus, hybrid PV-battery systems support a least cost, 100% RE-based power system, providing stability and reliability. These are complemented by gas turbines using synthetic natural gas for electricity production. Other storage technologies also contribute to the power system's balancing and flexibility.

One interesting observation that can be made from **Publication I** is the role of adiabatic compressed air energy storage (A-CAES) as mid-term storage. This storage plays a big role in the region-wide scenario, where each region is independent, thus storing wind power and discharging at times of low solar PV yield. However, as the level of grid integration increases, the role of A-CAES decreases, as electricity transmission via grids over a larger area is more economical than mid-term storage. The output from gas storage, which is e-methane produced via the PtG process, towards the electricity demand in the South Asian countries is low, as these countries do not have significant seasonal variation. Thus, they do not have a heating load in the winter season (Blakers *et al.*, 2019). However, installed gas storage capacities dominate the total storage capacities, particularly after 2040, when the VRE penetration reaches an average of 80% (Bogdanov and Breyer, 2016; Solomon *et al.*, 2019). These gas storage technologies have large capacities and low capacity factors, a result of low Capex, due to the assumption that existing gas storage sites, depleted oil and gas fields, and salt caverns are used for gas storage. For the case of

India (**Publication II and VII**), gas storage plays an important role when there is no or reduced solar PV output, especially in the monsoon and the winter season. Thus, gas storage contributes 6% of the total storage output during the year for a 100% RE-based power system. The gas storage is charged over the summer when the solar resource is at its maximum and slowly discharged over the monsoon and winter months. Similarly, the hydropower reservoirs provide complementarity to solar PV and wind power generation and are used for seasonal balancing. As part of a least cost solution, the battery-to-PtG effect was introduced for the first time in **Publication II.** This documents the value of a flexibly defined optimisation model, as any hard coded storage merit order would block such an effective low cost solution.

Besides the temporal balancing at the identical geographic location discussed in the previous paragraphs, spatial balancing at the identical point in time is provided by transmission grids enabled during the transition. The results from **Publication I** show the trade-off between energy storage technologies and transmission grids. Large-scale interconnection between the South Asian countries enables a decrease in LCOE compared to independent regions and countries, due to reduced capacities of electricity generation technologies and curtailment. Additionally, the need for storage technologies decreases as the cost of electricity shifted in time can be marginally substituted by electricity shifted in location. However, not in all cases are large-scale continental grids greatly beneficial, as observed by Gulagi et al. (2017b) for the case of Southeast Asia connected with Australia, Aghahosseini et al. (2019) for the case connecting North America with South America, and Breyer et al. (2020) summarising for various geographic cases and also presenting a global perspective. The authors concluded that in such cases, other energy carriers like synthetic natural gas (SNG) were more suitable than long distance transport of electricity. Furthermore, grid extension or connecting remote mountainous regions with the main central grid might not be possible or very expensive, as in Nepal and Bhutan (**Publication VI**). In such cases, decentralised hybrid PV-battery systems enable the electrification of remote locations (Bhandari and Stadler, 2011). However, interconnection between the states and regions within a country does enable access to low cost renewables from across the country, as was observed for the case of India in **Publication VII.** Also, transmission grids play an important role during the monsoon.

Monsoon season is a hindrance to a power system that is entirely reliant on renewable energy, especially when solar PV accounts for a large share in electricity generation. As seen from the results of **Publication III**, a decrease in solar resource availability in one region during the monsoon period can be overcome by an increase in power generation in some of the other regions. Transmission lines help balance the electricity demand of the regions affected by the monsoon by importing electricity from other regions that are not severely affected. It is observed that the monsoon season, which represents one-third of the year, accounts for approximately 38% of the annual net electricity trading, while the remaining 8 months account for 62%, indicating the highest period of electricity trading and transmission grid utilisation during the monsoon season. Similarly, the monsoon plays a big part in Bangladesh, a country with limited wind power and hydropower resource availability (Faijer and Arends, 2017). The results of **Publication IV** show that Bangladesh can overcome the solar resource variability by operating its CCGT and OCGT turbines using synthetic natural gas. This is a unique case for a country located in the Sunbelt and a direct consequence of a lack of wind power, hydropower reservoirs, and a comparably small geographic extension of a country that blocks regional balancing with transmission grids. Thus, Bangladesh can utilise its existing gas infrastructure with a fuel switch to e-methane in a fully renewable based power system. This shows the technical differences between the power system operation of two countries in overcoming the monsoon.

For the security and stability of an electricity system, ancillary services provided by conventional rotating generators would need to be substituted by synchronous condensers in a 100% RE-based system. These synchronous condensers provide all the necessary ancillary services, like fault current, inertia, and voltage support, while active power can be provided by renewable generators and storage technologies (Brown *et al.*, 2018). Thus, ongoing research is targeting various ways to manage 100% inverter based system operations, with power system operators continuously analysing the challenges for maintaining grid stability and reliability (Jouini *et al.*, 2018; ENTSO-E, 2019; ESIG, 2019; Qazi, 2020; Global PST Consortium, 2021). According to Oyewo et al. (2018), the synthetic inertia provided by renewable technologies and Li-ion batteries is extremely important for the stability of 100% RE systems. Additionally, a new class of inverters, such as grid-forming inverters, can provide stable operation of RE-based systems when no synchronous generators are running (Zhao and Flynn, 2022; Zhao *et al.*, 2022).

5.1.4 GHG emissions reduction and other benefits

The benefits related to an energy transition toward large scale integration of renewables are profound. **Publications I – VII** show that a transition to 100% RE leads to net zero CO_2 emissions, reduced air pollution related to the energy system, and the supply of clean water using desalination.

As the share of RE increases during the transition, a reduction in GHG emissions is observed in the South Asian countries. This reduction in GHG emissions is in line with the Paris Agreement target of limiting temperature rise to 1.5°C above pre-industrial levels by 2050, with zero GHG emissions across all energy sectors. South Asia, particularly India, has a high CO_{2eq} intensity due to large coal-based generation. During the transition, the CO_{2eq} intensity rapidly declines as coal is replaced by renewables, which indicates a deep defossilisation by 2030. The level of air pollution is also expected to decline throughout India during the transition, therefore reducing associated health impacts, which has both societal and economic benefits (Markandya *et al.*, 2018; Amann *et al.*, 2020; Rauner *et al.*, 2020). Additionally, as observed in **Publication IV**, CPS leads to an increase in GHG emissions, due to the installation of fossil fuel-based technologies. As a result, GHG emissions increase by 981% in 2050 compared to 2015. The direct CO_2 emissions released to the atmosphere are considered in this study. Particulate matter (PM) and other GHG emissions such as methane, nitrous oxide, ozone, chlorofluorocarbons, and hydrofluorocarbons are not considered. It can be inferred that proportional reduction is possible for other greenhouse gases and PM during the transition period for the BPS scenarios.

Additionally, a clean energy transition creates numerous jobs to replace those jobs lost in the fossil fuel value chain. According to a recent study (Ram *et al.*, 2022b), a clean energy transition to large shares of RE will not only be the least expensive but will also create new job markets

The South Asian region is one of the most highly water stressed regions in the world that is entirely dependent on irrigation from fresh groundwater resources (Rasul, 2014; Lutz *et al.*, 2022). These groundwater resources are depleting faster than ever (World Bank, 2015). Thus, seawater desalination can make a huge difference in solving the existing water crises in the region. **Publications I and V** show that low cost RE-based electricity can be used for desalination, mainly utilising SWRO desalination for its efficiency and relative cost competitiveness to other desalination technologies (CMI, 2016; Tsai *et al.*, 2016). Integration of these desalination plants has a positive influence on the cost of an energy system, as observed by Bogdanov et al. (2021a). However, they offer limited flexibility to the energy system, as found out by Caldera et al. (2018).

The countries in the South Asian region are highly dependent on fossil fuel imports to satisfy their energy needs. These countries spend more than 3% of their annual GDP on import of fossil fuels (IRENA, 2019a). With an increasing population and energy demand, the demand for energy supply will skyrocket in the future. This dissertation shows that the South Asian region can satisfy its growing power demand without any fossil fuel imports by investing in domestic indigenous renewable resources. Additionally, this transition will increase energy security, thus completely reducing their energy import expenditure and positively influencing the trade balance.

5.2 Policy implications for South Asia and India

Achieving a transition to 100% RE systems and net zero CO_2 emissions in the South Asian region is a monumental task. This is made even harder by the rapidly growing population, economic growth, and rising aspirations of the people. In this dissertation, it is shown that achieving 100% RE-based systems in South Asia is both technically feasible and economically viable. However, long term ambition, unwavering focus, political will, and coordination among all national and regional stakeholders will be required. This will ensure that the transition proceeds at the required pace without any delay to achieve the net-zero target by 2050. For a developing region like South Asia, where millions of people do not have access to basic electricity and billions still lack clean cooking, a transition will provide access to modern, affordable energy services. Against this backdrop, this dissertation offers the following implications of an energy transition towards 100% RE in the South Asian countries.

5.2.1 Electricity – a key enabler of energy transition

Among all energy end uses, electricity remains a critical energy carrier. Its growth has been the fastest, confirming its role as the backbone of the current and future energy systems in South Asia. The role of electricity is set to grow much more rapidly than the overall energy demand. This came to the forefront during the recent Covid-19 pandemic, as electricity kept societies functioning without any major disruptions (Birol, 2020). Additionally, the role of direct and indirect use of electricity in other end-use energy sectors reiterates the importance of low cost RE-based electricity as a key enabler of a sustainable and low cost energy transition. This growing trend of electrification necessitates the attention of South Asian policymakers and governments in developing a low-cost, resilient future power system, decoupling it from external price shocks of imported fossil fuels and increasing energy security. However, large-scale integration of VRE into the electricity generation mix calls for an overhaul of the current design of electricity markets and provides early signals for overall investment and also investment related to sources of flexibility and demand response (IEA, 2021b).

A low cost power system transition is possible, as seen in **Publications I-VII**, by enabling policies for large scale solar PV and Li-ion battery implementation. In addition, national and regional governments should encourage local manufacturing of solar PV panels and RE systems to be cost competitive and create additional employment opportunities. For example, India has prioritised local manufacturing of solar panels by enacting various policies and providing incentives (Shiradkar *et al.*, 2022). The formation of the Alternative Energy Development Board (AEDB) has given much needed impetus to the renewable energy sector in Pakistan, with various projects coming up, mostly related to solar PV (IFC, 2016). Similarly, in Bangladesh, the initiation of Sustainable and Renewable Energy Development (SREDA) in 2014 was a step in the right direction. With the experience in deploying SHS to provide electricity to its population, Bangladesh should utilise this expertise in prosumer and utility-scale solar PV deployment (Newcombe and Ackom, 2017).

5.2.2 Implementation of carbon pricing

Renewables displace fossil fuels from the energy system as the share of RE increases during the transition. As these fossil fuels are taxed, the revenue streams from the tax collection will be lost by the governments (Swamy *et al.*, 2021b). Therefore, it will be crucial to implement a taxing mechanism on the use of fossil fuels and their associated emissions during the transition. As can be seen from **Publications I-VII**, the transition pathways are shown with the implementation of CO_2 emission costs; however, even without the implementation of carbon pricing, as seen from **Publications IV and VI**, a cost optimal RE-based system with a renewable share of more than 95% is obtained in 2050.

While countries in the South Asian region are deliberating on the implementation of some sort of carbon pricing, such as Bangladesh (Islam, 2017), India has implemented a ‘fuel excise tax’ of 14.4 €/tCO_2 on fossil fuels (OECD, 2021). This is much lower than the GHG emissions cost implemented in this dissertation, which is based on a proactive climate perspective to encourage the deployment of renewable technologies. However, as explained previously, even without GHG emissions pricing, the power system is close to net zero emissions and almost 100% RE-based. In this context, India could consider some additional taxes on emissions or similar mechanisms to internalise the adverse effects of fossil fuels. Additionally, the revenue collected could be used towards the development of renewable energy and sustainable technologies (Swamy *et al.*, 2021b).

5.2.3 New fossil fuel power plants result in stranded assets

Various countries in the South Asian region have fossil fuel based power plant capacities in the pipeline for the next few decades. Pakistan and Bangladesh plan to invest in new coal power plants in the near future (Climate Analytics, 2019). For Bangladesh, its domestically available natural gas reserves will be exhausted by 2031 (BD News, 2015). Investments in new coal power capacity increase dependency on energy imports for countries with limited domestic production relative to their coal consumption (Climate Analytics, 2019). As seen from the results of **Publication IV**, investing in fossil fuel-based power plants results in serious risks such as the high cost of electricity, energy insecurity due to imports, and increasing GHG emissions. The level of risk is manifold for Bangladesh and Pakistan due to their rapidly growing population.

India has large capacities of coal power plants with variable costs higher than the present LCOE of solar PV plants, indicating a case for early retirement of these capacities purely on economic terms (Swamy *et al.*, 2021b). On top of this, India has about 33.1 GW of coal power plants under construction, which will add to the already financially stressed distribution companies as these inflexible assets cannot compete with low cost solar PV electricity production (Shah, 2021). Many of these coal power plants are operating at low plant load factor (PLF), thus reducing their profitability, and compounding their already dwindling financial returns. These financially unviable coal power plants are not able to make the required payment to the banks, thus reducing the bank's ability to fund renewable energy projects (IEEFA, 2019). The results from **Publications I-VII** show the stranded capacities of fossil fuels in a 100% RE-based system in 2050. Furthermore, these coal power plants can be repurposed, rather than decommissioned into hybrid PV-battery systems, which could be much more economical (Jindal and Shrimali, 2022).

5.2.4 **South Asia and Sustainable development goals**

The main aim of an energy transition towards renewables is to improve the lives and livelihoods of people in mainly developing and least developed countries. As a result, an inclusive and people-centred transition is required in these countries in order to achieve a collective goal of global transition to net-zero CO_2 emissions energy systems by 2050 (IEA, 2021b). The results in **Publication I-VII** comply with the United Nations' energy related SDG 7.1 of universal access to affordable, reliable, clean, and modern energy services for all. Also, the reduction in GHG emissions during the transition results in reducing air pollution, a major cause of premature deaths, in the bigger cities of South Asia, which are some of the most polluted in the world.

Solar PV emerges as a key enabler for achieving SDG 7.1. It is affordable, modular, and sustainable. Because of their low cost, Li-ion batteries can replace diesel-powered generators for evening electricity use. Access to on-grid electricity seems to be the most economic option for Indian consumers, with growing energy consumption (IEA, 2021a); however, uninterrupted access to on-grid electricity remains a challenge. On the other hand, remote rural locations can benefit from decentralised systems that offer and ensure reliable electricity services. Various policies by the Indian government backing SHS, solar pumps, and mini-grids are in place, which translate into steady growth of ownership in rural areas (IEA, 2021a). The achievement of SDG 7.1 requires coherent efforts from governments and other stakeholders. The benefits are multi fold, such as an economic boost, creating a local job market, and bringing improvements to social well-being by modernising health services and food chains (IEA, 2021b). Most of the time, relevant policies to achieve the SDGs and reduce the impacts of climate change should run in parallel; thus, synergies between several areas can have an overall positive effect on other goals. One example of this would be replacing fossil fuels with renewables, which reduces GHG emissions while also reducing air pollution and water stress. However, minimising potential trade-offs between achieving climate change goals and SDGs will be important in achieving a transition that caters to all the goals (IEA, 2021a). Electrification of the transport sector is important to reduce air pollution, but not at the expense of using coal-based electricity to power this transition.

5.2.5 India's role in the global energy transition

India's role in global energy affairs is set to increase in the years to come. Its actions in the coming years will have long term consequences for the global energy landscape and the global goal of limiting temperature rise to 1.5°C. As a result, all paths to a global clean energy transition necessitate a significant contribution from India. Recently, India announced its net zero emissions target by 2070, at the COP26 (Energy and Climate Intelligence Unit, 2021). Based on the results from **Publications II and VII**, India can leapfrog polluting technologies to achieve a rapid transition towards net zero emissions in the power sector. This transition can accommodate India's development imperatives of providing secure and affordable energy to each citizen while mitigating air pollution in its cities and maintaining robust economic growth.

All roads point in the right direction for India, starting with the power sector reforms like connecting all regional grids to create a single national grid, 100% electricity access to the households and massive increase in renewable energy installations in the last decade and ambitious future targets for renewable energy installations (Beyer, 2020). With population and energy demand expected to grow rapidly in the coming years, India is in a unique position to lead a model net-zero CO_2 emissions energy transition with all-inclusive growth. These aspects are already envisioned in India's future policies. With a positive outcome, it will be a model for other developing countries in the Global South, demonstrating that robust economic growth is possible with GHG emissions reduction and the achievement of SDG goals (IEA, 2021a). Also, the role of ISA in garnering financial support from private and public investors will facilitate faster action on large scale deployment of solar PV in the Global South.

India's power sector is experiencing a solar PV powered revolution. From the results of **Publications II and VII**, solar PV combined with batteries will form the backbone of India's energy transition. However, it will need policies and local production of technologies to be cost competitive in the global market. India aims to become a global leader in solar PV and battery manufacturing, with huge demand expected from the local market. But this ambition raises questions about the availability of secure supplies of critical minerals like lithium, silver, copper, aluminium, nickel, cobalt, manganese, rare earth elements, etc. (IEA, 2021a). While solutions do exist as pointed out by Greim et al. (2020) for the case of lithium. Thus, managing the associated value chain risks of these critical minerals will be an important task for India’s policy makers (IEA, 2021a).

5.3 Challenges, uncertainties and limitations

This dissertation analyses different energy transition pathways for the South Asian region. Within the scope of this study, it is technically feasible and economically viable with available renewable resources in each of the countries to satisfy the growing power and energy demand. While challenges exist, Brown et al. (2018) and Breyer et al. (2022) clearly respond to these major barriers and concerns that are often associated with 100% RE-based systems. Nevertheless, challenges and uncertainties do exist in the modelling of future energy systems.

- The primary concern with integrating large shares of RE is low inertia and inability of the power system to balance short-term frequency deviations. However, this decrease in inertia from rotating masses in a 100% RE-based power system can be mitigated by the integration of synthetic inertia and improved algorithms for power inverters for generation and batteries, as power system operators will gradually manage large integration of renewables with continuous ongoing research in the field (Oyewo *et al.*, 2018; Hodge *et al.*, 2020; Breyer *et al.*, 2022).
- The effect of uncertainties due to the impact of Covid-19 and related supply chain distortions, as well as the Russian war in Ukraine, on the cost development of renewable energy technologies was not part of this study. However, based on the historic learning rates of the technologies, this effect is expected to be temporary, and the trend of declining renewables costs is expected to continue during the transition period.
- The criticality of certain raw materials like silver, copper, aluminium, and lithium is seen as a potentially limiting factor in the fast growth of renewable energy and storage technologies. This might have major consequences for the transition, and it should be dealt with additional research and analysis. However, solutions do exist, as pointed out by Breyer et al. (2022) and dedicated policies fostering a circular economy would reduce primary production.
- Social acceptance of technologies and political will are the most uncertain aspects of the transition. These aspects change over time and are hard to integrate into techno-economic analysis. However, qualitative assessments can be made, and it is assumed

in this dissertation that society and government policies will follow a low-cost, sustainable, and climate compliant pathway.

Additionally, certain limitations of the current research should be taken into consideration when interpreting the results:

1. **Publications I-V and VII** focused primarily on the transition of the power sector, while the integration of other major sectors such as heat, transportation, and industry were excluded. Due to its geographic location, the heat demand for residential and commercial buildings does not constitute a major source of demand in the energy system. However, there is considerable demand for industrial process heat and energy demand for the transport sector. In hindsight, the power sector, or electricity, is projected to play an important role in future energy systems. Therefore, the structure of the primary results would not differ much even in an all-sector integrated scenario. However, future energy systems research should include an all-sector analysis for this region and the countries within it.

2. The cost of land for renewable technology installation is not considered in the analysis, but it is assumed that the land is procured, available, and ready for use. Land will be a premium asset in the future in the densely populated South Asian countries, so careful consideration of all factors and utilising floating PV and Agri-PV will be needed. A brief discussion on the land issues was added to **Publications I and IV.**

3. Several assumptions, projections, and estimations are part of the input data used in modelling of future energy systems. While all data and assumptions are not always readily available in the South Asian region, global assumptions were used in such cases. One of the most important assumptions is the WACC. A uniform assumption of 7% WACC is applied in **Publications I-VI** throughout the transition and across all the countries. This assumption is consistent with reports from international organisations such as IRENA. There is no proper analysis and publication on WACC projections into the future for individual countries; therefore, applying a uniform WACC was the most conservative and best choice available. Already, India has a lower cost of capital for solar PV projects than the 7% used in this dissertation, and economic development and stability in the future will lead to a lower WACC comparable to developed countries.

6 Conclusions

The main aim of this dissertation was to analyse least cost energy transition pathways for the rapidly developing South Asian region and the individual countries within it, using the LUT-ESTM, towards achieving the target set in the Paris Agreement of limiting the temperature rise to 1.5°C by 2050. The scenarios were compared based on the level of development of transmission lines, future policy planning from the government, and the implementation of carbon pricing.

The overall results of this dissertation show that a rapid transition away from fossil fuels and towards 100% RE across the different countries in South Asia can be achieved in a cost optimal way by integrating large shares of solar PV, Li-ion batteries, and wind power, supported by a strong transmission and distribution infrastructure within each of the countries. The South Asian region is blessed with abundant low cost renewable resources, especially solar PV; however, right policies are required to tap into this potential. This research identifies the most cost-effective ways to exploit this potential for their energy needs without extending the planetary boundaries. This transition not only decreases the cost of electricity generation by phasing out expensive and inefficient fossil fuels but also enables a rapid decrease in CO_2 emissions, increases energy security, and reduces water stress.

The South Asian region is on the cusp of a solar PV powered revolution, and the results of this study show that solar PV is the least cost option for the region, complemented by wind power, hydropower and to some extent by modern uses of biomass. **Publication I** show that wind will be an important resource in 2030, especially in Sri Lanka, Afghanistan, and the Southern part of Pakistan, due to excellent wind resource availability and its cost competitiveness with solar PV. However, as highlighted in **Publications II, IV, V, VI and VII**, fast declining cost of solar PV after 2030 results in high shares of solar PV in a fully renewable based system in the countries of this region. Other resources, such as hydropower, play an important role and support solar PV in Nepal and Bhutan, as these countries have a high exploitable potential, as highlighted in **Publication VI.**

However, integrating large shares of variable renewables into the energy system calls for various new least cost flexibility portfolio solutions. Li-ion batteries, transmission grids, power-to-gas, and resource complementarity provide the flexibility for a 100% renewable-based energy system. As the share of renewable energy increases, storage technologies, especially Li-ion batteries, play a vital role in providing flexibility to the power systems, as highlighted in **Publications I, II, IV, V, VI and VII.** Adiabatic compressed air energy storage plays an important role as mid-term storage when each of the sub-regions is independent and high wind power shares in power generation and seasonal variation are observed, as highlighted in **Publication I.** Power-to-gas is critical and provides the required flexibility in the monsoon season for Bangladesh, as highlighted in **Publication IV**. On the other hand, resource complementarity, transmission grids, and power-to-gas provide the required flexibility, overcoming the monsoon challenge for India as highlighted in **Publication III**. Across the different states in India, Li-ion batteries and transmission grids provide much needed flexibility during the transition without increasing the total cost of the system. With the cost of Li-ion batteries continuing to fall, a rapid transition of the power sector to 100% renewable energy is a real possibility. Therefore, policies targeting these flexibility options should be a priority given their importance. Additionally, sector coupling in countries like India and Pakistan could add further benefits, such as reduced curtailment, while delivering a fully sustainable energy system. Utilising the abundant solar potential could pave the way for new industrial avenues such as green e-hydrogen and e-fuel production, signalling a potential shift in geopolitical structure. Thus, utilising the huge resource potential of solar and wind energy should be the preferred strategy that the countries in South Asia focus on.

The countries in the South Asian region are grappling with growing water stress issues. **Publications I, II, and V** show that the South Asian countries can overcome the water scarcity issue using low cost renewables for seawater desalination and avert future water shortages due to the depletion of fresh groundwater resources. Thus, low cost renewables will not only solve the water stress issues and reduce toxic air pollution but also reduce the growing fossil fuel import bill in these countries. Additionally, this transition decreases the huge losses associated with generating electricity using fossil fuels. Thus, a 100% renewable-based energy system will be highly efficient.

Although a rapid transition of South Asia's energy system is cost-effective, there are also indirect economic benefits from reduced air pollution and associated health costs, as well as the creation of additional jobs. Finally, pathways showing fully renewable power systems fulfil a wide range of environmental, socio-economic, and ethical sustainability criteria in a comprehensive manner. Therefore, scenarios involving fully renewable energy systems should be regarded as real policy options and used as a reference for alternative pathways.

References

Abid, M., Abid, Z., Sagin, J., Murtaza, R., Sarbassov, D. and Shabbir, M. (2019) ‘Prospects of floating photovoltaic technology and its implementation in Central and South Asian Countries’, *International Journal of Environmental Science and Technology*. Springer, 16, no. 3, pp. 1755–1762. doi: 10.1007/s13762-018-2080-5.

Adeh, E. H., Good, S. P., Calaf, M. and Higgins, C. W. (2019) ‘Solar PV Power Potential is Greatest Over Croplands’, *Scientific Reports 2019 9:1*. Nature Publishing Group, 9, no. 1, pp. 1–6. doi: 10.1038/s41598-019-47803-3.

Adenle, A. A., Chertow, M. R., Moors, E. H. M. and Pannell, D. J. (2020) *Science, Technology, and Innovation for Sustainable Development Goals: Insights from Agriculture, Health, Environment, and Energy*. Edited by A. A. Adenle, M. R. Chertow, E. H. M. Moors, and D. J. Pannell. New York: Oxford University Press.

Afanasyeva, S., Bogdanov, D. and Breyer, C. (2018) ‘Relevance of PV with single-axis tracking for energy scenarios’, *Solar Energy*, 173, pp. 173–191. doi: 10.1016/j.solener.2018.07.029.

Aghahosseini, A., Bogdanov, D., Barbosa, L. S. N. S. and Breyer, C. (2019) ‘Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030’, *Renewable and Sustainable Energy Reviews*, 105, pp. 187–205. doi: 10.1016/j.rser.2019.01.046.

Aghahosseini, A. and Breyer, C. (2018) ‘Assessment of geological resource potential for compressed air energy storage in global electricity supply’, *Energy Conversion and Management*, 169, pp. 161–173. doi: 10.1016/j.enconman.2018.05.058.

Aghahosseini, A. and Breyer, C. (2020) ‘From hot rock to useful energy: A global estimate of enhanced geothermal systems potential’, *Applied Energy*, 279, pp. 115769. doi: 10.1016/j.apenergy.2020.115769.

Ahmed, M. and Suphachalasai, S. (2014) *Assessing the Costs of Climate Change and Adaptation in South Asia*. Asian Development Bank. Technical Report, Manila. Available at: https://www.adb.org/sites/default/files/publication/42811/assessing-costs-climate-change-and-adaptation-south-asia.pdf (Accessed: 19 May 2022).

van Alphen, K., van Sark, W. G. J. H. M. and Hekkert, M. P. (2007) ‘Renewable energy technologies in the Maldives—determining the potential’, *Renewable and Sustainable Energy Reviews*. Pergamon, 11, no. 8, pp. 1650–1674. doi: 10.1016/J.RSER.2006.02.001.

Amann, M., Kiesewetter, G., Schöpp, W., Klimont, Z., Winiwarter, W., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Gomez-Sabriana, A., Heyes, C., *et al.* (2020) ‘Reducing global air pollution: the scope for further policy interventions’, *Philosophical Transactions of the Royal Society A*. The Royal Society Publishing, 378, no. 2183. doi:

10.1098/RSTA.2019.0331.

Anwarzai, M. A. and Nagasaka, K. (2017) ‘Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis’, *Renewable and Sustainable Energy Reviews*. Pergamon, 71, pp. 150–160. doi: 10.1016/J.RSER.2016.12.048.

Aziz, S. and Chowdhury, S. A. (2021) ‘Determinants of off-grid electrification choice and expenditure: Evidence from Bangladesh’, *Energy*, 219, pp. 119578. doi: 10.1016/j.energy.2020.119578.

Azzuni, A., Aghahosseini, A., Ram, M., Bogdanov, D., Caldera, U. and Breyer, C. (2020) ‘Energy Security Analysis for a 100% Renewable Energy Transition in Jordan by 2050’, *Sustainability 2020, Vol. 12, Page 4921*. Multidisciplinary Digital Publishing Institute, 12, no. 12, pp. 4921. doi: 10.3390/SU12124921.

Azzuni, A. and Breyer, C. (2018) ‘Definitions and dimensions of energy security: a literature review’, *Wiley Interdisciplinary Reviews: Energy and Environment*. John Wiley and Sons Ltd, 7, no. 1. doi: 10.1002/WENE.268.

Azzuni, A. and Breyer, C. (2020) ‘Global Energy Security Index and Its Application on National Level’, *Energies 2020, Vol. 13, Page 2502*. Multidisciplinary Digital Publishing Institute, 13, no. 10, pp. 2502. doi: 10.3390/EN13102502.

Bali, N., Vermani, S. and Mishra, V. (2020) *Electricity Access and Benchmarking of distribution utilities in India*. Smart Power India-powered by The Rockefeller Foundation. Technical Report, New Delhi. Available at: https://smartpowerindia.org/wp-content/uploads/2021/07/WEB_SPI_Electrification_16.pdf.

Balli, E., Nazif Çatık, A. and Nugent, J. B. (2021) ‘Time-varying impact of oil shocks on trade balances: Evidence using the TVP-VAR model’, *Energy*. Pergamon, 217, pp. 119377. doi: 10.1016/J.ENERGY.2020.119377.

BD News (2015) *Gas Reserves in Bangladesh to Last till 2031 at Current Extraction Rate: State Minister Nasrul Hamid*. BDnews24.com. Dhaka. Available at: https://bdnews24.com/economy/gas-reserves-in-bangladesh-to-last-till-2031-at-current-extraction-rate-state-minister-nasrul-hamid.

Bertheau, P., Oyewo, A. S., Cader, C., Breyer, C. and Blechinger, P. (2017) ‘Visualizing National Electrification Scenarios for Sub-Saharan African Countries’, *Energies 2017, Vol. 10, Page 1899*. Multidisciplinary Digital Publishing Institute, 10, no. 11, pp. 1899. doi: 10.3390/EN10111899.

Beyer, S. (2020) *India needs a resilient power sector: Lessons from the Covid-19 crisis*. International Energy Agency, Paris. Available at: https://www.iea.org/commentaries/india-needs-a-resilient-power-sector-lessons-from-the-covid-19-crisis.

Bhandari, R. and Stadler, I. (2011) ‘Electrification using solar photovoltaic systems in Nepal’, *Applied Energy*. Elsevier Ltd, 88, no. 2, pp. 458–465. doi: 10.1016/j.apenergy.2009.11.029.

Birol, F. (2020) *The coronavirus crisis reminds us that electricity is more indispensable than ever*. International Energy Agency, Paris. Available at: https://www.iea.org/commentaries/the-coronavirus-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever.

Bjorn, A., Chandrakumar, C., Boulay, A. M., Doka, G., Fang, K., Gondran, N., Hauschild, M. Z., Kerkhof, A., King, H., Margni, M., *et al.* (2020) ‘Review of life-cycle based methods for absolute environmental sustainability assessment and their applications’, *Environmental Research Letters*. IOP Publishing, 15, no. 8, pp. 083001. doi: 10.1088/1748-9326/AB89D7.

Blakers, A., Stocks, M., Lu, B., Cheng, C. and Stocks, R. (2019) ‘Pathway to 100% Renewable Electricity’, *IEEE Journal of Photovoltaics*. IEEE Electron Devices Society, 9, no. 6, pp. 1828–1833. doi: 10.1109/JPHOTOV.2019.2938882.

Bloom, D. E., Canning, D. and Fink, G. (2008) ‘Urbanization and the Wealth of Nations’, *Science*. American Association for the Advancement of Science, 319, no. 5864, pp. 772–775. doi: 10.1126/SCIENCE.1153057.

BloombergNEF (2020) *Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh*. Bloomberg New Energy Finance. London. Available at: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.

BloombergNEF (2022) *Energy Transition Investment Trends 2022 Tracking global investment in the low-carbon energy transition*. Bloomberg New Energy Finance. London. Available at: https://www.bnef.com/interactive- (Accessed: 19 May 2022).

Bogdanov, D. and Breyer, C. (2016) ‘North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options’, *Energy Conversion and Management*, 112, pp. 176–190. doi: 10.1016/j.enconman.2016.01.019.

Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A. S., de Souza Noel Simas Barbosa, L. and Breyer, C. (2019) ‘Radical transformation pathway towards sustainable electricity via evolutionary steps’, *Nature Communications*. Springer US, 10, no. 1, pp. 1077. doi: 10.1038/s41467-019-08855-1.

Bogdanov, D., Gulagi, A., Fasihi, M. and Breyer, C. (2021a) ‘Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination', *Applied Energy*. Elsevier Ltd, 283, pp. 116273. doi: 10.1016/j.apenergy.2020.116273.

Bogdanov, D., Oyewo, A. S. and Breyer, C. (2022) *Hierarchical approach to energy system modelling on the case of Japan, Submitted*.

Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza Noel Simas Barbosa, L., Fasihi, M., Khalili, S., Traber, T. and Breyer, C. (2021b) 'Low-cost renewable electricity as the key driver of the global energy transition towards sustainability', *Energy*, 227, pp. 120467. doi: 10.1016/j.energy.2021.120467.

Bolinger, M. and Bolinger, G. (2022) 'Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density', *IEEE Journal of Photovoltaics*. IEEE Electron Devices Society. doi: 10.1109/JPHOTOV.2021.3136805.

Breyer, C. (2021) 'Low-cost solar power enables a sustainable energy industry system', *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 118, no. 49. doi: 10.1073/pnas.2116940118.

Breyer, C., Bogdanov, D., Aghahosseini, A., Gulagi, A. and Fasihi, M. (2020) 'On the Techno-economic Benefits of a Global Energy Interconnection', *Economics of Energy & Environmental Policy*. International Association for Energy Economics, 9, no. 1, pp. 83–102. doi: 10.5547/2160-5890.9.1.CBRE.

Breyer, C. and Gerlach, A. (2013) 'Global overview on grid-parity', *Progress in Photovoltaics: Research and Applications*, 21, no. 1, pp. 121–136. doi: 10.1002/pip.1254.

Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A. S., Aghahosseini, A., Gulagi, A., Solomon, A. A., Keiner, D., Lopez, G., *et al.* (2022) 'On the History and Future of 100% Renewable Energy Systems Research', *IEEE Access*, 10, pp. 78176–78218. doi: 10.1109/ACCESS.2022.3193402.

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H. and Mathiesen, B. V. (2018) 'Response to "Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems"', *Renewable and Sustainable Energy Reviews*, 92, pp. 834–847. doi: 10.1016/j.rser.2018.04.113.

Buckley, T. and Shah, K. (2019) *Pumped Hydro Storage in India*. Institute for Energy Economics and Financial Analysis. Report, Ohio. Available at: https://ieefa.org/wp-content/uploads/2019/03/IEEFA-India_Pumped-Hydro-Storage_Mar-2019.pdf.

Burke, M., Hsiang, S. M. and Miguel, E. (2015) 'Global non-linear effect of temperature on economic production', *Nature 2015 527:7577*. Nature Publishing Group, 527, no. 7577, pp. 235–239. doi: 10.1038/nature15725.

Caldera, U. and Breyer, C. (2018) ‘The role that battery and water storage play in Saudi Arabia’s transition to an integrated 100% renewable energy power system’, *Journal of Energy Storage*. Elsevier, 17, pp. 299–310. doi: 10.1016/J.EST.2018.03.009.

Caldera, U. and Breyer, C. (2020) ‘Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems’, *Energy*. Pergamon, 200, pp. 117507. doi: 10.1016/J.ENERGY.2020.117507.

Caldera, U., Sadiqa, A., Gulagi, A. and Breyer, C. (2021) ‘Irrigation efficiency and renewable energy powered desalination as key components of Pakistan’s water management strategy’, *Smart Energy*. Elsevier, 4, pp. 100052. doi: 10.1016/J.SEGY.2021.100052.

Cao, K. K., Cebulla, F., Gómez Vilchez, J. J., Mousavi, B. and Prehofer, S. (2016) ‘Raising awareness in model-based energy scenario studies—a transparency checklist’, *Energy, Sustainability and Society*. Springer Verlag, 6, no. 1, pp. 1–20. doi: 10.1186/S13705-016-0090-Z/TABLES/2.

Cazzaniga, R. and Rosa-Clot, M. (2021) ‘The booming of floating PV’, *Solar Energy*. Elsevier Ltd, 219, no. September 2020, pp. 3–10. doi: 10.1016/j.solener.2020.09.057.

CEA (2019) *Long Term Electricity Demand Forecasting*. Central Electricity Authority, Government of India. Report, New Delhi. Available at: https://cea.nic.in/wp-content/uploads/2020/04/Long_Term_Electricity_Demand_Forecasting_Report.pdf (Accessed: 20 May 2022).

CERC (2016) *Determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects applicable during FY 2016-17*. Central Electricity Regulatory Comission, Government of India. New Delhi. Available at: http://www.cercind.gov.in/2016/orders/SO17.pdf.

Chakravarty, S. and Somanathan, E. (2021) ‘There is no economic case for new coal plants in India’, *World Development Perspectives*. Elsevier, 24, pp. 100373. doi: 10.1016/J.WDP.2021.100373.

Charles Rajesh Kumar, J. and Majid, M. (2021) ‘Floating solar photovoltaic plants in India – A rapid transition to a green energy market and sustainable future’, *Energy & Environment*. SAGE PublicationsSage UK: London, England, pp. 0958305X2110571. doi: 10.1177/0958305X211057185.

Chauhan, A., Wason, D. and Gupta, R. (2021) *Renewables are the cheapest source of electricity in South Asia*. IHS Markit. London. Available at: https://ihsmarkit.com/research-analysis/renewables-are-the-cheapest-source-of-electricity-in-south-asia.html.

Chen, M., Zhang, H., Liu, W. and Zhang, W. (2014) ‘The Global Pattern of Urbanization and Economic Growth: Evidence from the Last Three Decades', *PLoS ONE*. Public Library of Science, 9, no. 8. doi: 10.1371/JOURNAL.PONE.0103799.

Child, M., Koskinen, O., Linnanen, L. and Breyer, C. (2018) 'Sustainability guardrails for energy scenarios of the global energy transition', *Renewable and Sustainable Energy Reviews*, pp. 321–334. doi: 10.1016/j.rser.2018.03.079.

Climate Analytics (2019) *Decarbonising South and South East Asia: Shifting energy supply in South Asia and South East Asia to non-fossil fuel-based energy systems in line with the Paris Agreement long-term temperature goal and achievement of Sustainable Development Goals*. Climate Analytics GmbH. Report, Berlin. Available at: www.climateanalytics.org/publications (Accessed: 19 May 2022).

Climate Watch (2020) *CAIT data: GHG emissions*. World Resources Institute. Washington D.C. Available at: https://www.climatewatchdata.org/ghg-emissions.

Climatewatch (2021) *Climate Watch historical GHG emissions. Accessed March 2021., ClimateWatch*. World Resources Institute. Washington DC. Available at: https://www.climatewatchdata.org/ghg-emissions?end_year=2018&start_year=1990%0Ahttps://www.climatewatchdata.org/ghg-emissions%0Ahttps://www.climatewatchdata.org/ghg-emissions?chartType=area&end_year=2018&regions=WORLD&start_year=1990%0Ahttps://www.climate.

CMI (2016) *Desalination Technologies and Economics: CAPEX, OPEX & Technological Game Changers to Come Mediterranean Regional Technical Meeting*. Marseille. Available at: https://www.cmimarseille.org/sites/default/files/newsite/library/files/en/1.6. C. Cosin_ Desalination technologies and economics_ capex, opex and technological game changers to come -ilovepdf-compressed.pdf (Accessed: 21 May 2022).

CO2 earth (2020) *CO2 earth: Numbers for living on Earth*. CO2.earth. Vancouver. Available at: https://www.co2.earth/.

Costantini, V. and Gracceva, F. (2004) *Social Costs of Energy Disruptions Market-based Options for Security of Energy Supply Insuring against Disruptions of Energy Supply*. Centre For European Policy Studies. Available at: http://www.ceps.be (Accessed: 22 August 2022).

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G. and Pietzcker, R. C. (2017) 'The underestimated potential of solar energy to mitigate climate change', *Nature Energy 2017 2:9*. Nature Publishing Group, 2, no. 9, pp. 1–9. doi: 10.1038/nenergy.2017.140.

Crutzen, P. J. (2006) *The Anthropocene, Earth System Science in the Anthropocene*. Edited by E. Ehlers and T. Krafft. Heidelberg: Springer Berlin Heidelberg. doi:

10.1007/3-540-26590-2_3/COVER.

CSE (2015) *India's first-ever environmental rating of coal-based power plants finds the sector's performance to be way below global benchmarks*. Centre for Science and Environment. New Delhi. Available at: https://www.cseindia.org/indias-first-ever-environmental-rating-of-coal-based-power-plants-finds-the-sectors-performance-to-be-way-below-global-benchmarks-5685.

Deane, J. P., Chiodi, A., Gargiulo, M. and Ó Gallachóir, B. P. (2012) 'Soft-linking of a power systems model to an energy systems model', *Energy*. Pergamon, 42, no. 1, pp. 303–312. doi: 10.1016/J.ENERGY.2012.03.052.

Delafield, G., Donnison, C., Roddis, P., Arvanitopoulos, T., Sfyridis, A., Dunnett, S., Ball, T. and Logan, K. G. (2021) 'Conceptual framework for balancing society and nature in net-zero energy transitions', *Environmental Science & Policy*. Elsevier, 125, pp. 189–201. doi: 10.1016/j.envsci.2021.08.021.

Deshmukh, R., Wu, G. C., Callaway, D. S. and Phadke, A. (2019) 'Geospatial and techno-economic analysis of wind and solar resources in India', *Renewable Energy*. Pergamon, 134, pp. 947–960. doi: 10.1016/J.RENENE.2018.11.073.

Diesendorf, M. and Elliston, B. (2018) 'The feasibility of 100% renewable electricity systems: A response to critics', *Renewable and Sustainable Energy Reviews*. Pergamon, 93, pp. 318–330. doi: 10.1016/J.RSER.2018.05.042.

Diffenbaugh, N. S. and Burke, M. (2019) 'Global warming has increased global economic inequality', *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 116, no. 20, pp. 9808–9813. doi: 10.1073/PNAS.1816020116/SUPPL_FILE/PNAS.1816020116.SAPP.PDF.

Diluiso, F., Walk, P., Manych, N., Cerutti, N., Chipiga, V., Workman, A., Ayas, C., Cui, R. Y., Cui, D., Song, K., *et al.* (2021) 'Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences', *Environmental Research Letters*, 16, no. 11, pp. 113003. doi: 10.1088/1748-9326/ac1b58.

Duffy, P. B., Field, C. B., Diffenbaugh, N. S., Doney, S. C., Dutton, Z., Goodman, S., Heinzerling, L., Hsiang, S., Lobell, D. B., Mickley, L. J., *et al.* (2019) 'Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases', *Science*. American Association for the Advancement of Science, 363, no. 6427. doi: 10.1126/SCIENCE.AAT5982/ASSET/7662EF3D-45FE-4063-8257-97329E8D28B9/ASSETS/GRAPHIC/363_AAT5982_F4.JPEG.

Eckstein, D., Künzel, V. and Schäfer, L. (2021) *Global Climate Risk Index 2021*. Germanwatch e.V. Report, Bonn. Available at: www.germanwatch.org (Accessed: 19 May 2022).

Edenhofer, O., Hirth, L., Knopf, B., Pahle, M., Schlömer, S., Schmid, E. and Ueckerdt, F. (2013) ‘On the economics of renewable energy sources’, *Energy Economics*. North-Holland, 40, pp. S12–S23. doi: 10.1016/j.eneco.2013.09.015.

Ember (2022a) *Data Explorer*. Ember. London. Available at: https://ember-climate.org/data/data-explorer/.

Ember (2022b) *Global Electricity Review 2022*. Ember. Report, London. Available at: https://ember-climate.org/app/uploads/2022/03/Report-GER22.pdf.

Energy and Climate Intelligence Unit (2021) *Net Zero Emission Race*. Energy and Climate Interlligence Unit. London. Available at: https://eciu.net/netzerotracker.

ENTSO-E (2017) *Managing Critical Grid Situations – Success & Challenges*. European Network of Transmission System Operators for Electricity. Report, Brussels. Available at: https://eepublicdownloads.entsoe.eu/clean-documents/news/170530_Managing_Critical_Grid_Situations-Success_and_Challenges.pdf.

ENTSO-E (2019) *High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters*. European Network of Transmission System Operators for Electricity. Brussels. Available at: https://euagenda.eu/upload/publications/untitled-292051-ea.pdf.

ESIG (2019) *Toward 100% Renewable Energy Pathways: Key Research Needs*. Energy Systems Integration Group. Virginia. Available at: https://www.esig.energy/resources/toward-100-%0Arenewable-energy-pathways-key-research-needs/.

ESMAP (2022) *Global Wind Atlas 3.0*. Energy Sector Management Assistance Program. Washington D.C. Available at: https://globalwindatlas.info/.

Faijer, M. J. and Arends, E. (2017) *Baseline Study Wind Energy Bangladesh Commissioned by the ministry of Foreign Affairs*. Wind Minds International. Hengelo. Available at: https://www.rvo.nl/sites/default/files/2017/05/baseline-study-wind-energy-bangladesh.pdf (Accessed: 21 May 2022).

Farfan, J. and Breyer, C. (2017) ‘Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator’, *Journal of Cleaner Production*. Elsevier Ltd, 141, pp. 370–384. doi: 10.1016/j.jclepro.2016.09.068.

Fuentes, U. and Chapman, A. (2021) *Shifting Investment Away From Fossil Fuels In Southeast Asia*. Climate Analytics GmbH. Report, Berlin. Available at: https://climateanalytics.org/media/shifting_investment_away_from_fossil_fuels_in_southeast_asia.pdf (Accessed: 19 May 2022).

Fuso Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., Borrion, A., Spataru, C., Castán Broto, V., Anandarajah, G., Milligan, B. and Mulugetta, Y. (2017) ‘Mapping synergies and trade-offs between energy and the Sustainable Development Goals’, *Nature Energy 2017 3:1*. Nature Publishing Group, 3, no. 1, pp. 10–15. doi: 10.1038/s41560-017-0036-5.

Gajardo, D., Goyal, A., Kuzma, S. and Goswami, S. (2021) *How Water Challenges Threaten India’s Energy Security*. World Resources Institute. Washington D.C. Available at: https://www.wri.org/insights/water-challenges-energy-sector-india.

García-Escribano, M., Mogues, T., Moszoro, M. and Soto, M. (2021) *The Spending Challenge of Achieving the SDGs in South Asia: Lessons from India*. International Monetary Fund. Washington D.C. Available at: https://www.imf.org/en/Publications/WP/Issues/2021/12/17/The-Spending-Challenge-of-Achieving-the-SDGs-in-South-Asia-Lessons-from-India-510879.

Gerlach, A., Werner, C. and Breyer, C. (2014) ‘Impact of Financing Cost on Global Grid-Parity Dynamics till 2030’, *29th EU PVSEC*, 21, no. 1, pp. 121–136. doi: 10.4229/25thEUPVSEC2010-6CV.4.11.

Gernaat, D. E. H. J., Bogaart, P. W., Vuuren, D. P. van, Biemans, H. and Niessink, R. (2017) ‘High-resolution assessment of global technical and economic hydropower potential’, *Nature Energy*. Nature Publishing Group, 2, no. 10, pp. 821–828. doi: 10.1038/s41560-017-0006-y.

Ghosh, U. (2022) *A comprehensive roundup on Indian EV Policies*. The Economic Times. New Delhi. Available at: https://auto.economictimes.indiatimes.com/news/faqs-a-comprehensive-roundup-on-indian-ev-policies/89290126.

Gilman, P., Cowlin, S. and Heimiller, D. (2009) *Potential for Development of Solar and Wind Resource in Bhutan*. National Renewable Energy Laboratory. Colorado. Available at: http://www.nrel.gov/docs/fy09osti/46547.pdf.

Global Carbon Project (2021) *Supplemental data of Global Carbon Project 2021 (1.0) [Data set]*. Global Carbon Project. Canberra. Available at: https://doi.org/10.18160/gcp-2021.

Global Energy Monitor (2022) *Global Energy Monitor’s Global Coal Plant Tracker*. Global Energy Monitor. California. Available at: https://globalenergymonitor.org/.

Global PST Consortium (2021) *Inaugural Research Agenda*. Global PST Consortium. California. Available at: https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf.

Greenstone, M., Nath, I., Wolak, F., Gillingham, K., Rose, N., Zaragoza-Watkins, M., Knittel, C., Schmalensee, D. and Bushnell, J. (2021) ‘Do Renewable Portfolio Standards

Deliver Cost-Effective Carbon Abatement? *’, *Working paper*.

Greim, P., Solomon, A. A. and Breyer, C. (2020) ‘Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation’, *Nature Communications*. Springer US, 11, no. 1, pp. 4570. doi: 10.1038/s41467-020-18402-y.

Grubler, A. (2012) ‘Energy transitions research: Insights and cautionary tales’, *Energy Policy*. Elsevier, 50, pp. 8–16. doi: 10.1016/J.ENPOL.2012.02.070.

Gulagi, A., Bogdanov, D. and Breyer, C. (2017a) ‘The Demand For Storage Technologies In Energy Transition Pathways Towards 100% Renewable Energy For India’, *Energy Procedia*, 135, pp. 37–50. doi: 10.1016/j.egypro.2017.09.485.

Gulagi, A., Bogdanov, D. and Breyer, C. (2018) ‘The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India’, *Journal of Energy Storage*, 17, pp. 525–539. doi: 10.1016/j.est.2017.11.012.

Gulagi, A., Bogdanov, D., Fasihi, M. and Breyer, C. (2017b) ‘Can Australia Power the Energy-Hungry Asia with Renewable Energy?’, *Sustainability 2017, Vol. 9, Page 233*. Multidisciplinary Digital Publishing Institute, 9, no. 2, pp. 233. doi: 10.3390/SU9020233.

Gulagi, A., Choudhary, P., Bogdanov, D. and Breyer, C. (2017c) ‘Electricity system based on 100% renewable energy for India and SAARC’, *PLOS ONE*. Edited by B. Merk, 12, no. 7, pp. e0180611. doi: 10.1371/journal.pone.0180611.

Gulagi, A., Pathak, S., Bogdanov, D. and Breyer, C. (2021) ‘Renewable Energy Transition for the Himalayan Countries Nepal and Bhutan: Pathways towards Reliable, Affordable and Sustainable Energy for All’, *IEEE Access*. Institute of Electrical and Electronics Engineers Inc., 9, pp. 84520–84544. doi: 10.1109/ACCESS.2021.3087204.

Gulagi, A., Ram, M., Bogdanov, D., Sarin, S. and Mensah, T. N. O. (2022) ‘The role of renewables for rapid transitioning of the power sector across states in India’, *Nature Communications*, accepted,.

Gulagi, A., Ram, M. and Breyer, C. (2020a) ‘Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India’, *IET Renewable Power Generation*, 14, no. 2, pp. 254–262. doi: 10.1049/iet-rpg.2019.0603.

Gulagi, A., Ram, M., Solomon, A. A., Khan, M. and Breyer, C. (2020b) ‘Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh’, *Renewable Energy*. Elsevier Ltd, 155, pp. 899–920. doi: 10.1016/j.renene.2020.03.119.

Gurung, A., Gurung, O. P. and Oh, S. E. (2011) ‘The potential of a renewable energy technology for rural electrification in Nepal: A case study from Tangting’, *Renewable*

Energy. Pergamon, 36, no. 11, pp. 3203–3210. doi: 10.1016/J.RENENE.2011.03.012.

GWEC (2022) *Global Wind Report 2022*. Global Wind Energy Council. Brussels. Available at: https://gwec.net/wp-content/uploads/2022/03/GWEC-GLOBAL-WIND-REPORT-2022.pdf.

Gyanwali, K., Komiyama, R. and Fujii, Y. (2021) 'Deep decarbonization of integrated power grid of eastern South Asia considering hydrogen and CCS technology', *International Journal of Greenhouse Gas Control*. Elsevier, 112, pp. 103515. doi: 10.1016/J.IJGGC.2021.103515.

Haegel, N. M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y. M., De Wolf, S., Dimmler, B., Feldman, D., Glunz, S., *et al.* (2019) 'Terawatt-scale photovoltaics: Transform global energy Improving costs and scale reflect looming opportunities', *Science*. American Association for the Advancement of Science, 364, no. 6443, pp. 836–838. doi: 10.1126/SCIENCE.AAW1845/SUPPL_FILE/AAW1845-HAEGEL-SM.PDF.

Hafner, M. and Tagliapietra, S. (2020) 'The Geopolitics of the Global Energy Transition'. Edited by M. Hafner and S. Tagliapietra. Cham: Springer Nature (Lecture Notes in Energy), 73, pp. 381. doi: 10.1007/978-3-030-39066-2.

Hansen, K., Breyer, C. and Lund, H. (2019) 'Status and perspectives on 100% renewable energy systems', *Energy*. Pergamon, 175, pp. 471–480. doi: 10.1016/J.ENERGY.2019.03.092.

Harijan, K., Uqaili, M. A. and Memon, M. (2008) 'Renewable energy for managing energy crisis in Pakistan', *Communications in Computer and Information Science*. Springer Verlag, 20 CCIS, pp. 449–455. doi: 10.1007/978-3-540-89853-5_48/COVER.

Harijan, K., Uqaili, M. A., Memon, M. and Mirza, U. K. (2011) 'Forecasting the diffusion of wind power in Pakistan', *Energy*. Pergamon, 36, no. 10, pp. 6068–6073. doi: 10.1016/J.ENERGY.2011.08.009.

Haydt, G., Leal, V., Pina, A. and Silva, C. A. (2011) 'The relevance of the energy resource dynamics in the mid/long-term energy planning models', *Renewable Energy*. Pergamon, 36, no. 11, pp. 3068–3074. doi: 10.1016/J.RENENE.2011.03.028.

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J. and Bryan, B. A. (2021) 'Future global urban water scarcity and potential solutions', *Nature Communications 2021 12:1*. Nature Publishing Group, 12, no. 1, pp. 1–11. doi: 10.1038/s41467-021-25026-3.

Heaps, C. G. (2022) *LEAP: The Low Emissions Analysis Platform*. Stockholm Environment Institute. Somerville. Available at: https://leap.sei.org.

Henderson, J. and Sen, A. (2021) *The Energy Transition: Key challenges for incumbent and new players in the global energy system Energy Transition*. Oxford Institute for

Energy Studies. Oxford. Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/09/Energy-Transition-Key-challenges-for-incumbent-players-in-the-global-energy-system-ET01.pdf.

Henderson, V. (2003) ‘The Urbanization Process and Economic Growth: The So-What Question’, *Journal of Economic Growth 2003 8:1*. Springer, 8, no. 1, pp. 47–71. doi: 10.1023/A:1022860800744.

Hoang, A. T., Sandro Nižetić, Olcer, A. I., Ong, H. C., Chen, W. H., Chong, C. T., Thomas, S., Bandh, S. A. and Nguyen, X. P. (2021) ‘Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications’, *Energy Policy*. Elsevier, 154, pp. 112322. doi: 10.1016/J.ENPOL.2021.112322.

Hodge, B. M. S., Jain, H., Brancucci, C., Seo, G. S., Korpås, M., Kiviluoma, J., Holttinen, H., Smith, J. C., Orths, A., Estanqueiro, A., *et al.* (2020) ‘Addressing technical challenges in 100% variable inverter-based renewable energy power systems’, *Wiley Interdisciplinary Reviews: Energy and Environment*. doi: 10.1002/wene.376.

Hofste, R. W., Reig, P. and Schleifer, L. (2019) *17 Countries, Home to One-Quarter of the World’s Population, Face Extremely High Water Stress*. World Resources Institute. Washington D.C. Available at: https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress (Accessed: 19 May 2022).

Hou, X. and Urpelainen, J. (2020) ‘Lock-in for lighting: The puzzle of continued kerosene use among electrified households in six Indian states’, *Energy Research & Social Science*. Elsevier, 69, pp. 101592. doi: 10.1016/J.ERSS.2020.101592.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M. and Roehrl, A. (2011) ‘OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development’, *Energy Policy*. Elsevier, 39, no. 10, pp. 5850–5870. doi: 10.1016/J.ENPOL.2011.06.033.

Huntington, H. G. (2015) ‘Crude oil trade and current account deficits’, *Energy Economics*. North-Holland, 50, pp. 70–79. doi: 10.1016/J.ENECO.2015.03.030.

Hurlbut, D., Joshi, M. and Palchak, D. (2020) *Cross-Border Electricity Trading and Renewable Energy Zones*. National Renewable Energy Laboratory. Colorado. Available at: https://www.nrel.gov/docs/fy20osti/76919.pdf (Accessed: 20 May 2022).

Hussain, A., Perwez, U., Ullah, K., Kim, C. H. and Asghar, N. (2021) ‘Long-term scenario pathways to assess the potential of best available technologies and cost reduction of avoided carbon emissions in an existing 100% renewable regional power system: A case study of Gilgit-Baltistan (GB), Pakistan’, *Energy*. Pergamon, 221, pp. 119855. doi: 10.1016/J.ENERGY.2021.119855.

IEA-PVPS (2022) *Snapshot of Global PV Markets - 2022*. International Energy Agency - Photovoltaic Power Systems Programme. Paris. Available at: https://iea-pvps.org/snapshot-reports/snapshot-2022/ (Accessed: 6 August 2022).

IEA (2016) *Water Energy Nexus. Excerpt From the World Energy Outlook 2016*. International Energy Agency. Paris. Available at: https://iea.blob.core.windows.net/assets/e4a7e1a5-b6ed-4f36-911f-b0111e49aab9/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf.

IEA (2017) *World Energy Outlook*. International Energy Agency. Paris. Available at: https://www.iea.org/reports/world-energy-outlook-2017.

IEA (2019a) *Share of electricity in total final energy consumption, historical and SDS*. International Energy Agency. Paris. Available at: https://www.iea.org/data-and-statistics/charts/share-of-electricity-in-total-final-energy-consumption-historical-and-sds.

IEA (2019b) *Status of Power System Transformation 2019*, *Status of Power System Transformation 2018*. International Energy Agency. Paris. doi: 10.1787/9789264302006-en.

IEA (2019c) *World Energy Outlook 2019*. International Energy Agency. Paris. Available at: https://www.iea.org/reports/world energy-outlook, 2019.

IEA (2020a) *Access to clean cooking*. International Energy Agency. Paris. Available at: https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking.

IEA (2020b) *Data and Statistics*. Paris. Available at: https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2019.

IEA (2020c) *India 2020 - Energy Policy Review*. International Energy Agency. Paris. Available at: https://iea.blob.core.windows.net/assets/2571ae38-c895-430e-8b62-bc19019c6807/India_2020_Energy_Policy_Review.pdf (Accessed: 20 May 2022).

IEA (2020d) *Renewable Energy Market Update, Outlook for 2020 and 2021*. International Renewable Energy Agency. Paris. Available at: https://www.iea.org/reports/renewable-energy-market-update (Accessed: 19 May 2022).

IEA (2021a) *India Energy Outlook 2021*. International Energy Agency. Paris. Available at: https://iea.blob.core.windows.net/assets/1de6d91e-e23f-4e02-b1fb-51fdd6283b22/India_Energy_Outlook_2021.pdf.

IEA (2021b) *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. International Energy Agency. Paris. Available at: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (Accessed: 15 April 2022).

IEA (2021c) *World Energy Outlook 2021*. International Energy Agency. Paris. Available at: www.iea.org/weo (Accessed: 19 May 2022).

IEA (2022a) *Energy Security*. International Energy Agency. Paris. Available at: https://www.iea.org/topics/energy-security.

IEA (2022b) *Global Energy Review: CO2 Emissions in 2021*. International Energy Agency. Paris. Available at: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

IEA and NITI Aayog (2021) *Renewables Integration report in India*. International Energy Agency and NITI Aayog. Paris. Available at: https://iea.blob.core.windows.net/assets/7b6bf9e6-4d69-466c-8069-bdd26b3e9ed1/RenewablesIntegrationinIndia2021.pdf.

IEA, IRENA, UN, WBG and WHO (2018) *Tracking SDG7 : The Energy Progress Report 2018*. The World Bank. Washington D.C. Available at: https://openknowledge.worldbank.org/handle/10986/29812.

IEEFA (2019) *Seriously Stressed and Stranded: The Burden of Non-Performing Assets in India's Thermal Power Sector*. Institute for Energy Economics and Financial Analysis. Ohio. Available at: https://ieefa.org/wp-content/uploads/2019/12/The-Burden-of-NonPerforming-Assets-in-India-Thermal-Power-Sector_December-2019.pdf.

IFAD (2019) *An Outlook On Asia's Agricultural And Rural Transformation: Prospects and options for making it an inclusive and sustainable one*. International Fund for Agricultural Development. Rome. Available at: https://www.ifad.org/documents/38714170/41201480/apr_outlook.pdf/a1f8762e-ee0d-490a-cf3a-399241e34087?t=1561034540000.

IFC (2016) *A solar developer's guide to Pakistan*. International Finance Corporation. Washington D.C. Available at: https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/p_report_solardevelopersguidetopakistan.

IFC (2017) *Climate Investment Opportunities in South Asia*. International Finance Corporation. Washington D.C. Available at: https://www.ifc.org/wps/wcm/connect/fa3bea68-20f1-4cb4-90b9-3e812d38067f/Climate+Investment+Opportunities+in+South+Asia+-+An+IFC+Analysis.pdf?MOD=AJPERES&CVID=l.raVua (Accessed: 19 May 2022).

Indrawati, S. M. (2015) *What you need to know about energy and poverty*. The World Bank. New York. Available at: https://blogs.worldbank.org/voices/what-you-need-know-about-energy-and-poverty (Accessed: 20 May 2022).

IPCC (2014) *AR5 Climate Change 2014: Mitigation of Climate Change*.

Intergovernmental Panel on Climate Change. Geneva. Available at: https://www.ipcc.ch/report/ar5/wg3/.

IPCC (2018) *Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. Intergovernmental Panel on Climate Change. Geneva. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change. Geneva. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf.

IPCC (2022) *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change. Geneva. Available at: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf.

IRADe (2021) *South Asia Regional Initiative For Energy Integration (SARI/EI) Prospects for Sustainable Energy Infrastructure Development and Role of Cross Border Energy Trade in South Asia Challenges, Opportunities and Way forward*. Integrated Research and Action for Development. New Delhi. Available at: https://irade.org/Sustainable-Energy-Infrastructure-Development-REPORT.pdf (Accessed: 20 May 2022).

IRENA (2013) *Southern African Power Pool: Planning and Prospects for Renewable Energy*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/SAPP.pdf (Accessed: 20 May 2022).

IRENA (2015) *Renewable Energy in the Water, Energy and Food Nexus*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Water_Energy_Food_Nexus_2015.pdf (Accessed: 19 May 2022).

IRENA (2018) *Global Energy Transformation: A Roadmap to 2050*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf (Accessed: 20 May 2022).

IRENA (2019a) *A new world: The geopolitics of the energy transformation*. Global

Comission on the Geopolitics of Rnergy Transformation and International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/Global_commission_geopolitics_new_world_2019.pdf (Accessed: 19 May 2022).

IRENA (2019b) *Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper)*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf (Accessed: 21 May 2022).

IRENA (2021a) *Majority of New Renewables Undercut Cheapest Fossil Fuel on Cost*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/newsroom/pressreleases/2021/Jun/Majority-of-New-Renewables-Undercut-Cheapest-Fossil-Fuel-on-Cost.

IRENA (2021b) *Renewable Capacity Statistics*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf.

IRENA (2021c) *Renewable Energy and Electricity Interconnections For a Sustainable Northeast Asia*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Electricity_Interconnections_NortheastAsia_2021.pdf (Accessed: 20 May 2022).

IRENA (2021d) *Renewable Power Generation Costs 2020*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020 (Accessed: 19 May 2022).

IRENA (2021e) *Statistical Profiles - Bhutan*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/IRENADocuments/Statistical_Profiles/Asia/Bhutan_Asia_RE_SP.pdf.

IRENA (2021f) *World Energy Transitions Outlook*. International Renewable Energy Agency. Abu Dhabi. Available at: https://irena.org/publications/2021/March/World-Energy-Transitions-Outlook.

IRENA (2022a) *Renewable Capacity Statistics*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022.

IRENA (2022b) *Renewable power generation costs in 2021*. International Renewable Energy Agency. Abu Dhabi. Available at: www.irena.org (Accessed: 16 August 2022).

IRENA (2022c) *World Energy Transitions Outlook 2022: 1.5°C Pathway*. International Renewable Energy Agency. Abu Dhabi. Available at: https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022 (Accessed: 19 May 2022).

ISA (2019) *ISA Prospective Member Countries*. International Solar Alliance. New Delhi. Available at: http://isolaralliance.org/MemberCont.aspx.

Islam, S. (2017) *Climate-threatened Bangladesh to impose carbon tax in June*. Thomson Reuters Foundation. Dhaka. Available at: https://www.reuters.com/article/us-bangladesh-climatechange-carbontax/climate-threatened-bangladesh-to-impose-carbon-tax-in-june-idUSKBN18J00V.

Jackson, R. B., Le Quéré, C., Andrew, R. M., Canadell, J. G., Korsbakken, J. I., Liu, Z., Peters, G. P. and Zheng, B. (2018) 'Global energy growth is outpacing decarbonization', *Environmental Research Letters*. IOP Publishing, 13, no. 12, pp. 120401. doi: 10.1088/1748-9326/AAF303.

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A. F., Goodman, S. C., Chapman, W. E., Cameron, M. A., Bozonnat, C., Chobadi, L., Clonts, H. A., Enevoldsen, P., *et al.* (2017) '100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World', *Joule*. Cell Press, 1, no. 1, pp. 108–121. doi: 10.1016/J.JOULE.2017.07.005.

Jacobson, M. Z., Delucchi, M. A., Cameron, M. A., Coughlin, S. J., Hay, C. A., Manogaran, I. P., Shu, Y. and von Krauland, A. K. (2019) 'Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries', *One Earth*. Cell Press, 1, no. 4, pp. 449–463. doi: 10.1016/J.ONEEAR.2019.12.003.

Jacobson, M. Z., Delucchi, M. A., Cameron, M. A. and Mathiesen, B. V. (2018) 'Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes', *Renewable Energy*. Pergamon, 123, pp. 236–248. doi: 10.1016/J.RENENE.2018.02.009.

Jain, S., Kumar Jain, N., Choudhary, P. and Vaughn, W. (2021) 'Designing terawatt scale renewable electricity system: A dynamic analysis for India', *Energy Strategy Reviews*. Elsevier, 38, pp. 100753. doi: 10.1016/j.esr.2021.100753.

Januta, A. (2021) *Extreme weather renews focus on climate change as scientists update forecasts*. Reuters. London. Available at: https://www.reuters.com/business/environment/extreme-weather-renews-focus-climate-change-scientists-update-forecasts-2021-07-26/.

Jenkins, J. D., Luke, M. and Thernstrom, S. (2018) ‘Getting to Zero Carbon Emissions in the Electric Power Sector’, *Joule*. Elsevier Inc., 2, no. 12, pp. 2498–2510. doi: 10.1016/j.joule.2018.11.013.

Jindal, A. and Shrimali, G. (2022) ‘Cost–benefit analysis of coal plant repurposing in developing countries: A case study of India’, *Energy Policy*. Elsevier, 164, pp. 112911. doi: 10.1016/j.enpol.2022.112911.

Jouini, T., Markovic, U. and Grosh, D. (2018) *Deliverable 3.3: New options for existing system services and needs for new system services*. European Union Horizon 2020 project. Brussels. Available at: https://www.h2020-migrate.eu/_Resources/Persistent/0298d5d56a3f1977e8b95e5476a88a7b840004cf/D3.3 - New options for existing system services and needs for new system services.pdf (Accessed: 21 August 2022).

Kamber, G. and Wong, B. (2020) ‘Global factors and trend inflation’, *Journal of International Economics*. North-Holland, 122, pp. 103265. doi: 10.1016/J.JINTECO.2019.103265.

Keiner, D., Ram, M., Barbosa, L. D. S. N. S., Bogdanov, D. and Breyer, C. (2019) ‘Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050’, *Solar Energy*. Pergamon, 185, pp. 406–423. doi: 10.1016/j.solener.2019.04.081.

Keiner, D., Salcedo-Puerto, O., Immonen, E., van Sark, W. G. J. H. M., Nizam, Y., Shadiya, F., Duval, J., Delahaye, T., Gulagi, A. and Breyer, C. (2022) ‘Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives’, *Applied Energy*. Elsevier, 308, pp. 118360. doi: 10.1016/J.APENERGY.2021.118360.

Khan, I. (2019) ‘Drivers, enablers, and barriers to prosumerism in Bangladesh: A sustainable solution to energy poverty?’, *Energy Research & Social Science*. Elsevier, 55, pp. 82–92. doi: 10.1016/J.ERSS.2019.04.019.

King, M. D., Howat, I. M., Candela, S. G., Noh, M. J., Jeong, S., Noël, B. P. Y., van den Broeke, M. R., Wouters, B. and Negrete, A. (2020) ‘Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat’, *Communications Earth & Environment 2020 1:1*. Nature Publishing Group, 1, no. 1, pp. 1–7. doi: 10.1038/s43247-020-0001-2.

Kompas, T., Pham, V. H. and Che, T. N. (2018) ‘The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord’, *Earth’s Future*. John Wiley & Sons, Ltd, 6, no. 8, pp. 1153–1173. doi: 10.1029/2018EF000922.

Kotilainen, K. (2020) *Energy Prosumers’ Role in the Sustainable Energy System*. Edited by F. W. Leal, A. Azul, L. Brandli, P. Ozuyar, and T. Wall. Washington D.C.: Springer, Cham. doi: 10.1007/978-3-319-71057-0_11-1.

Kovacovska, J. (2010) *Energy Security in European Conditions*. Masaryk University, Brno, Czech Republic. Available at: https://is.muni.cz/th/g0gvs/Kovacovska-Diplomova-praca.pdf.

Kressig, A., Byers, L., Friedrich, J., Luo, T. and Mccormick, C. (2018) *Water Stress Threatens Nearly Half the World's Thermal Power Plant Capacity*. World Resources Institute. Washington D.C. Available at: https://www.wri.org/insights/water-stress-threatens-nearly-half-worlds-thermal-power-plant-capacity (Accessed: 19 May 2022).

Kuckshinrichs, W. and Juelich, F. (2021) 'LCOE: A Useful and Valid Indicator—Replica to James Loewen and Adam Szymanski', *Energies 2021, Vol. 14, Page 406*. Multidisciplinary Digital Publishing Institute, 14, no. 2, pp. 406. doi: 10.3390/EN14020406.

Kumar, A., Ferdous, R., Luque-Ayala, A., McEwan, C., Power, M., Turner, B. and Bulkeley, H. (2019) 'Solar energy for all? Understanding the successes and shortfalls through a critical comparative assessment of Bangladesh, Brazil, India, Mozambique, Sri Lanka and South Africa', *Energy Research & Social Science*. Elsevier, 48, pp. 166–176. doi: 10.1016/J.ERSS.2018.10.005.

Lawrenz, L., Xiong, B., Lorenz, L., Krumm, A., Hosenfeld, H., Burandt, T., Löffler, K., Oei, P.-Y. and von Hirschhausen, C. (2018) 'Exploring Energy Pathways for the Low-Carbon Transformation in India—A Model-Based Analysis', *Energies*, 11, no. 11, pp. 3001. doi: 10.3390/en11113001.

Lazaro, L. L. B., Soares, R. S., Bermann, C., Collaço, F. M. A., Giatti, L. L. and Abram, S. (2022) 'Energy transition in Brazil: Is there a role for multilevel governance in a centralized energy regime?', *Energy Research & Social Science*. Elsevier, 85, pp. 102404. doi: 10.1016/J.ERSS.2021.102404.

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. and Schellnhuber, H. J. (2019) 'Climate tipping points — too risky to bet against', *Nature 2021 575:7784*. Nature Publishing Group, 575, no. 7784, pp. 592–595. doi: 10.1038/d41586-019-03595-0.

Levin, K., Boehm, S. and Carter, R. (2022) *6 Big Findings from the IPCC 2022 Report on Climate Impacts, Adaptation and Vulnerability*. World Resources Institute. Washington D.C. Available at: https://www.wri.org/insights/ipcc-report-2022-climate-impacts-adaptation-vulnerability.

Liu, J., Mei, C., Wang, H., Shao, W. and Xiang, C. (2018) 'Powering an island system by renewable energy—A feasibility analysis in the Maldives', *Applied Energy*. Elsevier, 227, pp. 18–27. doi: 10.1016/J.APENERGY.2017.10.019.

Liu, P. R. and Raftery, A. E. (2021) ‘Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 °C target’, *Communications Earth & Environment 2021 2:1*. Nature Publishing Group, 2, no. 1, pp. 1–10. doi: 10.1038/s43247-021-00097-8.

Loewen, J. (2019) ‘LCOE is an undiscounted metric that distorts comparative analyses of energy costs’, *The Electricity Journal*. Elsevier, 32, no. 6, pp. 40–42. doi: 10.1016/J.TEJ.2019.05.019.

Loewen, J. (2020) ‘LCOE is an undiscounted metric that inaccurately disfavors renewable energy resources’, *The Electricity Journal*. Elsevier, 33, no. 6, pp. 106769. doi: 10.1016/J.TEJ.2020.106769.

Löffler, K., Hainsch, K., Burandt, T., Oei, P. Y., Kemfert, C. and Von Hirschhausen, C. (2017) ‘Designing a model for the global energy system-GENeSYS-MOD: An application of the Open-Source Energy Modeling System (OSeMOSYS)’, *Energies*, 10, no. 10. doi: 10.3390/en10101468.

Lohani, S. P. and Blakers, A. (2021) ‘100% renewable energy with pumped-hydro-energy storage in Nepal’, *Clean Energy*, 5, no. 2, pp. 243–253. doi: 10.1093/ce/zkab011.

Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C. and Breyer, C. (2019) ‘Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery’, *Nature Energy*, 4, no. 12, pp. 1040–1048. doi: 10.1038/s41560-019-0501-4.

Loo, Y. Y., Billa, L. and Singh, A. (2015) ‘Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia’, *Geoscience Frontiers*. Elsevier, 6, no. 6, pp. 817–823. doi: 10.1016/J.GSF.2014.02.009.

Lu, S., Zhang, X., Peng, H., Skitmore, M., Bai, X. and Zheng, Z. (2021a) ‘The energy-food-water nexus: Water footprint of Henan-Hubei-Hunan in China’, *Renewable and Sustainable Energy Reviews*. Pergamon, 135, pp. 110417. doi: 10.1016/J.RSER.2020.110417.

Lu, X., Chen, S., Nielsen, C. P., Zhang, C., Li, J., Xu, H., Wu, Y., Wang, S., Song, F., Wei, C., He, K., McElroy, M. B. and Hao, J. (2021b) ‘Combined solar power and storage as cost-competitive and grid-compatible supply for China’s future carbon-neutral electricity system’, *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 118, no. 42. doi: 10.1073/PNAS.2103471118/SUPPL_FILE/PNAS.2103471118.SAPP.PDF.

Lu, X., McElroy, M. B. and Kiviluoma, J. (2009) ‘Global potential for wind-generated electricity’, *Proceedings of the National Academy of Sciences*, 106, no. 27, pp. 10933–10938. doi: 10.1073/pnas.0904101106.

Luderer, G., Madeddu, S., Merfort, L., Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., Schreyer, F., Bauer, N., Baumstark, L., *et al.* (2021) ‘Impact of declining renewable energy costs on electrification in low-emission scenarios’, *Nature Energy 2021 7:1*. Nature Publishing Group, 7, no. 1, pp. 32–42. doi: 10.1038/s41560-021-00937-z.

Lugovoy, O., Jyothiprakash, V., Chatterjee, S., Sharma, S., Mukherjee, A., Das, A., Thakur, B., Some, S., Dinesha, D. L., Das, N., *et al.* (2021) ‘Towards a Zero-Carbon Electricity System for India in 2050: IDEEA Model-Based Scenarios Integrating Wind and Solar Complementarity and Geospatial Endowments’, *Energies 2021, Vol. 14, Page 7063*. Multidisciplinary Digital Publishing Institute, 14, no. 21, pp. 7063. doi: 10.3390/EN14217063.

Lund, H., Thellufsen, J. Z., Østergaard, P. A., Sorknæs, P., Skov, I. R. and Mathiesen, B. V. (2021) ‘EnergyPLAN – Advanced analysis of smart energy systems’, *Smart Energy*. Elsevier, 1, pp. 100007. doi: 10.1016/J.SEGY.2021.100007.

Luo, T. and Christianson, G. (2018) *Water Shortages Cost Indian Energy Companies Billions*. World Resources Institute. Washington D.C. Available at: https://www.wri.org/insights/water-shortages-cost-indian-energy-companies-billions (Accessed: 19 May 2022).

Luo, T., Krishnan, D. and Sen, S. (2018) *Parched Power: Water Demands, Risks, and Opportunities for India’s Power Sector*. World Resources Institute. Available at: http://www.wri.org/sites/default/files/parched-power-india.pdf.

Lutz, A. F., Immerzeel, W. W., Siderius, C., Wijngaard, R. R., Nepal, S., Shrestha, A. B., Wester, P. and Biemans, H. (2022) ‘South Asian agriculture increasingly dependent on meltwater and groundwater’, *Nature Climate Change 2022*. Nature Publishing Group, pp. 1–8. doi: 10.1038/s41558-022-01355-z.

Malu, P. R., Sharma, U. S. and Pearce, J. M. (2017) ‘Agrivoltaic potential on grape farms in India’, *Sustainable Energy Technologies and Assessments*. Elsevier, 23, pp. 104–110. doi: 10.1016/J.SETA.2017.08.004.

Markandya, A., Sampedro, J., Smith, S. J., Van Dingenen, R., Pizarro-Irizar, C., Arto, I. and González-Eguino, M. (2018) ‘Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study’, *The Lancet Planetary Health*. Elsevier B.V., 2, no. 3, pp. e126–e133. doi: 10.1016/S2542-5196(18)30029-9.

Mathis, W. (2021) *Building New Renewables Is Cheaper Than Burning Fossil Fuels*. Bloomberg. London. Available at: https://www.bloomberg.com/news/articles/2021-06-23/building-new-renewables-cheaper-than-running-fossil-fuel-plants.

Mathur, R. and Shekhar, S. (2020) ‘India’s energy sector choices—options and implications of ambitious mitigation efforts’, *Climatic Change 2020 162:4*. Springer, 162, no. 4, pp. 1893–1911. doi: 10.1007/S10584-020-02885-1.

Matsuo, Y., Endo, S., Nagatomi, Y., Shibata, Y., Komiyama, R. and Fujii, Y. (2020) ‘Investigating the economics of the power sector under high penetration of variable renewable energies’, *Applied Energy*. Elsevier, 267, pp. 113956. doi: 10.1016/J.APENERGY.2019.113956.

Matthews, H. D. and Caldeira, K. (2008) ‘Stabilizing climate requires near-zero emissions’, *Geophys. Res. Lett.*, 35, no. 4, pp. L04705. doi: 10.1029/2007gl032388.

Mayer, A. (2022) ‘Fossil fuel dependence and energy insecurity’, *Energy, Sustainability and Society 2022 12:1*. BioMed Central, 12, no. 1, pp. 1–13. doi: 10.1186/S13705-022-00353-5.

Meadows, D. H., Randers, J. and Meadows, D. (2004) *Limits To Growth: The 30-Year Update*. Vermont: Chelsea Green Publishing Company.

Mensah, T. N. O., Oyewo, A. S. and Breyer, C. (2021) ‘The role of biomass in sub-Saharan Africa’s fully renewable power sector – The case of Ghana’, *Renewable Energy*. Pergamon, 173, pp. 297–317. doi: 10.1016/J.RENENE.2021.03.098.

Mercure, J. F., Salas, P., Vercoulen, P., Semieniuk, G., Lam, A., Pollitt, H., Holden, P. B., Vakilifard, N., Chewpreecha, U., Edwards, N. R. and Vinuales, J. E. (2021) ‘Reframing incentives for climate policy action’, *Nature Energy 2021 6:12*. Nature Publishing Group, 6, no. 12, pp. 1133–1143. doi: 10.1038/s41560-021-00934-2.

Meschede, H., Bertheau, P., Khalili, S. and Breyer, C. (2022) ‘A review of 100% renewable energy scenarios on islands’, *WIREs Energy and Environment*. Wiley. doi: 10.1002/WENE.450.

Miemois, M. and Zhang, S. (2018) *Hybrid solar, a new era in baseload solar*. Wärtsilä. Helsinki. Available at: https://www.wartsila.com/insights/article/hybrid-solar-a-new-era-in-baseload-solar.

Miller, C. A., Iles, A. and Jones, C. F. (2013) ‘The Social Dimensions of Energy Transitions’, *https://doi.org/10.1080/09505431.2013.786989*. Routledge , 22, no. 2, pp. 135–148. doi: 10.1080/09505431.2013.786989.

MNRE (2022a) *Physical Progress*. Ministry of New and Renewable Energy, Government of India. New Delhi. Available at: https://mnre.gov.in/the-ministry/physical-progress.

MNRE (2022b) *Solar Schemes*. Ministry of New and Renewable Energy, Government of India. New Delhi. Available at: https://mnre.gov.in/solar/schemes.

MNRE (2022c) *Wind Energy*. Ministry of New and Renewable Energy, Government of India. New Delhi. Available at: https://mnre.gov.in/wind/current-status/.

Modi, A. (2022) *India to replace 30GW of thermal power with renewables*. Argus Media.

Mumbai. Available at: https://www.argusmedia.com/en/news/2337920-india-to-replace-30gw-of-thermal-power-with-renewables (Accessed: 22 August 2022).

Mosek (2017) *Mosek version 8*. MOSEK ApS. Copenhagen. Available at: https://www.mosek.com/downloads/.

Muhammad, A., Muhammad, U. and Abid, Z. (2021) 'Potential of floating photovoltaic technology in Pakistan', *Sustainable Energy Technologies and Assessments*. Elsevier, 43, pp. 100976. doi: 10.1016/j.seta.2020.100976.

Mukherjee, K., Mukherjee, A., Verma, K., Tripathy, S. and Govil, A. (2019) *Energy Transitions: Adapting to the New Normal of the Changing World*. Boston Consulting Group. New Delhi. Available at: https://web-assets.bcg.com/img-src/BCG-Energy-Transitions-Report_tcm9-235156.PDF.

Murshed, M. (2021) 'Can regional trade integration facilitate renewable energy transition to ensure energy sustainability in South Asia?', *Energy Reports*. Elsevier, 7, pp. 808–821. doi: 10.1016/J.EGYR.2021.01.038.

Mustafa, D., Akhter, M. and Nasrallah, N. (2013) *Understanding Pakistan's water-security nexus*. United States Institute of Peace. Washington D.C. Available at: https://www.usip.org/sites/default/files/PW88_Understanding-Pakistan%27s-Water-Security-Nexus.pdf.

NASA (no date) *Global Warming vs. Climate Change Resources – Climate Change: Vital Signs of the Planet*. NASA's Jet Propulsion Laboratory | California Institute of Technology. California. Available at: https://climate.nasa.gov/resources/global-warming-vs-climate-change/ (Accessed: 17 May 2022).

Nepal, R. and Paija, N. (2019) 'Energy security, electricity, population and economic growth: The case of a developing South Asian resource-rich economy', *Energy Policy*. Elsevier, 132, pp. 771–781. doi: 10.1016/J.ENPOL.2019.05.054.

Neupane, D., Kafle, S., Karki, K. R., Kim, D. H. and Pradhan, P. (2022) 'Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis', *Renewable Energy*. Pergamon, 181, pp. 278–291. doi: 10.1016/J.RENENE.2021.09.027.

Newcombe, A. and Ackom, E. K. (2017) 'Sustainable solar home systems model: Applying lessons from Bangladesh to Myanmar's rural poor', *Energy for Sustainable Development*, 38, pp. 21–33. doi: 10.1016/j.esd.2017.03.002.

NITI Aayog (2018) *Composite Water Management Index*. NITI Aayog, Government of India. New Delhi. Available at: https://www.niti.gov.in/sites/default/files/2019-06/Final Report of the Research Study on Composite Water Resources Management Index for Indian States conducted by Dalberg Global Development Advisors Pvt. Ltd_New

Delhi.pdf.

O’Brien, K., Hayward, B. and Berkes, F. (2009) ‘Rethinking Social Contracts: Building Resilience in a Changing Climate’, *Ecology and Society*, 14, no. 2, pp. art12. doi: 10.5751/ES-03027-140212.

OECD (2021) *Carbon pricing in India*. Organisation for Economic Co-operation and Development. Paris. Available at: https://www.oecd.org/tax/tax-policy/carbon-pricing-india.pdf.

Oyewo, A. S., Aghahosseini, A., Ram, M. and Breyer, C. (2020) ‘Transition towards decarbonised power systems and its socio-economic impacts in West Africa’, *Renewable Energy*. Pergamon, 154, pp. 1092–1112. doi: 10.1016/J.RENENE.2020.03.085.

Oyewo, A. S., Farfan, J., Peltoniemi, P. and Breyer, C. (2018) ‘Repercussion of large scale hydro dam deployment: The case of congo Grand Inga hydro project’, *Energies*. doi: 10.3390/en11040972.

Palchak, D. and Chernyakhovskiy, M. J. (2022) *Power Sector Decarbonization in South Asia — Pathways for Research , Modeling , and Implementation*. National Renewable Energy Laboratory. Colorado. Available at: https://www.nrel.gov/analysis/dsgrid.html (Accessed: 20 May 2022).

Palit, D. (2019) *The journey towards universal electrification in India*. Friends of Europe. Brussels. Available at: https://www.friendsofeurope.org/insights/the-journey-towards-universal-electrification-in-india/.

Papadis, E. and Tsatsaronis, G. (2020) ‘Challenges in the decarbonization of the energy sector’, *Energy*. Pergamon, 205, pp. 118025. doi: 10.1016/J.ENERGY.2020.118025.

Parikh, J., Agrawal, K. K., Khare, D., Panda, R. R. and Mohla, P. (2013) *Prospects for regional cooperation on cross-Border electricity trade in South Asia*. Integrated Research and Action for Development. New Delhi. Available at: https://irade.org/Background Paper revised, Write Media, Oct18.pdf.

Parry, J.-E., Osman, H., Terton, A., Asad, S. A. and Ahmed, T. (2017) *The Vulnerability of Pakistan’s Water Sector to the Impacts of Climate Change: Identification of Gaps and Recommendations for Action*. International Institute for Sustainable Development. Winnipeg. Available at: https://www.iisd.org/publications/report/vulnerability-pakistans-water-sector-impacts-climate-change-identification-gaps.

Prina, M. G., Manzolini, G., Moser, D., Nastasi, B. and Sparber, W. (2020) ‘Classification and challenges of bottom-up energy system models - A review’, *Renewable and Sustainable Energy Reviews*. Pergamon, 129, pp. 109917. doi: 10.1016/J.RSER.2020.109917.

Pursiheimo, E., Holttinen, H. and Koljonen, T. (2019) ‘Inter-sectoral effects of high renewable energy share in global energy system’, *Renewable Energy*. Pergamon, 136, pp. 1119–1129. doi: 10.1016/j.renene.2018.09.082.

PwC (2017) *The Long View How will the global economic order change by 2050?* PricewaterhouseCoopers International Limited. London. Available at: https://www.pwc.com/gx/en/research-insights/economy/the-world-in-2050.html (Accessed: 19 May 2022).

Qazi, H. (2020) *Technical Shortfalls for Pan European Power System With High Levels of Renewable Generation*. European Comission. Brussels. Available at: https://eu-sysflex.com/wp-content/uploads/2020/05/EU-SysFlex_D2.4_Scarcity_identification_for_pan_European_-System_V1.0_For-Submission.pdf.

Quitzow, R., Bersalli, G., Eicke, L., Jahn, J., Lilliestam, J., Lira, F., Marian, A., Süsser, D., Thapar, S., Weko, S., Williams, S. and Xue, B. (2021) ‘The COVID-19 crisis deepens the gulf between leaders and laggards in the global energy transition’, *Energy Research & Social Science*. Elsevier, 74, pp. 101981. doi: 10.1016/J.ERSS.2021.101981.

Rahman, H., Wijayatunga, P. D. C., Gunatilake, H. and Fernando, P. N. (2012) *Energy Trade in South Asia: Opportunities and Challenges*. Asian Development Bank. Available at: www.adb.org (Accessed: 23 April 2022).

Rahman, M. M., Saidi, K. and Mbarek, M. Ben (2020) ‘Economic growth in South Asia: the role of CO2 emissions, population density and trade openness’, *Heliyon*. Elsevier, 6, no. 5, pp. e03903. doi: 10.1016/J.HELIYON.2020.E03903.

Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, S. A., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., SNS Barbosa, L., *et al.* (2019) *Global Energy System based on 100% Renewable Energy: Power, heat, transport and Desalination Sectors*. Energy Watch Group and LUT University. Lappeenranta, Berlin. doi: 10.13140/RG.2.2.10143.00160.

Ram, M., Child, M., Aghahosseini, A., Bogdanov, D., Lohrmann, A. and Breyer, C. (2018) ‘A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030’, *Journal of Cleaner Production*, 199, pp. 687–704. doi: 10.1016/j.jclepro.2018.07.159.

Ram, M., Gulagi, A., Aghahosseini, A., Bogdanov, D. and Breyer, C. (2022a) ‘Energy transition in megacities towards 100% renewable energy: A case for Delhi’, *Renewable Energy*. Elsevier BV, 195, pp. 578–589. doi: 10.1016/j.renene.2022.06.073.

Ram, M., Gulagi, A., Breyer, C. and Keiner, D. (2017) *Role of solar PV prosumers in enabling the energy transition towards a fully renewables based power system for India*. In Proceedings of the 1st International Conference on Large-Scale Grid Integration of

Renewable Energy in India. New Delhi.

Ram, M., Osorio-Aravena, J. C., Aghahosseini, A., Bogdanov, D. and Breyer, C. (2022b) ‘Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050’, *Energy*. Pergamon, 238, pp. 121690. doi: 10.1016/j.energy.2021.121690.

Rao, N. D. (2013) ‘Does (better) electricity supply increase household enterprise income in India?’, *Energy Policy*. Elsevier, 57, pp. 532–541. doi: 10.1016/J.ENPOL.2013.02.025.

Rasul, G. (2014) ‘Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region☆’, *Environmental Science & Policy*. Elsevier, 39, pp. 35–48. doi: 10.1016/J.ENVSCI.2014.01.010.

Rasul, G. (2016) ‘Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia’, *Environmental Development*. Elsevier, 18, pp. 14–25. doi: 10.1016/J.ENVDEV.2015.12.001.

Rauner, S., Hilaire, J., Klein, D., Strefler, J. and Luderer, G. (2020) ‘Air quality co-benefits of ratcheting up the NDCs’, *Climatic Change*. Springer Science and Business Media B.V., 163, no. 3, pp. 1481–1500. doi: 10.1007/S10584-020-02699-1/FIGURES/7.

REC (2018) *Saubhagya Dashboard*. Rural Electricity Corporation of India. New Delhi. Available at: http://www.saubhagya.gov.in/dashboard.

REN21 (2021) *Renewables 2021 Global Status Report*. REN21 Secretariat. Paris. Available at: https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf.

Renn, J., Schlögl, R., Rosol, C. and Steininger, B. (2017) *A rapid transition of the world’s energy systems*. Max Plank Gesellschafts. Berlin.

Ritchie, H., Roser, M. and Rosado, P. (2020) *Energy:Our World in Data*. Published online at OurWorldInData.org. Oxford. Available at: https://ourworldindata.org/energy.

Rizvi, S. M. A. H., Bastas, A. and Liyanage, K. (2022) ‘Sustainability assessment of electricity generation technologies: a transition pathway for Pakistan’, *https://doi.org/10.1080/14786451.2022.2039141*. Taylor & Francis. doi: 10.1080/14786451.2022.2039141.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., *et al.* (2009) ‘A safe operating space for humanity’, *Nature 2009 461:7263*. Nature Publishing Group, 461, no. 7263, pp. 472–475. doi: 10.1038/461472a.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. and Meinshausen, M. (2016) 'Paris Agreement climate proposals need a boost to keep warming well below 2 °C', *Nature 2016 534:7609*. Nature Publishing Group, 534, no. 7609, pp. 631–639. doi: 10.1038/nature18307.

Roser, M. (2013a) *Economic Growth*. Published online at OurWorldInData.org. Oxford. Available at: https://ourworldindata.org/economic-growth.

Roser, M. (2013b) *Future Population Growth*. Published online at OurWorldInData.org. Oxford. Available at: https://ourworldindata.org/future-population-growth.

Sadiqa, A., Gulagi, A., Bogdanov, D., Caldera, U. and Breyer, C. (2022) 'Renewable energy in Pakistan: Paving the way towards a fully renewables-based energy system across the power, heat, transport and desalination sectors by 2050', *IET Renewable Power Generation*. The Institution of Engineering and Technology, 16, no. 1, pp. 177–197. doi: 10.1049/RPG2.12278.

Sadiqa, A., Gulagi, A. and Breyer, C. (2018) 'Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050', *Energy*, 147, pp. 518–533. doi: 10.1016/j.energy.2018.01.027.

Sadovskaia, K., Bogdanov, D., Honkapuro, S. and Breyer, C. (2019) 'Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally', *International Journal of Electrical Power & Energy Systems*. Elsevier, 107, pp. 98–109. doi: 10.1016/J.IJEPES.2018.11.012.

Schafer, H. and Roome, J. (2021) *A roadmap to deliver a green, inclusive and resilient recovery in South Asia*. The World Bank. New York. Available at: https://blogs.worldbank.org/endpovertyinsouthasia/roadmap-deliver-green-inclusive-and-resilient-recovery-south-asia (Accessed: 20 May 2022).

Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., Goetzberger, A. and Weber, E. (2020) 'Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications', *Applied Energy*. Elsevier, 265, pp. 114737. doi: 10.1016/j.apenergy.2020.114737.

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G. and Ürge-Vorsatz, D. (2016) 'Carbon Lock-In: Types, Causes, and Policy Implications', *http://dx.doi.org/10.1146/annurev-environ-110615-085934*. Annual Reviews , 41, pp. 425–452. doi: 10.1146/ANNUREV-ENVIRON-110615-085934.

Shah, K. (2021) *New Coal-fired Power Plants in India: Reality or Just Numbers? New Coal Capacity Additions Face Major Stranded Asset Risk*. Institute for Energy Economics and Financial Analysis. Ohio. Available at: https://ieefa.org/wp-content/uploads/2021/05/New-Coalfired-Power-Plants-in-India_Reality-or-Just-

Numbers_June-2021.pdf (Accessed: 21 May 2022).

Sharma, A., Agrawal, S. and Urpelainen, J. (2020) ‘The adoption and use of solar mini-grids in grid-electrified Indian villages’, *Energy for Sustainable Development*. Elsevier, 55, pp. 139–150. doi: 10.1016/J.ESD.2020.01.005.

Shetty, D. (2021) *22 Out Of Top 30 World’s Most Polluted Cities In India*. Forbes. New Jersey. Available at: https://www.forbes.com/sites/dishashetty/2021/03/16/22-out-of-top-30-worlds-most-polluted-cities-in-india/?sh=6e7b134575ad.

Shiradkar, N., Arya, R., Chaubal, A., Deshmukh, K., Ghosh, P., Kottantharayil, A., Kumar, S. and Vasi, J. (2022) ‘Recent developments in solar manufacturing in India’, *Solar Compass*. Elsevier, 1, pp. 100009. doi: 10.1016/J.SOLCOM.2022.100009.

Shrestha, R. M., Limbu, T. R., Pradhan, B. B., Paudel, A. and Karki, P. (2007) *Energy Efficiency in South Asia : Opportunities for Energy Sector Transformation*. Asian Development Bank. Manila. doi: 10.22617/TCS200435.

Shukla, A. K., Sudhakar, K. and Baredar, P. (2017) ‘Renewable energy resources in South Asian countries: Challenges, policy and recommendations’, *Resource-Efficient Technologies*. No longer published by Elsevier, 3, no. 3, pp. 342–346. doi: 10.1016/J.REFFIT.2016.12.003.

Shumkov, I. (2021) *New solar can beat existing coal already in China, India and Europe - BNEF*. Renewables Now. Available at: https://renewablesnow.com/news/new-solar-can-beat-existing-coal-already-in-china-india-and-europe-bnef-745571/.

Singh, A., Jamasb, T., Nepal, R. and Toman, M. (2018) ‘Electricity cooperation in South Asia: Barriers to cross-border trade’, *Energy Policy*. Elsevier, 120, pp. 741–748. doi: 10.1016/J.ENPOL.2017.12.048.

Solomon, A. A., Bogdanov, D. and Breyer, C. (2018) ‘Solar driven net zero emission electricity supply with negligible carbon cost: Israel as a case study for Sun Belt countries’, *Energy*, 155, pp. 87–104. doi: 10.1016/j.energy.2018.05.014.

Solomon, A. A., Bogdanov, D. and Breyer, C. (2019) ‘Curtailment-storage-penetration nexus in the energy transition’, *Applied Energy,* 235, pp. 1351–1368. doi: 10.1016/j.apenergy.2018.11.069.

Solomon, B. D. and Krishna, K. (2011) ‘The coming sustainable energy transition: History, strategies, and outlook’, *Energy Policy*. Elsevier, 39, no. 11, pp. 7422–7431. doi: 10.1016/J.ENPOL.2011.09.009.

Soman, A., Kaur, H., Jain, H. and Ganesan, K. (2020) *Can Electric Mobility Support India’s Sustainable Economic Recovery Post COVID-19? India’s Electric Vehicle Transition REY 1C*. Council for Energy, Environment and Water. New Delhi. Available at: https://www.ceew.in/press-releases/india-could-save-over-inr-1-lakh-crore-annually-crude-oil-imports-increased-ev (Accessed: 22 August 2022).

Song, L. L. (2019) *How South Asia can continue as world’s fastest growing subregion*. Manila: Asian Development Bank. Available at: https://www.adb.org/news/op-ed/how-south-asia-can-continue-world-s-fastest-growing-subregion-lei-lei-song.

Sovacool, B. K. (2016) ‘How long will it take? Conceptualizing the temporal dynamics of energy transitions’, *Energy Research & Social Science*. Elsevier, 13, pp. 202–215. doi: 10.1016/J.ERSS.2015.12.020.

Sovacool, B. K., Gilbert, A. and Nugent, D. (2014) ‘An international comparative assessment of construction cost overruns for electricity infrastructure’, *Energy Research & Social Science*. Elsevier, 3, no. C, pp. 152–160. doi: 10.1016/J.ERSS.2014.07.016.

Sreekumar, N., Josey, A. and Mandal, M. (2018) ‘Rural Electrification in India: From “Connections for All” to “Power for All”’, *Economic and Political Weekly*, 53, no. 45, pp. 31.

Srinivasan, S., Kholod, N., Chaturvedi, V., Ghosh, P. P., Mathur, R., Clarke, L., Evans, M., Hejazi, M., Kanudia, A., Koti, P. N., Liu, B., Parikh, K. S., Ali, M. S. and Sharma, K. (2018) ‘Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation’, *Applied Energy*. Elsevier Ltd, 210, pp. 673–684. doi: 10.1016/j.apenergy.2017.04.079.

SSEA (2020) *Renewable Energy Resource Development Plan 2021-2026 Sri Lanka Sustainable Energy Authority*. Sri Lanka Sustainable Authority. Colombo. Available at: http://www.energy.gov.lk/images/renewable-energy/re-development-plan-english.pdf (Accessed: 23 August 2022).

Stackhouse, P. and Whitlock, C. (2008) *Surface meteorology and solar energy (SSE) release 6.0 Methodology*. National Aeronautic and Space Administration (NASA). Langley.

Stackhouse, P. and Whitlock, C. (2009) *Surface Meteorology and Solar Energy (SSE) Release 6.0 Methodology*. National Aeronautic and Space Administration (NASA). Langley.

Steadman, S. (2021) *The role of prosumers in future energy markets*. Thesis, Loughborough University. Loughborough. doi: https://doi.org/10.26174/thesis.lboro.14955021.v1.

Steffen, W., Crutzen, P. J. and McNeill, J. R. (2007) ‘The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature’, *AMBIO: A Journal of the Human Environment*, 36, no. 8, pp. 614–621. Available at: https://bioone.org/journals/ambio-a-journal-of-the-human-environment/volume-36/issue-8/0044-

7447(2007)36%5B614%3ATAAHNO%5D2.0.CO%3B2/The-Anthropocene--Are-Humans-Now-Overwhelming-the-Great-Forces/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2.short (Accessed: 18 May 2022).

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., *et al.* (2015) 'Planetary boundaries: Guiding human development on a changing planet', *Science*. American Association for the Advancement of Science, 347, no. 6223. doi: 10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF.

Stetter, D. (2012) *Enhancement of the REMix energy system model: global renewable energy potentials optimized power plant siting and scenario validation*. Dissertation, University of Stuttgart. Stuttgart. Available at: https://elib.uni-stuttgart.de/handle/11682/6872.

Swamy, D., Mitra, A., Agarwal, V., Mahajan, M. and Orvis, R. (2021a) *A Tool for Designing Policy Packages To Achieve India's Climate Targets: Methods, Data, and Reference Scenario of the India Energy Policy Simulator*. World Resources Institute. Washington D.C. doi: 10.46830/writn.21.00108.

Swamy, D., Mitra, A., Agarwal, V., Mahajan, M. and Orvis, R. (2021b) *Pathways for Decarbonizing India's Energy Future: Scenario Analysis Using the India Energy Policy Simulator*. World Resources Institute. Washington D.C. doi: 10.46830/wriwp.21.00096.

Terrapon-Pfaff, J. C., Ortiz, W., Viebahn, P., Kynast, E. and Flörke, M. (2020) 'Water Demand Scenarios for Electricity Generation at the Global and Regional Levels', *Water 2020, Vol. 12, Page 2482*. Multidisciplinary Digital Publishing Institute, 12, no. 9, pp. 2482. doi: 10.3390/W12092482.

Teske, S. (2019) *Achieving the Paris Climate Agreement Goals, Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5C and +2C*. Edited by S. Teske. Cham: Springer International Publishing. doi: 10.1007/978-3-030-05843-2.

Teske, S., Pregger, T., Simon, S., Naegler, T., Pagenkopf, J., Deniz, Ö., van den Adel, B., Dooley, K. and Meinshausen, M. (2021) 'It is still possible to achieve the paris climate agreement: Regional, sectoral, and land-use pathways', *Energies*. MDPI AG, 14, no. 8, pp. 2103. doi: 10.3390/EN14082103/S1.

The Economic Times (2021) *India to achieve 50% clean energy share, 500 GW RE capacity targets before 2030 deadline*. Published in The Economic Times. New Delhi. Available at: https://economictimes.indiatimes.com/industry/renewables/india-to-achieve-50-clean-energy-share-500-gw-re-capacity-targets-before-2030-deadline-singh/articleshow/87604552.cms.

The Economic Times (2022) *Farmers unite in push for share of India's solar power* *bonanza*. Published in The Economics Time. New Delhi. Available at: https://economictimes.indiatimes.com/industry/renewables/farmers-unite-in-push-for-share-of-indias-solar-power-bonanza/articleshow/89608958.cms?from=mdr.

Toh, L. (2021) *Let's Come Clean: The Renewable Energy Transition Will Be Expensive*. Columbia Climate School. New York. Available at: https://news.climate.columbia.edu/2021/10/26/lets-come-clean-the-renewable-energy-transition-will-be-expensive/ (Accessed: 20 August 2022).

Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D. and Breyer, C. (2019) 'Long term load projection in high resolution for all countries globally', *International Journal of Electrical Power and Energy Systems*. Elsevier Ltd, 111, pp. 160–181. doi: 10.1016/j.ijepes.2019.03.055.

Tollefson, J. (2021a) 'COVID curbed carbon emissions in 2020 - but not by much', *Nature*. NLM (Medline), 589, no. 7842, pp. 343. doi: 10.1038/D41586-021-00090-3.

Tollefson, J. (2021b) 'IPCC climate report: Earth is warmer than it's been in 125,000 years', *Nature*. NLM (Medline), 596, no. 7871, pp. 171–172. doi: 10.1038/D41586-021-02179-1.

Trading Economics (2015) *Bangladesh Agricultural Land (% of Total Land Area)*. Trading economics. New York. Available at: https://tradingeconomics.com/%0Abangladesh/agricultural-land-percent-of-land-area-wb-data.html.%0A.

Tsai, Y. C., Chiu, C. P., Ko, F. K., Chen, T. C. and Yang, J. T. (2016) 'Desalination plants and renewables combined to solve power and water issues', *Energy*. Pergamon, 113, pp. 1018–1030. doi: 10.1016/J.ENERGY.2016.07.135.

Ul-Haq, A., Hassan, M. S., Jalal, M., Ahmad, S., Anjum, M. A., Khalil, I. U. and Waqar, A. (2019) 'Cross-Border Power Trade and Grid Interconnection in SAARC Region: Technical Standardization and Power Pool Model', *IEEE Access*. Institute of Electrical and Electronics Engineers Inc., 7, pp. 178977–179001. doi: 10.1109/ACCESS.2019.2958407.

Ul-Haq, A., Jalal, M., Sindi, H. F. and Ahmad, S. (2020) 'Energy Scenario in South Asia: Analytical Assessment and Policy Implications', *IEEE Access*, 8, pp. 156190–156207. doi: 10.1109/ACCESS.2020.3019648.

UNESCAP (2018) *Integrating South Asia's Power Grid for a Sustainable and Low Carbon Future*. UN Economic and Social Comission for Asia and the Pacific and The Asian and Pacific Energy Forum. New York. Available at: https://www.unescap.org/sites/default/files/Integrating South Asia's Power Grid for a Sustainable and Low Carbon Future_WEB.pdf (Accessed: 20 May 2022).

UNFCC (2015) *Adoption of the Paris Agreement*. United Nations. Paris. Available at: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

United Nations (2017) *Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development*. United Nations. New York. Available at: https://documents-dds-ny.un.org/doc/UNDOC/GEN/N17/207/63/PDF/N1720763.pdf?OpenElement.

United Nations (2019) *World Population Prospects 2019 Highlights*. United Nations, Department of Economic and Social Affairs. New York. Available at: https://population.un.org/wpp/publications/files/wpp2019_highlights.pdf (Accessed: 19 May 2022).

United Nations (2021a) *Enabling SDGs Through Inclusive, Just Energy Transitions Towards The Achievements Of SDG 7 And Net-Zero Emissions Executive Summary*. United Nations. New York. Available at: https://www.un.org/en/conferences/energy2021/about (Accessed: 18 May 2022).

United Nations (2021b) *Energy Access Towards The Achievement Of SDG 7 And Net-Zero Emissions*. United Nations. New York. Available at: https://www.un.org/en/conferences/energy2021/about (Accessed: 18 May 2022).

United Nations (2021c) *World Economic Situation and Prospects*. United Nations. New York. Available at: https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2021_CH3_SA.pdf.

United Nations (no date) *Around 2.5 billion more people will be living in cities by 2050, projects new UN report, 2018*. United Nations. Available at: https://www.un.org/en/desa/around-25-billion-more-people-will-be-living-cities-2050-projects-new-un-report (Accessed: 8 August 2022).

UTS (2019) *100% Renewable Energy for Bangladesh*. Institute of Sustainable Futures. Sydney. Available at: https://www.worldfuturecouncil.org/wp-content/uploads/2019/10/Summary-for-the-Policy-Makers-100-RE-for-Bangladesh.pdf.

Vaclav, S. (2010) *Energy Myths and Realities: Bringing Science to the Energy Policy Debate*. Washington D.C.: American Enterprise Institute for Public Policy Research. Available at: https://vaclavsmil.com/2010/06/01/energy-myth-and-realities-bringing-science-to-the-energy-ploicy-debate/.

Vaidyanathan, G. (2021) ‘Scientists cheer India’s ambitious carbon-zero climate pledge’, *Nature*. Springer Science and Business Media LLC. doi: 10.1038/D41586-021-03044-X.

Walker, S. (2020) *Triple Threat: Water, Energy and Food Insecurity*. World Resources Institute. Washington D.C. Available at: https://www.wri.org/insights/triple-threat-water-energy-and-food-insecurity.

WHO (2021) *Household air pollution and health*. World Health Organisation. Geneva. Available at: https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health.

WHO and World Bank (2014) *Access to Modern Energy Services for Health Facilities in Resource-Constrained Settings*. World Health Oraganization. Geneva. Available at: www.who.int (Accessed: 18 May 2022).

Wood, J. (2021) *India is now producing the world's cheapest solar power*. World Economic Forum. Geneva. Available at: https://www.weforum.org/agenda/2019/06/india-is-now-producing-the-world-s-cheapest-solar-power/.

World Bank (2015) *Drilling Down into South Asia's Groundwater Dilemma*. World Bank. Washington D.C. Available at: https://www.worldbank.org/en/news/feature/2015/05/26/drilling-down-into-south-asias-groundwater-dilemma.

World Bank (2021a) *Climate Change Action Plan 2021 -2025 South Asia Roadmap*. World Bank Group. Washington D.C. Available at: https://openknowledge.worldbank.org/handle/10986/36321 (Accessed: 17 May 2022).

World Bank (2021b) *Energy imports, net (% of energy use) - South Asia (database*. World Bank. Washington D.C. Available at: https://data.worldbank.org/indicator/EG.IMP.CONS.ZS?locations=8S&view=chart.

World Bank (2021c) *Energy transition in South Asia is critical to reaching global net-zero*. World Bank. New York. Available at: https://blogs.worldbank.org/endpovertyinsouthasia/energy-transition-south-asia-critical-reaching-global-net-zero (Accessed: 20 May 2022).

World Bank (2021d) *Thematic Priotities: South Asia Climate Roadmap*. World Bank Group. Washington D.C. Available at: https://documents1.worldbank.org/curated/en/320221639544660452/pdf/Thematic-Priorities-South-Asia-Climate-Roadmap.pdf.

World Bank (2021e) *Tracking SDG7 – The Energy Progress Report 2021*. World Bank. Washington D.C. Available at: www.worldbank.org (Accessed: 5 August 2022).

World Bank (2022a) *Reshaping Norms : A New Way Forward. South Asia Economic Focus*. World Bank. Washington D.C. Available at: https://openknowledge.worldbank.org/handle/10986/37121.

World Bank (2022b) *World Bank Open Data - World Development Indicators*. World Bank Group. Washington D.C. Available at: http://wdi.worldbank.org/table/4.2.

Worringham, C. (2021) *Agrivoltaics in India: Fertile Ground? Multiple Social and Economic Benefits of Farmland Solar Are Possible-But Not Without New Policy Settings*. Institute for Energy Economics and Financial Analysis. Ohio. Available at: https://ieefa.org/wp-content/uploads/2021/11/Agrivoltaics-in-India_December-2021.pdf (Accessed: 21 May 2022).

Zhang, C., Chen, X., Li, Y., Ding, W. and Fu, G. (2018) 'Water-energy-food nexus: Concepts, questions and methodologies', *Journal of Cleaner Production*. Elsevier, 195, pp. 625–639. doi: 10.1016/j.jclepro.2018.05.194.

Zhang, C., Wang, Y., Xiao, X., Ma, Y., Zhang, Z., Huo, M., Li, S., Meng, J., Zheng, H., Zhang, N., Huo, J., Li, Y. and Guan, D. (2021) 'The driving forces behind the change in energy consumption in developing countries', *Environmental Research Letters*. IOP Publishing, 16, no. 5, pp. 054002. doi: 10.1088/1748-9326/ABDE05.

Zhang, F. (2019) *In the Dark : How Much Do Power Sector Distortions Cost South Asia?* World Bank. Washington D.C. Available at: https://openknowledge.worldbank.org/handle/10986/30923 (Accessed: 20 May 2022).

Zhao, X. and Flynn, D. (2022) 'Stability enhancement strategies for a 100% grid-forming and grid-following converter-based Irish power system', *IET Renewable Power Generation*. The Institution of Engineering and Technology, 16, no. 1, pp. 125–138. doi: 10.1049/rpg2.12346.

Zhao, X., Thakurta, P. G. and Flynn, D. (2022) 'Grid-forming requirements based on stability assessment for 100% converter-based Irish power system', *IET Renewable Power Generation*. The Institution of Engineering and Technology, 16, no. 3, pp. 447–458. doi: 10.1049/rpg2.12340.

Ziegler, M. S. and Trancik, J. E. (2021) 'Re-examining rates of lithium-ion battery technology improvement and cost decline', *Energy & Environmental Science*. The Royal Society of Chemistry, 14, no. 4, pp. 1635–1651. doi: 10.1039/D0EE02681F.

Publication I

Gulagi, A., Choudhary, P., Bogdanov, D., and Breyer, C.

Electricity system based on 100% renewable energy for India and SAARC

Reprinted with permission from
PLoS ONE
Vol. 12(7), e0180611, 2017

PLOS ONE

RESEARCH ARTICLE

Electricity system based on 100% renewable energy for India and SAARC

Ashish Gulagi[1]*, **Piyush Choudhary**[2], **Dmitrii Bogdanov**[1], **Christian Breyer**[1]

1 Lappeenranta University of Technology, Lappeenranta, Finland, **2** Indian Institute of Technology (BHU), Varanasi, India

* Ashish.Gulagi@lut.fi

Abstract

The developing region of SAARC (South Asian Association for Regional Cooperation) is home to a large number of people living below the poverty line. In future, providing affordable, universally accessible, reliable, low to zero carbon electricity in this region will be the main aim. A cost optimal 100% renewable energy system is simulated for SAARC for the year 2030 on an hourly resolved basis. The region was divided into 16 sub-regions and three different scenarios were set up based on the level of high voltage direct current (HVDC) grid connections. The results obtained for a total system levelised cost of electricity (LCOE) showed a decrease from 71.6 €/MWh in a decentralized to 67.2 €/MWh for a centralized grid connected scenario. An additional scenario was simulated to show the benefits of integrating industrial gas production and seawater reverse osmosis desalination demand, and showed the system cost decreased by 5% and total electricity generation decreased by 1%. The results show that a 100% renewable energy system could be a reality in the SAARC region with the cost assumptions used in this research and it may be more cost competitive than nuclear and fossil carbon capture and storage (CCS) alternatives. One of the limitations of this study is the cost of land for installation of renewables which is not included in the LCOE calculations, but regarded as a minor contribution.

1. Introduction

Energy is critical, directly or indirectly, to the entire process of evolution, growth and survival of all living beings. In addition, it plays a vital role in the socio-economic development and human welfare of a country, and any uncertainty in its supply can threaten the functioning of an economy, particularly in developing countries [1]. The region of interest for this research is the developing region of South Asia, which is made up of the following countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. Collectively, they are also called SAARC (South Asian Association for Regional Cooperation). Providing affordable, universally accessible, reliable, low to zero carbon electricity in the developing countries will be the main aim of electricity generation in the next decades [2]. A report published by WWF lists ten recommendations for a 100% renewable energy (RE) future. The top two recommendations include, firstly, developing new and existing renewable energy sources to provide

Citation: Gulagi A, Choudhary P, Bogdanov D, Breyer C (2017) Electricity system based on 100% renewable energy for India and SAARC. PLoS ONE 12(7): e0180611. https://doi.org/10.1371/journal.pone.0180611

Editor: Bruno Merk, University of Liverpool, UNITED KINGDOM

Received: September 16, 2016

Accepted: June 19, 2017

Published: July 19, 2017

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14. The first author would like to thank Fortum Foundation for the valuable scholarship.

Competing interests: The authors have declared that no competing interests exist.

clean energy, and secondly, exchange of clean energy through grids, making use of sustainable resources in different areas [3]. A least cost energy system needs to be obtained without compromising the above mentioned objectives.

There is a need for sustainable energy supply as 87% of global (and SAARC region) energy supply is not sustainable [4]. The need for a sustainable energy system is eminent due to lack of availability of non-renewable resources, environmental consequences [5], or severe lasting security problems for nuclear power [6]. The SAARC region has a vast potential for sustainable energy due to the availability of abundant solar energy, vast land mass, sea waves, bioenergy, rivers, windy areas, mountains and other natural means. Harvesting the vast, available renewable energy resources is the way forward in achieving sustainable development.

The largest country in the SAARC region in terms of population and gross domestic product (GDP) is India with 1.2 billion inhabitants which accounts for 17% of world population [7]. India is the fourth-largest consumer of energy, accounting for 4.9% of global consumption, which is dominated by coal and imported oil [8]. With a high rate of population growth and GDP expected to grow at 8% per annum till 2030 and 6% beyond that [9], it is evident that the demand for electricity is expected to grow in the future [10]. As a matter of fact, in 2014, 240 million people in India did not have access to electricity, while 840 million people relied on wood, crop waste, dung and biomass to cook in traditional cook stoves, which is the major cause of indoor air pollution and premature death [11]. Climate change will affect most Indians due to flooding, change in the monsoon cycle and water scarcity [12, 13].

Coal is India's primary source of energy and the country is the world's third largest coal producer after China and the United States [14]. Coal is followed by oil and gas generation. According to International Monetary Fund, India has huge subsidies for coal and other fossil fuels [15]. India's post tax subsidies for coal for the year 2015 were at 196 bUSD. Also, the government supports coal mining through research and development and several tax benefits for coal transportation [16]. Further, coal-fired power plants are associated with high health costs and heavy metal emissions [17, 18, 19] which are actually not yet taken into account in India in optimizing the societal cost of energy supply. The total subsidies for coal-based and gas-based electricity generation can be estimated for the year 2010 at 84 €/MWh_{el} and 15 €/MWh_{el}, based on estimated total subsidies of 8.7 USD/GJ (coal) and 2.2 USD/GJ (gas) according to the IMF [20], primary energy demand for electricity of 2338 TWh_{th} (coal) and 302 TWh_{th} (gas), electricity generation of 653 TWh_{el} (coal) and 118 TWh_{el} (gas) according to the IEA [21] and long-term USD/€ exchange rate of 1.3. Taking away the subsidies from the fossil fuels and investing in RE would enable India to achieve the climate change mitigation goals and zero carbon emissions.

The annual Conference of Parties (COP) 21 held in Paris during December 2015 was an action driven event, when the fight against climate change took a dramatic turn. The conference presented political and business leaders with the opportunity to take the critical decisions needed to keep average temperature rise to no more than 1.5 or 2 degrees Celsius, which finally requires net zero greenhouse gas emissions shortly after the middle of this century [22]. Deliberations among country representatives observed that dynamic change is happening in energy supply, but important is that change needs to happen faster. The Energy [R]evolution scenario of Greenpeace in cooperation with the German Aerospace Center [23, 24] proposes a pathway to restrict global CO_2 emissions and in turn restricting temperature rise to 2°C by including renewable energy sources and phasing out nuclear energy.

The International Energy Agency [11] has projected India at the centre of the world energy stage in terms of projected rise in energy demand and will contribute the single largest share of around one-quarter in global energy demand by the year 2040. With policies in place to accelerate the country's modernization and develop its manufacturing base (via the "Make in

India" programme), population and incomes on the rise and an additional 315 million people anticipated to live in India's cities by 2040, India is entering a sustained period of rapid growth in energy consumption [11].

But the good news for India is the effort and the will shown by the government to provide electricity for all in a sustainable way while reducing the effects of climate change. According to Shearer et al.[25], the average cost of electricity produced from coal power plants in 2020 is more expensive than solar PV and onshore wind and this will lead to underutilization or stranded coal plants. Already there has been decrease in average plant load factor which fell from 79% to 64% from 2007 to 2015 [26]. This has given rise to reduced demand of imported coal and it was evident from the statistics, as coal imports fell by 15% from the last year in April 2016 [27]. According to the energy minister of India, a new coal power plant will give costlier power than a solar plant, which is due to the rapid decrease in solar prices in recent years [28]. This is evident from the government's plan to scrap 16 GW ultra-mega coal fired power plants [29]. The Central Electricity Authority [30] in its draft National Electricity Plan specifically mentions that till 2022 India does not require any more coal based capacity to be added above the current levels.

India has ambitious plans to expand the deployment of solar and wind power. The targeted levels of deployment for renewables is 175 GW by 2022 (of which 100 GW is solar and 60 GW is wind), a powerful statement of intent from the Government of India [31]. According to the draft electricity plan published by the government of India, it forecasts around 54% of India's total electricity capacity will come from renewables, thereof 43% new renewables and 11% hydropower, 2% from nuclear energy and 44% from fossil power plants by 2027 and the Paris Agreement target was 40% by 2030 [30]. The Government's goal of 'Electricity for All' to be achieved would require huge investments, infusion of new technology and international support [32]. The main renewable energy driver is 'The National Solar Mission', which aims to promote the development and use of solar energy for power generation with an ultimate aim of making solar cost competitive with fossil based energy options through long term policy, large scale deployment goals, aggressive R&D and domestic production of critical raw materials [33]. India offers huge growth potential for the solar PV industry.

During COP 21, India launched the International Solar Alliance (ISA) with countries located in between the Tropic of Cancer and Tropic of Capricorn [34]. ISA is conceived as a coalition of solar resource rich countries to address their special energy needs and will provide a platform to collaborate on addressing the identified gaps through a common, agreed approach. It will not duplicate or replicate the efforts that others (like International Renewable Energy Agency (IRENA), Renewable Energy and Energy Efficiency Partnership (REEEP), International Energy Agency (IEA), Renewable Energy Policy Network for the 21st Century (REN21), United Nations bodies, bilateral organizations etc.) are currently engaged in, but will establish networks and develop synergies with them and supplement their efforts in a sustainable and focused manner.

Human development and economic growth in the SAARC region and particularly in India can be achieved through growth in energy use and its spread to all remote areas. Electricity will play an important role in improving human development and quality of human life. For India, economic growth hinges on bringing the rural population out of the dark and providing clean, continuous electricity supply. Electricity generation from renewable energy sources in a decentralized manner is one of the options to meet rural electricity needs [35, 36]. For locations far away from the existing grid or where grid extension is not possible, economically or technically, decentralized generation would provide basic electricity and likely overcome the problem of frequent blackouts. Long term planning will be essential for energy security, which will be based on renewable resources in a centralized and decentralized manner, and will help in sustainable development as well as minimize the carbon footprint.

For SAARC and India there is no research yet on the sustainable energy transition pathways into the future decades or none of them integrated all aspects in the required manner. The list of various future scenarios for SAARC and India with the key findings is given in Table 1. However, none of them considered the following approaches as applied in this study, such as hourly based model that guarantees that the hourly total electric energy supply in a year in the sub-regions covers the local demand from all sectors (which is most relevant during the monsoon season); different transmission grid development levels that are able to reduce the need of energy storage and total costs; and an integrated scenario that assumes electricity demand, water desalination and industrial gas demand.

2. Methodology

The model applied to the simulation uses linear optimization for the energy system parameters under previously defined limitations which are applied to the system and the assumptions for the future RE power generation and demand. The detailed description of the model can be found in Bogdanov and Breyer [41], but the main functionalities are summarised in the following sections. Required storage technologies, including additional water desalination and synthetic natural gas generation, are the flexible demands in the model. One key limitation for the system optimization is that demand should be satisfied by power generation on an hourly basis for an entire year as shown in Eq 1. To obtain a least cost energy system is the main target

Table 1. Key findings of different scenario studies for SAARC.

Study	Scope	Key findings
Abhyankar N. and Phadke A., [37]	India	Based on the simulation results of the hourly grid dispatch simulation for the year 2047. Various scenarios were simulated. In the minimum emissions scenario, installed capacities of solar and wind is 930 and 472 GW, respectively.
IEA [11]	India	For the year 2030, the installed capacity of fossil fuels is 419 GW and renewables is 462 GW. Solar PV contributes 100 GW and wind 102 GW
Teske S. et al., [23]	all countries including India	The share of renewables in the electricity generation would be 56% (2030) and 93% (2050). The installed capacities of the renewables will reach 770 GW (2030), 2240 GW (2050) and 100% RE scenario 3260 GW. PV installed capacities of 390 GW and wind 449 GW in 2030.
Powergrid Corporation of India, [38]	India	Deserts from the western part and northern part of India would be utilized to power the electricity demand for the whole country. Mainly powered by solar and wind, which have installed capacity of about 485 GW
TERI and WWF-India [9]	India	In the 100% RE scenario for 2051, installed capacity for solar is 1200 GW, offshore wind 1113 GW and onshore wind 117 GW. The total installed capacity would be 2870 GW.
WWF-India and WISE [36]	For the state of Kerala, India	In a 100% RE scenario for 2050, solar contributes 51% and wind contributes 24% of the total electricity generation mix
Teske S. et al., [39]	India	The share of renewables in the electricity generation would be 32% (2020), 62% (2030) and 92% (2050). Wind, solar thermal energy and PV will contribute 74% of electricity generation. The installed capacities of renewables will reach 548 GW in 2030 and 1356 GW by 2050.
Teske S. et al., [40]	India	The share of renewables in electricity generation would be 69% by 2050, with an installed capacity of 1659 GW.

https://doi.org/10.1371/journal.pone.0180611.t001

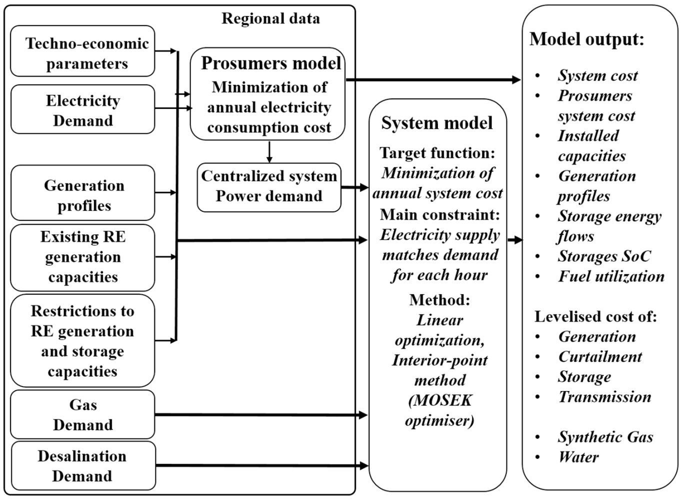


Fig 1. Model flow diagram with the input data, system model optimization and output data.

https://doi.org/10.1371/journal.pone.0180611.g001

of system optimization. The costs are calculated as sum of the annualised costs of all installed capacities of the different technologies, energy generation and generation ramping. Also, the system consists of PV prosumers for residential, commercial and industrial sectors. The term prosumer is used to refer to energy consumers who also produce their own power from a range of different onsite generators, e.g. diesel generators, combined heat-and-power systems, wind turbines, and PV systems [42]. In this study, only onsite consumption and generation from PV systems are considered and termed as prosumers [43, 44]. The PV prosumers install the required individual capacities of rooftop PV systems and batteries. Minimizing cost of consumed energy is the target function for the prosumers. The cost of consumed energy is calculated as sum of PV self-consumption, annual cost and cost of electricity consumed from the grid. The prosumers can sell electricity to the grid at 2 €ct/kWh, however they have to satisfy their own demand before selling. The flowchart of the model is presented in Fig 1.

$$\begin{aligned}\forall h \in [1, 8760] \left(\sum\nolimits_{t}^{tech} E_{gen,t}\right), h + \left(\sum\nolimits_{r}^{reg} E_{imp,r}\right), h + \left(\sum\nolimits_{t}^{stor} E_{stor,disch}\right), h \\ = (E_{demand}), h + \left(\sum\nolimits_{r}^{reg} E_{exp,r}\right), h + \left(\sum\nolimits_{t}^{stor} E_{stor,ch}\right), h + (E_{curt}), h \qquad (1)\end{aligned}$$

$$min\left(\sum\nolimits_{r=1}^{reg}\sum\nolimits_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t) \cdot instCap_{t,r} + OPEXvar_t \cdot E_{gen,t,r} + rampCost_t \cdot totRamp_{t,r}\right) \qquad (2)$$

The main constraint of the system optimization is given in Eq 1. It is defined as for every hour of a year in a particular region, electricity generation from all the technologies ($E_{gen,t}$), imported electricity from the regions ($E_{imp,r}$) and electricity from storage discharge ($E_{stor,disch}$) should be equal to the total demand for an hour (E_{demand}), electricity exported to other regions ($E_{exp,r}$), electricity for charging storage technologies ($E_{stor,ch}$)and curtailed electricity (E_{curt}).

The other abbreviations used in this equation are: hours (h), technology (t), all technologies used in modelling ($tech$), sub-region (r), all sub-regions (reg). Eq 2 provides the target function for system optimization. The abbreviations used here include ($CAPEX_t$)—capital cost of each technology, (crf_t)–capital recovery factor for each technology, ($OPEXfix_t$)–fixed operational cost for each technology, ($OPEXvar_t$)—variable operational cost each technology, installed capacity in a region ($instCap_{t,r}$), electricity generation by each technology ($E_{gen,t,r}$), ramping cost of each technology ($rampCost_t$) and annual total power ramping values for each technology ($totRamp_{t,r}$). The balancing of the system is mainly done by gas peakers, fuelled by biomethane or synthetic natural gas based on power-to-gas technology. The open cycle gas turbine (OCGT) and combined cycle gas turbine (CCGT) power plants can be ramped within a few minutes and 60 minutes, respectively[45, 46], which is within the resolution of the applied model. Base generation plants do not exist in the model, except hydro run-of-river, however there is of course variation due to the hydro resource availability. Batteries can react on millisecond scale and can even receive control information from the frequency in the grid.

The equations used for calculating total levelized cost of electricity (LCOE), primary LCOE, levelized cost of curtailment (LCOC), levelized cost of storage (LCOS), levelized cost of transmission (LCOT), total annual cost of the system and total capital cost are presented below (Eqs 3–9)

$$totalCost\ system = \sum_{r}^{reg} LCOE_r \cdot E_{demand,r} \tag{3}$$

$$LCOE_r = LCOE_{prim,r} + LCOC_r + LCOS_r + LCOT_r \tag{4}$$

$$LCOE_{prim_r} = \frac{\sum_{t=1}^{REtech} (CAPEX_t \cdot crf_t + OPEXfix_t) \cdot Cap_{t,r} + OPEXvar_t \cdot E_{gen,t,r}}{E_{demand,r} + E_{exp,r} - E_{imp,r}} \tag{5}$$

$$LCOC_r = LCOE_{prim_r} \cdot \frac{E_{curt,r}}{E_{demand,r} + E_{exp,r} - E_{imp,r}} \tag{6}$$

$$LCOS_r = \frac{\sum_{t=1}^{Storagetech} (CAPEXcrf_t + OPEXfix_t) \cdot Cap_{t,r} + OPEXvar_t \cdot E_{storage,disch,t,r}}{E_{demand,r} + E_{exp,r} - E_{imp,r}} \tag{7}$$

$$LCOT_r = \frac{totalCost_{TR} \cdot share_r}{E_{demand,r} + E_{exp,r} - E_{imp,r}} \tag{8}$$

$$CAPEX_{tot} = \sum_{r}^{reg} \sum_{t}^{tech} CAPEX_t \cdot Cap_{t,r} \tag{9}$$

2.1 Input data for the model

Detailed information of the input data used for the model is given in Bogdanov and Breyer [41] and additional calculations related to geothermal energy, desalination water demand and industrial gas demand data are described here.

- The potential for geothermal energy for the sub-regions is calculated on the available information related to heat flow rate and ambient temperature of the surface [47, 48] for the year

2005. For the sub-regions where the heat flow data were not available, extrapolation was performed to get the required data. Based on the available data, different temperature levels and available heat at the mid-point of a 1 km thick deep layer and for between the depths of 1 km to 10 km [49, 50, 51] globally with 0.45° x 0.45° spatial resolution, the required potential is derived.

- For every sub-region, projected water desalination demand is calculated as projections for water consumption and stress level [52] with an assumption that water stress more than 50% will be covered by desalinated seawater. Detailed calculations for the technical constraints and financial cost of seawater reverse osmosis desalination are described Caldera et.al. [53].
- Natural gas consumption was derived in the non-energy sector for every sub-region. Industrial gas consumption data are based on IEA statistics for non-energy sector demand [54].

2.2 Applied technologies

For the SAARC region, technologies used for energy system optimization can be divided into four main categories

• **Technologies for converting renewable energy sources into electricity.** The technologies used for transforming RE sources into electricity are: two different types of ground mounted PV systems (optimally fixed tilted and single-axis north-south oriented horizontal continuous tracking), rooftop PV for prosumers, concentrating solar thermal power (CSP), onshore wind turbines, hydro power divided into run-of-river and dams, biomass which is divided into biogas and solid biomass, waste-to-energy and geothermal power plants.

• **Energy storage.** The energy storage technologies utilized in the model are system and prosumer batteries, pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES) and power-to-gas (PtG) technology. Technologies such as water electrolysis, methanation, CO_2 scrubbing from air, gas storage, and both combined and open cycle gas turbines (CCGT, OCGT) are part of the synthesis of synthetic natural gas (SNG) and its reconversion to electricity. The PtG technologies have to be operated in synchronization because of the absence of hydrogen and CO_2 storage. As part of the system also there is a biogas buffer storage for 48 hours and part of the biogas can be upgraded to biomethane and introduced to the gas storage.

• **Energy bridging technologies.** The bridging technologies used in this model provide the required flexibility to the energy system in terms of reducing the overall cost of an optimized system. For example, gas produced from PtG can be used for industrial gas demand rather than storage for the electricity sector. Similarly, for producing clean water, excess electricity is utilized by seawater reverse osmosis (SWRO) coupling water and electricity sectors.

• **Electricity transmission technologies.** Electricity transmission inside the sub-regions is assumed to be based on alternating current (AC) grids and not included in the model, and between the sub-regions on high voltage direct current (HVDC). Loss of electricity is due to the transmission lines and in converter stations at the interconnection with the AC grid.

The full block model diagram is presented in Fig 2.

3. Scenario assumptions for the SAARC region

3.1 Subdivision of the region and grid structure

The SAARC region is subdivided into 16 sub-regions, according to population distribution, electricity consumption and countries' grid structure. The different sub-regions can be seen

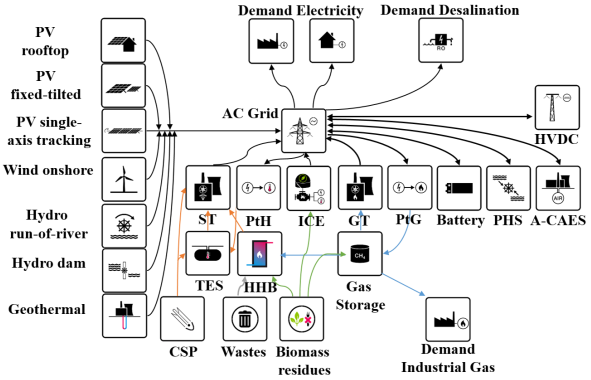


Fig 2. Block diagram of the all the energy technologies applied in the model for the SAARC region.

https://doi.org/10.1371/journal.pone.0180611.g002

from Fig 3. India is subdivided into 10 different regions, Pakistan into two regions and the other remaining countries are treated as individual regions. The grid connection between the regions is shown in Fig 3, which includes interconnections within the countries shown by dark line and between the countries shown by dotted lines.

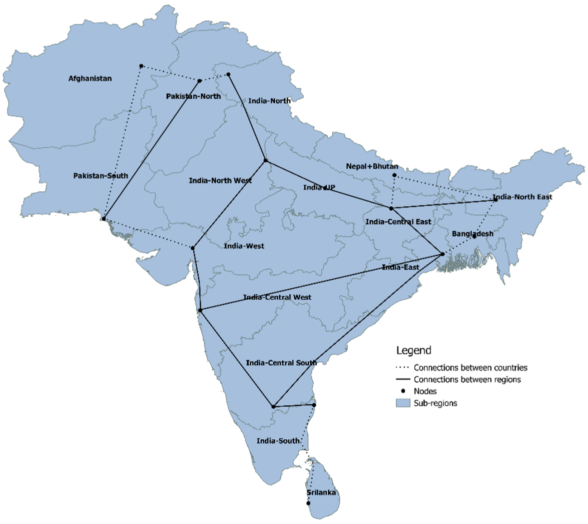


Fig 3. The different SAARC regions and HVDC grid configuration.

https://doi.org/10.1371/journal.pone.0180611.g003

3.2 Applied scenarios

The different scenarios taken into consideration in this paper for the analysis of the energy system of SAARC region are:

- Region-wide scenario: the regions do not depend on each other and have no interconnections so the demand for electricity is covered by region's own generation capacity.
- Country-wide scenario: regions of the same country are interconnected via HVDC lines
- Area-wide scenario: energy systems of the countries are interconnected
- Integrated scenario: area-wide scenario plus SWRO desalination and industrial gas demand to provide flexibility to the system where PtG technology also covers industrial gas demand.

3.3 Financial and technical assumptions

The model optimization is based on an assumed cost structure and state of technology for the year 2030. The financial assumptions for all the energy system technologies, HVDC lines and converter stations, which are given as net transmission capacity (NTC) for 2030 reference year, are tabulated in Table A of S1 File. The weighted average cost of capital (WACC) is set to 7% (real) for all investments, expect for residential PV prosumers, for which a real WACC of 4% is applied, due to lower financial return requirements. The WACC may not reflect the financing situation in each country but an uniform assumption is required for comparing the results. However, the authors assume that a 7% real WACC will be achieved in the countries of these region by the year 2030. The technical assumptions for energy to power ratios of storage technologies, efficiency numbers for generation and storage technologies and power losses in HVDC transmission lines [55] and converters are presented in Tables B, C and D of S1 File. Price of electricity for residential, commercial and industrial consumers for all the countries is taken from Gerlach et al. [56] and only applied for deriving beneficial self-consumption of PV prosumers. The electricity prices for Nepal and Bhutan are assumed to be similar to India. The electricity prices for 2030 are calculated according to the assumptions that grid electricity prices rise by 5% per annum for <0.15 €/kWh, by 3% per annum for 0.15–0.30 €/kWh and by 1% per annum for >0.30 €/kWh [57]. The electricity prices for all the regions are provided in Table E of S1 File. It should be noted that electricity prices only affect the prosumers of electricity in the model. The renewable energy investments' financial incentives, such as Renewable Energy Certificate mechanism and Perform Achieve Trade (PAT), are not considered in the assumptions, since a cost-based model is applied.

Table 2 presents the financial assumptions for the storage components utilized in the modelling. For the case of the SAARC region, the cost of batteries will be important as this is the most important storage technology. The general consensus is that, cost will fall as production volumes increase and this is supported by historical cost developments of Lithium-ion

Table 2. Financial assumptions for storage components for year 2030 conditions.

	Capex	Opex fix	Opex var	Lifetime
	[€/kWh]	[€/kWh]	[€/kWh]	[a]
Battery	150	10	0.0002	10
PHS	70	11	0.0002	50
A-CAES	31	0.4	0.0012	40
Thermal energy storage (TES)	24	2	0	20
Gas storage	0.05	0.001	0	50

https://doi.org/10.1371/journal.pone.0180611.t002

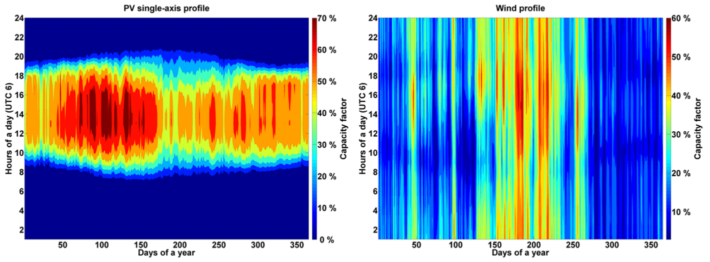


Fig 4. Yearly profile for PV single-axis tracking (left) and wind onshore (right).

https://doi.org/10.1371/journal.pone.0180611.g004

batteries. An average value has been used for the battery capex comparing various sources [58, 59, 60, 61, 62, 63].

3.4 Feed-in for solar and wind energy

Solar CSP, optimally tilted and single-axis tracking PV, and wind energy generation profiles were calculated according to Bogdanov and Breyer [41]. Fig 4 represents aggregated profiles of solar PV generation (optimally tilted and single-axis tracking), wind energy power generation and CSP solar field, normalized to maximum capacity averaged for the SAARC region, are presented in Fig 4. The computed average full load hours (FLH) for optimally tilted, single-axis tracking PV systems, wind power plants and CSP are provided in Table F of S1 File.

For hydro power, generation profiles are computed based on the monthly resolved precipitation data for the year 2005 as a normalized sum of precipitation throughout the regions.

3.5 Biomass and geothermal potential

The biomass and waste resources are divided into three categories: Solid wastes, solid residues and biogas. The potential for these resources are taken from [64] and cost associated with all the biomass resources is calculated according to the data from International Energy Agency [65] and Intergovernmental Panel on Climate Change [66]. For solid fuels a 75 €/ton fee for the waste incineration is assumed and it is reflected in the negative cost for solid fuels. The heating values are based on lower heating values (LHV).

The geothermal heat potential for all the regions were calculated based on the spatial data for available heat, temperature and geothermal plants for depths from 1 km to 10 km. For each 0.45° x 0.45° area and depth, LCOE for geothermal is calculated and optimal depth is determined. The assumption for available geothermal heat is that only 10% of it will be utilized as an upper resource limit. The total available heat for all the regions was calculated using the same weighted average formula as for solar and wind feed-in as described in Bogdanov and Breyer [41], with an exception of areas with geothermal LCOE exceeding 100 €/MWh, which are excluded. The calculated potentials for solid biomass, biogas, solid waste and respective costs, and geothermal heat potentials are provided in Tables G and H of S1 File.

3.6 Upper and lower limitations on installed capacities

The data for current installed capacities for optimally fixed-tilted PV, wind turbines, hydro power and pumped hydro storage are taken from Farfan and Breyer [67] and summarized in Table I of S1 File. The upper limits for all the above mentioned RE technologies were

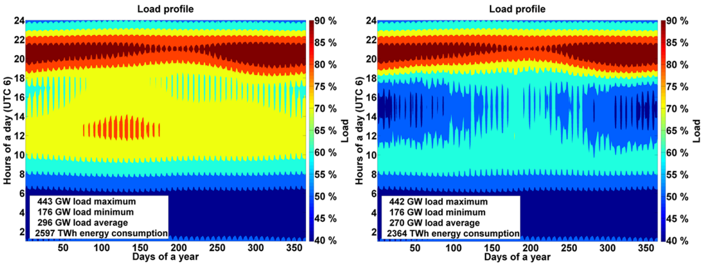


Fig 5. Aggregated load curve (left) and load curve with prosumers influence (right) for the SAARC region for the year 2030.

https://doi.org/10.1371/journal.pone.0180611.g005

calculated according to Bogdanov and Breyer [41] and are summarized in Table J of S1 File. It is assumed for biomass residues, biogas and waste to energy plants, that the available and specified amount of the fuel is utilized during the year due to energy efficiency.

3.7 Load

The load profile for each region is calculated as a fraction of the total demand in that particular country based on synthetic load data weighted by the region's population. Fig 5 represents the area aggregated demand profile for all the regions considered in SAARC. The additional impact of solar PV prosumers can be observed on the residual load in reduction of overall energy demand and maximum load, by 9% and 0.2%, respectively (Fig 5). The demand for gas in industries and desalination water demand for the SAARC region is given in Table K of S1 File.

4. Results

4.1 Structure and cost of an optimized energy system

The cost structure of the different scenarios were analysed with the set of parameters calculated as given in Bogdanov and Breyer [41] plus the model extension described in section 2.1. The key financial results for the different scenarios for the SAARC region is presented in Table 3. The results are given as the total system (LCOE) levelised cost of electricity (including PV self-consumption and the centralized system), levelised cost of electricity for primary generation (LCOE primary), levelised cost of curtailment (LCOC), levelised cost of storage technologies (LCOS), levelised cost of transmission (LCOT), total annualized cost, total capital expenditures and other results, which include the total renewable capacity and total primary generation.

Table 3. Financial results for the four scenarios applied for the SAARC region.

2030 Scenarios	Total LCOE	LCOE primary	LCOC	LCOS	LCOT	Total ann. cost	Total CAPEX	RE capa-cities	Gener-ated electri-city
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[b€]	[b€]	[GW]	[TWh]
Region-wide	71.6	42.3	1.5	27.8	0.0	187	1539	1377	2948
Country-wide	69.6	41.9	1.1	25.5	1.1	181	1468	1294	2865
Area-wide	67.2	41.4	0.7	22.7	2.3	174	1421	1210	2818
Integrated scenario	67.9	40.8	1.4	22.6	3.1	299	2562	2213	4988

https://doi.org/10.1371/journal.pone.0180611.t003

Table 4. Installed RE technologies and storage capacities for the four scenarios for SAARC region.

		Region-wide	Country-wide	Area-wide	Integrated scenario
PV self-consumption	[GW]	145	145	145	145
PV optimally tilted	[GW]	21	23	3	3
PV single-axis tracking	[GW]	782	721	640	1131
PV total	[GW]	947	889	789	1280
CSP	[GW]	0	0	0	0
Wind energy	[GW]	242	229	245	694
Biomass power plants	[GW]	64	64	61	65
MSW incinerator	[GW]	3	3	3	3
Biogas power plants	[GW]	21	16	22	14
Geothermal power	[GW]	2	6	8	8
Hydro Run-of-River	[GW]	22	21	21	21
Hydro dams	[GW]	35	35	35	35
Battery PV self-consumption	[GWh]	4	4	4	4
Battery System	[GWh]	1389	1522	1450	1682
Battery total	[GWh]	1393	1526	1454	1686
PHS	[GWh]	44	44	44	44
A-CAES	[GWh]	2416	551	3	3187
Heat storage	[GWh]	0	0	0	0
PtG electrolysers	[GW_{el}]	43	30	20	115
CCGT	[GW]	50	43	41	99
OCGT	[GW]	3	2	2	0
Steam Turbine	[GW]	0	0	0	0

https://doi.org/10.1371/journal.pone.0180611.t004

The benefit due to interconnection of the sub-regions via HVDC power lines has a positive impact on the LCOE and total annual cost of the system, but this impact is only marginal due to limited grid utilization. LCOE and annual cost of the system are decreased by 6.1% and 6.9%, respectively, from region-wide to area-wide scenarios. Also, grid utilization decreases installed capacities and total electricity generated from RE sources by 12.1% and 4.4%, respectively. The cost of transmitting electricity with HVDC power lines is small in comparison to the cost of storage; therefore, total system cost and LCOE are reduced. The transmission lines decrease the need for storage technologies, since energy shifted in time (storage) can partly be cost effectively substituted by energy shift in the location. Also, cost of curtailment is reduced when electricity is transmitted to other sub-regions as seen in Table 3. The components that make up the LCOE in region-wide, country-wide, area-wide and integrated scenarios are presented in Table L of S1 File.

The installed capacities of all the renewable energy technologies show a decrease with increase in installation of HVDC lines as shown in Table 4. The total installed capacities of PV decrease by 16.7% from region-wide to area-wide scenarios due to efficient use of solar resources available in the region. The installed capacity for wind shows a slight increase in the area-wide scenario due to low solar irradiation in the monsoon months. The installed capacities of PV and wind in the integrated scenario increase due to the additional demand of seawater desalination and industrial gas. In the SAARC region, PV is the least cost RE source followed by wind energy. The share of PV single-axis tracking and PV self-consumption of the total solar PV installed capacity for the area-wide scenario is 82.6% and 15.3%, respectively.

In the integrated scenario, additional flexible demand from the desalination and industrial gas sectors leads to an increase in installed capacities of the low cost solar by 38.3% and wind

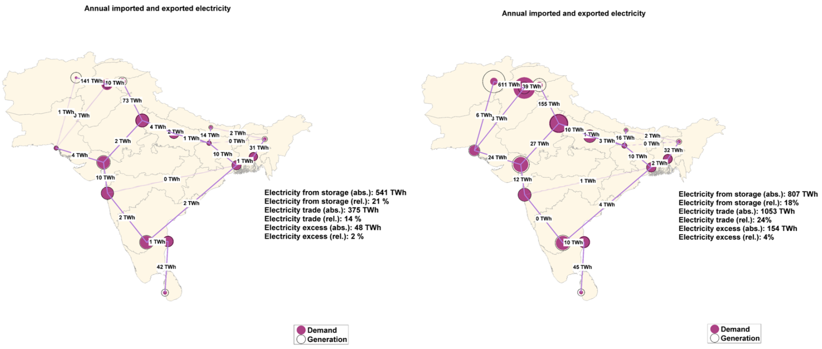


Fig 6. Sub-regional annual import and export of electricity for area-wide (left) and integrated scenario (right).

https://doi.org/10.1371/journal.pone.0180611.g006

resources by 64.7% with respect to the area-wide scenario. There is a slight increase in the installed capacities of the biomass resources. The capacity of the hydro dams does not change as it provides the system with required flexibility. Despite an upper limit of 50% higher than the current capacity considered for hydro dams and hydro run-of-river plants, installed capacities do not increase in the integrated scenario as PV and wind are least cost technologies in the SAARC region.

The generation curves for electricity can be represented for the whole year divided into 8760 hours and sorted according to the generation minus the load, which is represented by a black line as shown in Figure F of S2 File for the area-wide scenario. All the storage technologies used in the system are charged for about 3500 hours in a year, which is due to higher electricity generation than demand. As solar and wind are highly inflexible generation sources, in these particular hours in the SAARC region there is a high electricity generation. The other flexible generation options such as hydro dams, biomass, biogas and discharge of storage technologies are required to balance the high inflexibility. The inflexible electricity generation options reduce significantly in the other hours of the year as the electricity demand decreases and there is a need for flexible electricity generation options, discharge of storage technologies and utilization of the grid. Curtailment of electricity is for only some hundred hours of the year since for all the other hours the HVDC lines enable the export of the electricity from the best RE producing sub-regions to other sub-regions.

4.2 Sub-regional analysis on an optimized energy system

The sub-regional distribution of system optimized RE resources can be observed from Fig 6. Circles represent demand (solid) and generation (line), with some sub-regions with the best renewable resources represented as net exporters and the others as net importers. The share of export is defined as the ratio of net exported electricity to the generated primary electricity of a sub-region and the share of import is defined as the ratio of imported electricity to the electricity demand. The area average is composed of sub-regional values weighted by the electricity demand. The sub-regions with best renewable energy resources help balance out sub-regions where the availability of renewable resources is scarce. For the region-wide scenario, individual SAARC sub-regions need to match their own demand using their own available RE resources. When the sub-regions are interconnected, as in case of country-wide, area-wide and integrated

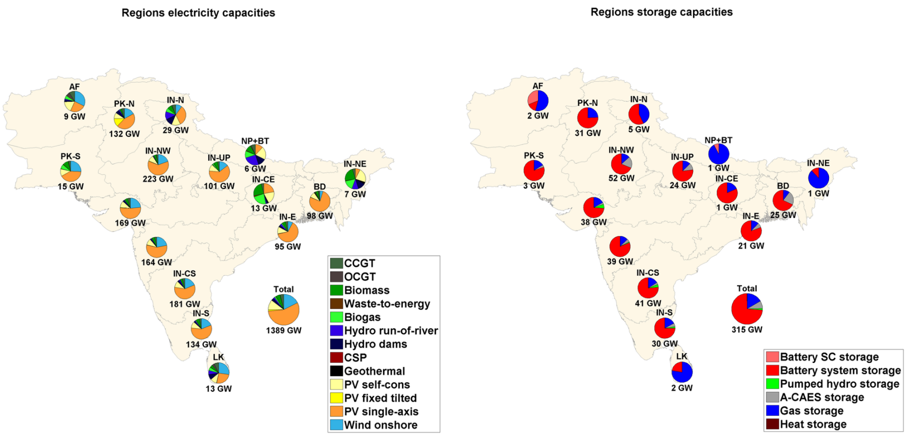


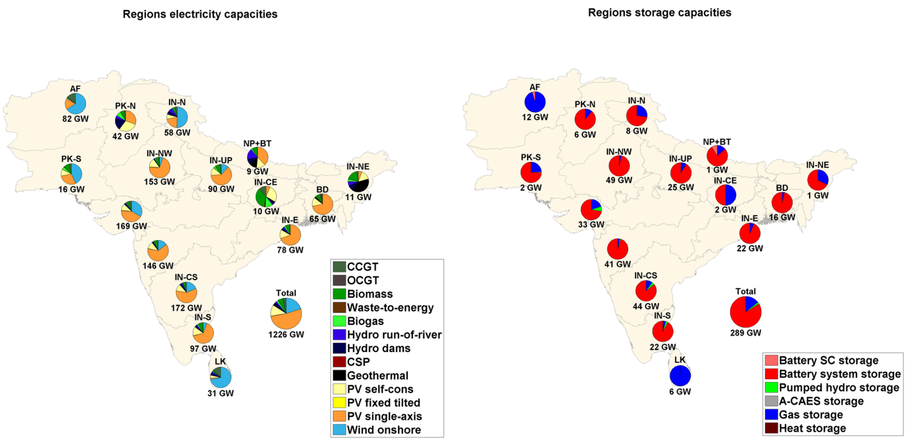
Fig 7. Installed capacities RE generation (left) and storage capacities (right) for the SAARC sub-regions for region-wide scenario.

https://doi.org/10.1371/journal.pone.0180611.g007

scenario, sub-regions act as net exporters and importers of electricity. Fig 6 points out the net exporters and importers of electricity in an area-wide and integrated scenario. The differences observed between the demand and generation are mainly due to import and export and also due to losses related to storage. The net exporter regions for SAARC are: Afghanistan, Sri Lanka, India North and India Northeast due to excess of very good RE resources. The net importer regions are: Pakistan North, India Northwest, Bangladesh and India South. Due to a high electricity demand for additional desalination and SNG production, the integrated scenario tends to increase the electricity generation between the regions to fulfil the increased demand. The hourly resolved profiles for Afghanistan, Pakistan North and Sri Lanka are presented in Figures C, D and E of S2 File. The import/export shares in all regions and scenarios are summarized in Table L of S1 File.

The grid utilization profile for the SAARC region can be found in Figure H of S2 File. Electricity trade increases during the night and morning hours almost throughout the year and more so in the monsoon period. This can be explained by the high share of solar PV generation in the region, where electricity is imported by the sub-regions with high inflexible generation. In the monsoon period, due to less solar PV electricity generation, more trading of wind energy takes place within the sub-regions. The capacity of the power lines and grid utilization between the sub-regions for the area-wide open trade scenario is shown in Figure H of S2 File and Table O of S1 File.

The installed capacities for RE generation and storage technologies for all sub-regions in region-wide, area-wide and integrated scenarios are shown in Figs 7, 8 and 9 respectively. The installed solar PV capacities exceed 50% of the total RE installed capacities in the Western and Southern part of India despite full load hours (FLH) of wind being comparable or exceeding FLH of solar PV. It is observed in the sub-regions that have excellent wind conditions, low cost wind energy is the next preferred technology after solar PV, which is lowest in cost. In Sri Lanka and Afghanistan, installed capacities of wind energy are 71% and 65% of the total RE installed capacity in the area-wide scenario, as these countries have among the best wind



Regions electricity capacities

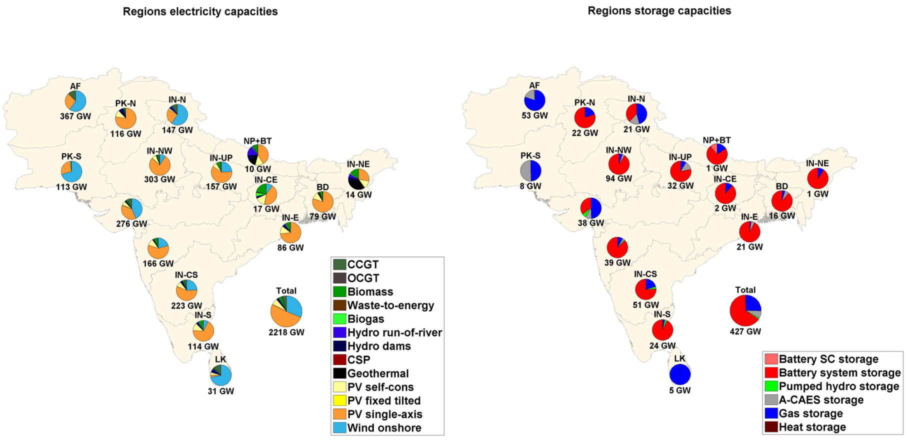
Regions storage capacities

Fig 8. Installed capacities RE generation (left) and storage capacities (right) for the SAARC sub-regions for area-wide scenario.

https://doi.org/10.1371/journal.pone.0180611.g008

resources in the region and export of wind energy takes place from Sri Lanka to high demand centres in Southern India.

The total storage capacity required is greatly influenced by the connection of the sub-regions via HVDC transmission lines, and RE generation and demand in a particular sub-region. Also, the mix of storage technologies for a particular sub-region depends on the above mentioned factors. The throughput of A-CAES, and gas storage technologies decreases by



Regions electricity capacities

Regions storage capacities

Fig 9. Installed capacities RE generation (left) and storage capacities (right) for the SAARC sub-regions for integrated scenario.

https://doi.org/10.1371/journal.pone.0180611.g009

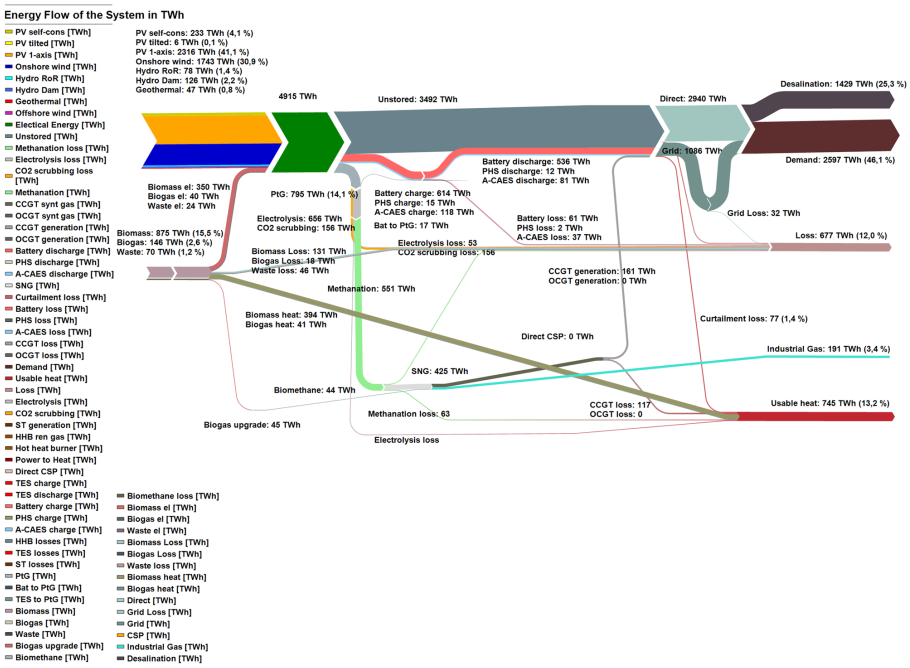


Fig 10. Energy flow of the system in the integrated scenario for the year 2030.

https://doi.org/10.1371/journal.pone.0180611.g010

99.8% and 30.5% respectively, from the region-wide to the area-wide scenario. The discharge capacities, annual throughput of storage technologies and full load cycles per year are provided in Table N of S1 File. State of charge profile diagrams for the area-wide scenario for battery, PHS, A-CAES and gas storage are given in Figure G of S2 File. PV self-consumption does not influence the system in a big way in the SAARC region due to low electricity prices. PV self-generation covers 38.8%, 36.8% and 37.3% of residential, commercial and industrial prosumer demand, respectively. An overview of PV self-consumption is provided in Table M of S1 File.

4.3 Energy flow for the optimised power systems for SAARC

The energy flow of the system from generation to demand for the integrated scenario is presented in Fig 10. The energy flow diagram is made up of RE resources, storage technologies for the generated energy and the transmission of this energy via HVDC grids. The end use of electricity for the integrated scenario consists of electricity, desalination and industrial gas demand. The potentially usable heat generated and the losses incurred are comprised of curtailed electricity, heat produced by biomass, biogas and waste-to-energy power plants, heat generated from electrolysers for transforming power-to-hydrogen, in the methanation process transforming hydrogen-to-methane, and methane-to-power in gas turbines. Efficiency losses incurred in A-CAES, PHS, battery storage and HVDC transmission grid losses form part of the overall losses. The energy flow diagrams for the region-wide and area-wide scenario are presented in Figures I and J of S2 File.

4.4 Effect of monsoon on the energy system

Interesting observations were made in the simulations regarding the effect of monsoon on the energy system. Monsoon in India normally starts from June and lasts till September and the starting period depends on a particular region. In India solar is a constant resource for energy. However, in the period of monsoon, there is reduced solar activity due to cloudy and rainy days. But in the monsoon period it was observed that there is a substantial increase in wind resources as shown in Fig 4. For the Western region of India a particular week in the summer months and in the monsoon period shows the flexible operation mode of the RE system, as depicted in Figures A and B of S2 File. In the period of low solar radiation, wind and to some extent hydro balance the system to provide electricity and to keep the energy system running without power failure.

5. Discussion

The installation of HVDC transmission grid between the sub-regions enables significant decrease in the cost of electricity and in installed capacities of RE technologies in a 100% RE based system. The benefit due to grid integration varies for different regions of the world [41, 68]. For the SAARC region, benefit due to grid integration seems to be marginal as local storage options seem to be more cost effective than transmission of the electricity. The regional interconnection helps to decrease the cost of storage technologies needed but in a region where there is a high influence of solar power in the system and almost stable solar conditions all around year, batteries are required to store this energy to help balance the night time demand. The solar PV-battery system is a cheaper option than importing electricity via grids.

The total levelised cost of electricity in the SAARC region decreased from 71.6 €/MWh for the region-wide open trade scenario to 69.6 €/MWh for the country-wide open trade scenario and 67.2 €/MWh for the area-wide open trade scenario. The total annualized cost of the system decreased from 187 b€ to 174 b€ from the region-wide to area-wide scenario. The capital expenditure for the system decreased from 1539 b€ to 1421 b€ from the region-wide to the area-wide open trade scenario, respectively. For the country-wide and the area-wide open trade scenario, the cost incurred from installations of HVDC transmission lines is compensated by a decrease in installed capacities of electricity generation sources and storage capacities, which enable lower efficiency losses and import of low cost electricity from other regions. The installation of HVDC lines may not cover the non-electrified people in the rural areas of the SAARC region, which in fact is home to the largest non-electrified population in the world. The best way to bring electricity to these people is to install RE-based mini-grids and solar home systems depending on the population density. Also, grid extension can be a solution for the people living near the grid [69, 70].

PV technologies play a vital role in the SAARC region as it has the highest share of the installed capacities for a 100% RE energy system. The installation of distributed, small-scale PV and more centralized, utility-scale PV has already achieved grid-parity and respective profitability in most parts of the world [57, 71].

The storage requirements for the SAARC region are mainly based on batteries due a high influence of solar PV on the system. The batteries provide 74%–91% of the total stored electricity. The other storage technology which plays a big role in the region-wide scenario is the A-CAES storage which acts as a mid-term storage for storing wind energy and discharging at times of low solar radiation [72]. The impact of A-CAES on the system decreases as the level of grid integration increases due to transferring of electricity via grids over a larger area being more economical than mid-term storage.

The integrated scenario presents a possibility to cover the projected natural gas demand in the industrial sector (except for demand in power generation and residential use) by flexible generation of synthetic natural gas (SNG), and providing clean water in water stressed areas by SWRO desalination. Providing clean water in the SAARC region is most important in the future because lot of regions are under severe water stress. The flexibility provided by integrated scenario to the system is most useful in compensating seasonal fluctuations. The abundance of solar and wind resources in all the sub-regions of SAARC is sufficient to cover additional demand for electricity required for producing 190.7 TWh_{LHV} of SNG and 298.4 billion m^3 of renewable water. The total electricity required for gas synthesis and SWRO desalination water is 1619.3 TWh_{el} which leads to additional installations of 491 GW of PV and 449 GW of wind energy. The additional demand for gas synthesis leads to a substantial increase of electrolyser units of about 95 GW (+83%) compared to the area-wide scenario. The cost of desalinated water obtained is 1.2 €/m^3 and the cost of SNG is 141.8 €/MWh.

The different processes used for converting RE sources to electricity give rise to heat as a by-product. The heat generated from biogas and biomass CHP plants, waste-to-energy incinerators, gas turbines, electrolysers and methanation plants can be used for the heating demand in the industrial sector, which has not been integrated into this system. Also, curtailed electricity can be converted to heat and the excess heat can be stored in heat storage and used when required by the heat sector. The area-wide open trade scenario generates usable heat of 595 TWh_{th} per year, for the region-wide scenario it is 533 TWh_{th} per year, and for the integrated scenario it is 745 TWh_{th} per year. The higher usable heat in the integrated scenario is due to a higher curtailment of electricity and more SNG production. The heat generated as a by-product of biomass and biogas plants is evenly distributed over the year. The demand due to the cooling sector is included in the electricity demand; therefore, no additional demand for cooling is considered.

The self-consumption of the generated electricity from PV plays a vital role in the power sector and has a noticeable impact on the system parameters. The comparison between the decentralized system and centralized system gives vital insights into the total annual costs of the system. The total annualized cost for a more centralized 100% RE system is 1.1%, 1.2% and 3.1% lower than decentralized system for region-wide, country-wide and area-wide scenarios, respectively. However, potential positive effects at the distribution grid level and a lower risk level of power cuts has been not taken into account in the modelling. The target function used for prosumers is different than for a centralized generation, and this gives an additional costs to the system. Prosumers tend to reach minimum annual cost of electricity consumption. To get the most out of PV self-consumption, its LCOE must be lower than the grid electricity purchase price but it can be higher than the total system LCOE. In addition to prosumers' higher electricity generation cost, there is a tendency to increase the cost of the system by installing more flexible options like low cost RE or more storage capacities, which induce a disturbance in the system demand profile. However, the peak demand of the entire system is reduced marginally (Fig 4), particularly the noon time demand is reduced by PV prosumers. PV self-consumption can be particularly valuable in area constrained regions of SAARC, since rooftop area can be utilized for local electricity generation, which in turn reduces losses incurred due to electricity transmission.

There has been no study performed for a 100% RE scenario for the SAARC region so far, connecting the various countries for future electricity trading. Apart from India there are no studies on high shares of renewables for the future for other countries in the SAARC region. However, future scenarios for India seem to be lacking in some aspects. According to Teske et al., [23, 39, 40], renewables would contribute 56–69% and 92–93% for 2030 and 2050, respectively, to the total electricity generated. The installed capacities of the renewables will reach 548–770 GW and 1356–2240 GW by 2030 and 2050, respectively. According to our results, for a 100% RE based system for 2030 the total installed capacity is 1105 GW, of which solar PV contributes 756 GW and onshore wind contributes 204 GW. Abhyankar and Phadke [37] simulated various scenarios for an hourly grid dispatch model for the year 2047. In the minimum emissions scenario, solar will have the highest installed capacity with 930 GW and wind with 472 GW. The results from our simulation for 2030 also emphasize solar playing a major part in the electricity generation mix followed by wind. The excellent solar conditions and rapid cost reduction of solar systems would play a vital role in the future.

In a 100% RE scenario simulated by TERI and WWF-India [9] for the year 2051, the total installed capacity of renewables would be 2870 GW, of which solar PV would contribute 1200 GW, offshore wind 1113 GW and onshore wind 117 GW. According to our results, solar PV contributes much more than wind energy due to excellent solar conditions in India. Wind will play a vital role in periods of monsoon when there is low solar radiation. In the simulation for this research, offshore wind was not included in the study. For the state of Kerala in India, WWF-India and WISE [36], have done a study on a 100% RE scenario for the year 2050. The results from the study indicate an energy system in which PV contributes 51% and wind contributes to 24% to the total electricity generation mix. The results are in accordance with the results of this study for solar PV, which contributes more than 50%. However, the influence of wind on the system is less.

The Powergrid Corporation of India [38], conducted a study of powering the entire country's electricity demand through the deserts situated in the Western and Northern part of India. All the regions would be connected via HVDC transmission lines. It was assumed, that even in 2050, coal will play a major part (50%) in the generation mix. This is in contradiction with the results obtained from our study, which indicates that a 100% RE based system is possible in 2030. In addition, it is in strong contradiction to the COP21 agreement for a net zero carbon emission target in the world by the middle of the 21st century [22].

The IEA recently published its 'India Energy Outlook 2015' [11], which projects installed capacity of 182–221 GW of solar PV and 134–160 GW for other renewables in India for the year 2040, which is in drastic contrast to the findings of this study. The cost assumptions used in the IEA study for India seem to be questionable. The PV LCOE is assumed to be 82 USD/MWh (61.5 €/MWh at 1.33 USD/€), which seems to be too high for the year 2040. For European solar PV power plants, capital expenditures of 850 €/kWp have already been achieved in 2015 and are expected to further decrease to 470 €/kWp in 2030 [71]. According to KPMG [73], the installed capacity for PV will be 166 GW in 2024/25, compared to 2033/34 as predicted by IEA. KMPG assumes 550–670 USD/kWp capex for utility-scale PV plants for the year 2025, which is even lower than assumed in this study. The IEA [11] report does not reflect the already achieved cost reductions of solar PV nor the future cost reduction potential, which is in drastic contrast to the more market related reports [71, 73]. Moreover, the IEA report is also in drastic violation to the set renewables and in particular solar energy targets of the Government of India [31, 74].

The year on year variation in the renewable energy resources is less as compared to daily or monthly variation. Using a different year for solar PV and wind time series would not affect the installed capacities dramatically. As the energy system in the SAARC region is dependent on solar PV, variation in solar radiation is negligible in different years. Also, forecasting errors to the reality are very low. The forecasting errors on a 24 hour time scale are shifting of resource than the amount of resource. These resource fluctuations can be handled by the flexibility options used in the modelling.

There are some limitations of the approach which is used in this study. The use of overnight approach for simulation rather it being a transition. In the real world conditions, a transition of an energy system to a fully sustainable is a better representative. The applied resource limits are dependent on local acceptance. However due to that we have used rather low number of maximum area usable for energy generation, such as a 4% area limit for wind energy, but this would have a rather low impact on agricultural production. The cost of land for installation of solar and wind power plants will be considered in the future, even though they form the smallest component of the total capital expenditure. According to the government of India's benchmark cost of installing solar power plants, cost of land form the smallest component of the total cost of installing a solar power plant [75]. Wind turbines can be placed well in areas of agricultural production and not dramatically affecting the harvested crops. In addition solar PV is expected to be mainly placed in zero impact areas as suggested by Denholm and Margolis [76] and Szabó et al. [77], such as rooftops, landfills, contaminated industrial and mining sites and further barren land. Power grids are only modelled for interconnecting the sub-regions, but not within the sub-regions, due to lack of respective data and existing modelling constraints.

The results obtained show a low LCOE for the year 2030 in all the scenarios considered in this study. The growth of RE policies in this region has been remarkable in recent years, particular so in India with ambitious projects from the Ministry of New and Renewable Energy [78, 79] and the formation of the International Solar Alliance at COP 21 [34]. These initiatives will support the development of a 100% RE based system for the future in this region. The obtained results from this study can be compared to recent alternatives for non-renewable low carbon technology options in Europe such as nuclear energy, natural gas and coal carbon capture and storage [80], which can partly comply with the climate change mitigation policy for a low carbon based energy system. According to Agora Energiewende [80], the LCOE of the alternatives are 112 €/MWh for a new nuclear plant (assumed for 2023 in the UK and Czech Republic), 112 €/MWh for gas CCS (assumed for 2019 in the UK, and 126 €/MWh for coal CCS (assumed for 2019 in the UK). A report by the European Commission [81], indicates that CCS technology will not be available till the year 2030, and a report by Citigroup questions whether it will ever be profitable at all [82]. The results obtained for a 100% renewable energy based system show the available least cost RE electricity generation options, which would help achieve the goal of net zero GHG emissions set at COP 21 [22]. The results of this paper indicate various scenarios where a 100% RE-based system is possible and lower in cost than the high risk options which have disadvantages related to proliferation risk, nuclear melt down, unsolved nuclear waste disposal, CO_2 emissions from power plants with CCS technology, health risk due to heavy metal emissions from coal fired power plants and diminishing fossil fuel reserves. Also, nuclear fission has limitations similar to those mentioned above. Also, the associated financial and human research and development resources spent will not solve the energy problems in the world [83]. The criteria for a low cost, fully sustainable energy system are not satisfied by the above mentioned alternative options.

6. Conclusion and policy implications

In the recent union budget of 2015–2016, India has set renewable energy targets to install 175 GW by 2022, which is comprised of 100 GW of solar, 60 GW of wind, 10 GW of biomass and 5 GW small hydro capacity [84, 85]. The rapid progress in developing renewable energy in recent years coupled with the above policy goals, demonstrate the seriousness of India's pledge towards climate change and electricity access to all in a sustainable way. According to Ernst & Young [86], India has been ranked fourth in the world in terms of renewable energy attractiveness. India has taken initiative to launch the most powerful solar alliance ever, which would provide India and the sun-belt countries with an ability to collaborate and disseminate the knowledge on solar technologies [34]. During the annual COP 21 held in Paris, critical decisions were taken and supported by India to limit global warming to below 2 degree Celsius [32]. India is one of the most vulnerable countries to the effects of climate change due to the high population, about 70% of which lives in rural areas and are heavily dependent on natural resources. Increased temperatures, erratic rainfall with droughts and floods, and rising sea levels would have a high impact on the people living in India [12, 13].

Previously, India was negative in its approach and took a corner seat in most international conferences, but in Paris the Prime Minister of India introduced the concept of climate justice and drove home the message of sustainable development [26]. The steps taken by the government of India include discouraging the use of fossil fuels by levying 5.3 €/tonne (1 INR = 0.013 €) green tax on coal, plans to control vehicular pollution, and policies on waste management [26].

The results of this research support the policy goals of the Indian Government, predicting the influence of solar on the energy system. Due to the abundant sunlight received, developing and installing solar energy would be the way forward in achieving sustainable development and energy for all. From the simulation results of this study for the year 2030, India would have 700 GW and 191 GW of installed PV and wind capacity.

To achieve the above goals in the desired timeframe, renewable energy may require financial support from the government in the form of subsidies as received by the fossil fuels [87]. But already according to KPMG [73], solar power is cheaper than imported coal and would be cheaper than domestic coal in 2019 without any subsidies. According to the Indian energy minister, a new coal-fired power plant would produce costlier power than a solar plant [28]. Solar is already a cheaper source to produce electricity than coal and it will require more political support and will of the government than financial support to get it implemented at a faster rate.

The government already has in place various incentives for large scale solar power projects, which can reduce the impact of tariff on the distribution companies. The incentives include a bundling scheme, a viability gap funding scheme and a generation based incentive scheme [88].

For the above targets to be reached, it would be supportive to accelerate local demand for renewable energy by providing preferential feed-in tariffs (FIT) and other incentives such as accelerated depreciation, tax holidays, renewable energy funds, initiatives for international partnerships/collaboration, incentives for new technologies, human resources development, zero import duty on capital equipment and raw materials, excise duty exemption, and low interest rate loans [89].

In order to achieve such a sustainable, RE-based future for the Indian economy, policy recommendations include timely availability of alternative, commercially-viable technological solutions across sectors, rapid scaling-up, together with accelerated strengthening of supporting infrastructure. It further advocates the development of appropriate skill-sets, regulatory and institutional frameworks and adequate manufacturing capacities [9].

In the SAARC region, a 100% RE-based system is achievable and the real policy option. Renewable energy sources can cover the electricity demand for 2030 in sectors such as power, SWRO desalination and synthetic natural gas demand by industry using PtG technology. The proposed energy system configuration can handle the hurdle due to the monsoon season quite effectively. The LCOE obtained was from 67.2–71.6 €/MWh depending on the geographical and sectorial integration. The obtained price range for electricity is lower than for non-renewable energy resources while matching climate change targets. The cost of land for installation of renewable energy sources is not included in this study, however as this cost forms a small component it will not substantially alter the cost of electricity. The heating demand in the industrial and residential sectors may be partly covered by the excess heat generated as a by-product of synthetic natural gas generation and conversion of curtailed electricity to heat. In all the scenarios, solar PV plays a vital role in power generation followed by wind energy in all the regions except Sri Lanka, Afghanistan and Pakistan South, where wind is the least cost energy due to very high FLH. For the scenarios, the storage requirements are mainly based on batteries, which provide 74%– 91% of the total stored electricity. The role of other storage technologies is notable, especially A-CAES, which has a vital role in the region-wide scenario as a mid-term storage between batteries and PtG, particularly in areas of high wind and high seasonal variation. The HVDC transmission grid plays a vital role in the transmission of low cost electricity from Afghanistan and India North to Pakistan North, where trading is more cost competitive than local storage technologies available and also due to high demand of electricity. As the level of grid integration increases, economic benefit due to A-CAES is reduced but other storage technologies such as batteries and PtG are still required. A slight increase of 1%–3% in the total cost of electricity because of PV self-consumption is due to the utilization of solar electricity and in particular respective batteries for self-consumption at a higher cost level. The most important advantage of PV self-consumption is the reduction of noon and afternoon peak hours in the year. In the integrated scenario, seasonal SNG storage is substituted by industrial SNG generation for the electricity sector. The system restricts synthetic natural gas production in the case of energy deficit as a major source of flexibility. A 100% renewable energy system for India and SAARC seems to be highly attractive, in particular due to the fact that it costs less than only the subsidies for a coal-based energy system.

Supporting information

S1 File. Table A: Financial assumptions for energy system components [53, 71, 90, 91, 92, 93, 94]
Table B: Efficiencies and energy to power ratio of storage technologies [90].
Table C: Efficiency assumptions for energy system components for the 2020 and 2030 reference years [63, 90].
Table D: Efficiency assumptions for HVDC transmission [55].
Table E: Regional grid electricity costs [56].
Table F: Average full load hours and LCOE for PV single-axis tracking, PV optimally tilted, CSP and wind power plants in SAARC sub-regions.
Table G: Regional biomass potentials and geothermal energy potentials.
Table H: Regional biomass costs.
Table I: Lower limits of installed capacities in the SAARC sub-regions.
Table J: Upper limits on installable capacities in SAARC sub-regions in units of GW_{th} for CSP and GW_{el} for all other technologies.
Table K: Annual industrial gas demand and water demand for year 2030 in the SAARC sub-regions.
Table L: Total LCOE components in all sub-regions of SAARC.
Table M: Prosumer electricity costs, installed capacities and electricity utilization for SAARC.
Table N: Overview on storage capacities, throughput, full cycles and utilization of A-CAES potential per year for the four scenarios.
Table O: Electricity transmission line parameters for the area-wide scenario for SAARC.
(DOCX)

S2 File. Figure A: Hourly generation profile for a representative week in a summer month for India West.
Figure B: Hourly generation profile for a representative week in a monsoon month for India West.
Figure C: Hourly generation profile for a net exporter region, Afghanistan.
Figure D: Hourly generation profile for a net importer region, Pakistan North.
Figure E: Hourly generation profile for Sri Lanka.
Figure F: Electricity generation curves for a whole year for area-wide open trade scenario for the SAARC region.
Figure G: Aggregated yearly state-of-charge for storage technologies, battery (top left), A-CAES (top right), PHS (bottom left), gas storage (bottom right).
Figure H: Profile for interregional electricity trade between regions for area-wide open trade scenario (left) and hydro dam storage (right).
Figure I: Energy flow of the system for the region-wide open trade scenario for 2030.
Figure J: Energy flow of the system for the area-wide open trade scenario for 2030.
(DOCX)

Acknowledgments

The authors would like to thank Michael Child for proofreading.

Author Contributions

Funding acquisition: Christian Breyer.

Investigation: Ashish Gulagi.

Methodology: Ashish Gulagi, Dmitrii Bogdanov, Christian Breyer.

Project administration: Christian Breyer.

Supervision: Christian Breyer.

Validation: Christian Breyer.

Visualization: Ashish Gulagi, Dmitrii Bogdanov.

Writing – original draft: Ashish Gulagi, Piyush Choudhary.

Writing – review & editing: Ashish Gulagi, Christian Breyer.

References

1. Chakrabarti S., Rathore G.S., Kumar S., Hada A.S., Bajaj R., 2013. Energy Statistics, Central Statistics Office, Ministry of Statistics and Programme Implementation, Government of India, New Delhi. http://mospi.nic.in/mospi_new/upload/Energy_Statistics_2013.pdf
2. Cochran J., Miller M., Milligan M., Ela E., Arent D., Bloom A., et. al., 2013. Market evolution: Wholesale electricity market design for 21st century power systems, Technical report for NREL, Colorado.
3. Singer S., 2010. The energy report: 100% renewable energy by 2050, report by Ecofys, Utrecht.
4. [IEA]–International Energy Agency, 2013. World Energy Outlook 2013, IEA publications, Paris.
5. Lawson, R. L., et al., 2008. A 21st century Marshall plan for energy, water and agriculture in developing countries, Policy paper, The Atlantic Council of the United States, Washington.
6. Barnaby F. and Kemp J., (eds.), 2007. Secure Energy?–Civil Nuclear Power, Security and Global Warming, Oxford Research Group, London.
7. [UN]—United Nations, Department of Economic and Social Affairs, Population Division, 2015. World Population Prospects: The 2015 Revision. New York.
8. British Petroleum, 2015. BP Statistical Review of World Energy, London.

9. TERI and WWF, 2011. The Energy Report India: 100% Renewable Energy by 2050, New Delhi. http://awsassets.wwfindia.org/downloads/the_energy_report_india.pdf.

10. Garg P., 2012. Energy Scenario and Vision 2020 in India, Journal of Sustainable Energy & Environment vol. 3, pp 7–17.

11. [IEA]–International Energy Agency, 2015. India Energy Outlook, IEA publications, Paris.

12. [WBGU]—German Advisory Council on Global Change, 2007. Climate Change as a Security Risk, Berlin, Earthscan, London www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2007/wbgu_jg2007_engl.pdf

13. [IPCC]—Intergovernmental Panel on Climate Change, 2014. Special report on Impacts, Adaption and Vulnerability. Intergovernmental panel on climate change; Geneva.

14. Enerdata, 2014. Global Energy Statistical Yearbook 2014, Grenoble. (https://yearbook.enerdata.net/)

15. Coady D., Parry I., Sears L., Shang B., 2015. How large are global energy subsidies?, International Monetary Fund, Washington.

16. Ministry of Finance, 2015. Indian Public Finance Statistics, Government of India, New Delhi (http://finmin.nic.in/reports/IPFStat201415.pdf)

17. Duguid B. (ed.), 2010. Ontario's Long-Term Energy Plan, Ontario Ministry of Energy, Toronto.

18. Epstein P. and Buonocore J., 2011. Full cost accounting for the life cycle of coal, Annals of the New York Academy of Sciences, 1219, 73–98. https://doi.org/10.1111/j.1749-6632.2010.05890.x PMID: 21332493

19. Buonocore J. J., Luckow P., Norris G., Spengler J. D., Biewald B., Fisher J., and Levy J. I., 2016. Health and climate benefits of different energy-efficiency and renewable energy choices, Nature Climate Change, 6, 100–105.

20. [IMF]–International Monetary Fund, 2014. Getting Energy Prices Right—From Principles to Practice, Washington.

21. [IEA]–International Energy Agency, 2012. World Energy Outlook 2012, IEA publications, Paris.

22. [UNFCCC]–United Nations Framework Convention on Climate Change, 2015. Adoption of the Paris Agreement—Proposal by the President, UNFCCC, Paris. http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf.

23. Teske S., Sawyer S., Schäferet. O., et al., 2015. Energy [R]evolution: A Sustainable World Energy Outlook. Technical report. Greenpeace International, Global Wind Energy Council (GWEC) and SolarPowerEurope, Amsterdam.

24. Krewitt W., Teske S., Simon S., Pregger T., Graus W., Blomen E., Schmid S., Schäfer O., 2009. Energy [R]evolution 2008-a sustainable world energy perspective. Energy Policy 37, 5764–5775.

25. Shearer C., Fofrich R., Davis S.J., 2017. Future CO2 emissions and electricity generation from proposed coal-fired power plants in India. Earth's Future, vol. 5: 408–416.

26. Ministry of Power, 2016. Press release, India to ratify COP 21 Global Climate Agreement on April 22, Government of India, New Delhi. http://pib.nic.in/newsite/PrintRelease.aspx?relid=138511

27. Buckley T., 2016. More Evidence India Is on Track to End Coal Imports, Institute for Energy Economics and Financial Analysis, Cleveland. http://ieefa.org/evidence-india-track-end-coal-imports%E2%80%A8/

28. King E., 2016. Solar is now cheaper than coal, says India energy minister, ClimateChangeNews, London, April 18. www.climatechangenews.com/2016/04/18/solar-is-now-cheaper-than-coal-says-india-energy-minister/

29. Buckley T., 2016. Cancellation of Ultra-Mega-Power Plants Underscores India's Commitment to Energy Transition, Institute for Energy Economics and Financial Analysis, Cleveland.

30. [CEA]–Central Electricity Authority, 2016. Draft National Electricity Plan, Government of India. New Delhi. www.cea.nic.in/reports/committee/nep/nep_dec.pdf

31. Buckley T. and Sharda J., 2015. India's Electricity-Sector Transformation, Institute of Energy Economics and Financial Analysis, Cleveland. http://ieefa.org/wp-content/uploads/2015/08/IEEFA-Indian-Electricity-Sector-Transformation-August-2015.pdf

32. [UNFCCC]–United Nations Framework Convention on Climate Change, 2015. India's intended nationally determined contribution: working towards climate justice, Technical report, Bonn.

33. Pratap A., Ram M., Pathanjali A. P., 2013. Powering Ahead with Renewables—Leaders and Laggards, report by Greenpeace India, Bangalore. http://www.greenpeace.org/india/Global/india/report/2013/powering-ahead-with-renewables.pdf

34. [ISA]—International Solar Alliance, 2015. Working Paper on International Solar Alliance, Ministry of New and Renewable Energy, Govt. of India, Gurgoan. http://isolaralliance.com/pdf/ISA-Working-Paper.pdf.

35. Planning Commission, 2011. Faster, Sustainable and More Inclusive Growth-An Approach to the Twelfth Five Year Plan, report by the Planning Commission, Government of India, New Delhi. http://planningcommission.gov.in/plans/planrel/12appdrft/appraoch_12plan.pdf

36. [WWF]–World Wildlife Fund—India and [WISE]–World Institute of Sustainable Energy, 2013. The Energy Report Kerela: 100% Renewable Energy by 2050, New Delhi. http://wisein.org/WISE_Projects/kerala_energy_report_3_jan.pdf

37. Abhyankar N. and Phadke A., 2015. Assessing the Technical Feasibility of Integrating Renewable Energy Targets in the India Energy Security Scenarios 2047 v2: Investment and Operational Insights from Grid Planning and Dispatch Analysis, Prepared for the NITI Aayog, Berkeley Lab, California. http://www.indiaenergy.gov.in/iess/docs/PC Model Stress Test Documentation v6.pdf

38. Powergrid Corporation of India Ltd, 2013. Desert Power India– 2050:Integrated Plan for Desert Power Development in India, report for Government of India, Gurgoan.

39. Teske S., Pratap A., Sawyer S., et. al., 2012. Energy [R]evolution: A Sustainable India Energy Outlook. Technical report. Greenpeace International, European Renewable Energy Council (EREC) and Global Wind Energy Council (GWEC), Amsterdam.

40. Teske S., Gopal V and Krishnaswamy S., 2008. Energy [R]evolution: A Sustainable India Energy Outlook. Technical report. Greenpeace International and European Renewable Energy Council (EREC), Amsterdam.

41. Bogdanov D. and Breyer Ch., 2016. North-East Asian Super Grid for 100% Renewable Energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. Energy Conversion and Management, 112, 176–190.

42. [IEA-RETD]—International Energy Agency-Renewable Energy Technology Deployment, 2014. Residential Prosumers—Drivers and Policy Options, Ecofys, Utrecht. http://iea-retd.org/wp-content/uploads/2014/06/RE-PROSUMERS_IEA-RETD_2014.pdf

43. Eid C., Guillén J. R., Marín P. F., & Hakvoort R., 2014. The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives. Energy Policy, 75, 244–254.

44. Pillai G. G., Putrus G. A., Georgitsioti T., & Pearsall N. M., 2014. Near-term economic benefits from grid-connected residential PV (photovoltaic) systems. Energy, 68, 832–843.

45. Romero S M. and Hughes W., 2015. Bringing Variable Renewable Energy up to Scale: Options for Grid Integration Using Natural Gas and Energy Storage, Technical report by Energy Sector Management Assistance Program (ESMAP) and The World Bank, Washington D.C. https://openknowledge.worldbank.org/bitstream/handle/10986/21629/ESMAP_Bringing Variable Renewable Energy Up to Scale_VRE_TR006-15.pdf

46. Papaefthymiou G., Grave K., Dragoon K., 2014. Flexibility options in electricity systems, Ecofys, Utrecht. www.ecofys.com/files/files/ecofys-eci-2014-flexibility-options-in-electricity-systems.pdf

47. IASPEI, 2015. International Association of Seismology and Physics of the Earth's Interior, The International Heat Flow Commission, Colorado, USA. IHFC database. www.heatflow.und.edu/index2.html

48. AAPG, 2015. Global Heat Flow Database. American Association of Petroleum Geologists, Tulsa, USA, www.datapages.com/gis-map-publishing-program/gis-open-files/global-framework/global-heat-flow-database

49. Chamorro C.R., García-Cuesta J.L., Mondéjar M.E., Pérez-Madrazo A., 2014. An estimation of the enhanced geothermal systems potential for the Iberian Peninsula. Renewable Energy 66, 1–14.

50. Chamorro C.R., García-Cuesta J.L., Mondéjar M.E., Pérez-Madrazo A., 2014. Enhanced geothermal systems in Europe: An estimation and comparison of the technical and sustainable potentials. Energy 65, 250–263.

51. Huenges E., 2012. Geothermal Energy Systems, Exploration, Development and Utilization, 2nd edition, Weinheim, Germany.

52. Luck M., Landis M., Gassert F., 2015. Aqueduct Water Stress Projections: Decadal projections of water supply and demand using CMIP5 GCMs, Washington DC, World Resources Institute.

53. Caldera U., Bogdanov D., Breyer Ch., 2016. Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate, Desalination, 385, 207–216.

54. [IEA]–International Energy Agency, 2013. Energy Balances of non-OECD Countries, IEA publications, Paris.

55. Dii, 2012. 2050 Desert power—perspectives on a sustainable power system for EUMENA. Dii, Munich.

56. Gerlach A., Werner Ch. and Breyer Ch., 2014. Impact of financing costs on global grid-parity dynamics till 2030. 29th EU PVSEC, Amsterdam, September 22–26.

57. Breyer Ch. and Gerlach A., 2013. Global Overview on Grid-Parity, Progress in Photovoltaics: Research and Applications 21, 121–136.

58. Nykvist B., Nilsson M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nat. Clim. Chang. 5, 329–332.

59. [IRENA]–International Renewable Energy Agency, 2015. Battery Storage for renewables: Market Status and Technology Outlook, Technical report, Bonn. www.irena.org/DocumentDownloads/Publications/IRENA_Battery_Storage_report_2015.pdf

60. Feldman D., Margolis R., Denholm P. and Stekli J. 2016. Exploring the Potential Competitiveness of Utility-Scale Photovoltaics plus Batteries with Concentrating Solar Power, 2015–2030. Technical report from NREL, Colorado. www.nrel.gov/docs/fy16osti/66592.pdf

61. [BNEF]–Bloomberg New Energy Finance, 2015. Distributed Solar and Storage—ICEF Roadmap 1.0, Report by Innovation for Cool Earth Forum and Bloomberg New Energy Finance, London.

62. Hummel P., Lesne D., Radlinger J., Golbaz C., Langan C., Takahashi K., Mulholland D., Stott A., Haire G., Mittermaier M., et al., 2017. UBS Evidence Lab Electric Car Teardown—Disruption Ahead?, UBS report, Basel.

63. Hoffmann W., 2014. Importance and evidence for cost effective electricity storage. 29th EU PVSEC, Amsterdam, September 22–26.

64. DBFZ, 2009. Regionale und globale räumliche Verteilung von Biomassepotenzialen. German Biomass Research Centre. [in German]

65. [IEA]—International Energy Agency, 2012. Technology Roadmap—Bioenergy for Heat and Power. IEA Publishing, Paris.

66. [IPCC]–Intergovernmental Panel on Climate Change, 2011. Special report on Renewable Energy sources and Climate Change mitigation. Intergovernmental Panel on Climate Change, Geneva.

67. Farfan J. and Breyer Ch., 2017. Structural Changes of the global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator, Journal of Cleaner Production, 141, 370–384.

68. Breyer Ch., Bogdanov D., Gulagi A., Aghahosseini A., Barbosa L.S.N.S, Koskinen O., Barasa M., Caldera U., Afanasyeva S., Child M., Farfan J., Vainikka P., 2017. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, Prog. Photovolt: Res. Appl., https://doi.org/10.1002/pip.2885

69. Bertheau P., Blechinger P., Cader C., Breyer Ch., 2012. Business Models for the Implementation of Renewable Energy Systems for upgrading Diesel Generators in Developing Countries for the Examples of Peru, Tanzania and Cambodia. 5th International Conference on Integration of Renewable Energy and Distributed Energy Resources (IRED), Berlin, December 4–6.

70. Breyer C., Werner C., Rolland S., Adelmann P., 2011. Off-grid photovoltaic applications in regions of low electrification: high demand, fast financial amortization and large market potential, 26th EU PVSEC, Hamburg.

71. Vartiainen E., Masson G., Breyer Ch., 2015. PV LCOE in Europe 2015–2050. 31th EU PVSEC, Hamburg, September 14–18.

72. Gulagi A., Aghahosseini A., Bogdanov D. and Breyer Ch., 2016.Comparison of the potential role of adiabatic compressed air energy storage (A-CAES) for a fully sustainable energy system in a region of significant and low seasonal variations, 10th International Renewable Energy Storage Conference, March 15–17.

73. KPMG, 2015. The Rising Sun—Disruption on the horizon, Report published in ENRich—KPMG Energy Conference, India. https://www.kpmg.com/IN/en/IssuesAndInsights/ArticlesPublications/Documents/ENRich2015.pdf

74. [JNNSM]—Jawaharlal Nehru National Solar Mission, 2015. Initiative by Gov. of India, New Delhi, http://pib.nic.in/newsite/pmreleases.aspx?mincode=28

75. [CERC]–Central Electricity Regulatory Commission, 2016. Determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects applicable during FY 2016–17, Government of India, New Delhi. www.cercind.gov.in/2016/orders/SO17.pdf

76. Denholm P., Margolis R.M., 2008. Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. Energy Policy 36, 3531–3543.

77. Szabó S., Bódis K., Kougias I., Moner-Girona M., Jäger-Waldau A., Barton G., Szabó L., 2017. A methodology for maximizing the benefits of solar landfills on closed sites. Renewable and Sustainable Energy Reviews 76, 1291–1300.

78. [JNNSM]—Jawaharlal Nehru National Solar Mission, 2011. Initiative by Gov. of India, New Delhi, http://mnre.gov.in/filemanager/UserFiles/jnnsm_gridconnected_24082011.pdf.

79. [GOI]–Government of India, 2015. Report on India's Renewable Electricity Roadmap 2030: Towards Accelerated Renewable Electricity Deployment. NITI Aayog, Govt. of India, New Delhi.

80. Agora Energiewende, 2014. Comparing the cost of low-carbon technologies: what is the cheapest option? report by Prognos AG on behalf of Agora Energiewende, Berlin. p. 10–13. www.prognos.com/fileadmin/pdf/publikationsdatenbank/140417_Prognos_Agora_Analysis_Decarbonisationtechnologies_EN.pdf

81. European Commission, 2014. Integration of renewable energy in Europe, study prepared by KEMA Consulting, DNV GL—Energy, Imperial College and NERA Economic Consulting on behalf of DG Energy, Brussels, p. 7–8 and 54.

82. Citi Research Equities, 2015. Paris Climate Change Agreement, Sydney, December 15.

83. Dittmar M., 2012. Nuclear energy: Status and future limitations, Energy, 37, 35–40.

84. [MNRE]–Ministry of New and Renewable Energy, 2014. Physical Progress (Achievements) in the renewable energy sector, Government of India, New Delhi. http://mnre.gov.in/ mission-and-vision-2/achievements/

85. [PwC]—PricewaterhouseCoopers and Mytrah, 2015. A joint report on Renewable energy's transformation of the Indian electricity landscape, New Delhi. http://www.pwc.in/assets/pdfs/publications/2015/renewable-energys-transformation.pdf

86. Ernst &Young, 2012. Renewable Energy Country Attractiveness Indices, issue 33, London. http://www.ey.com/Publication/vwLUAssets/Renewable_energy_country_attractiveness_indices_-_Issue_33/$FILE/EY_RECAI_issue_33.pdf〉.

87. Shrimali G., Srinivasan S., Goel S., Trivedi S. and Nelson D., Reaching India's Renewable Energy Targets Cost-Effectively, A joint report by Climate Policy Initiative and Indian School of Business, India. http://climatepolicyinitiative.org/wp-content/uploads/2015/04/Reaching-Indias-Renewable-Energy-Targets-Cost-Effectively.pdf

88. [MCG]–Mercom Group Capital, 2014. Jawaharlal Nehru National Solar Mission: Guidelines for Grid Connected Solar PV Projects, Bangalore. http://mercomcapital.com/assets/files/JNNSMPhaseIIBatchIFactSheet-Mercom25Feb14.pdf

89. Goswami D., 2014. Can India achieve 100% renewable energy?, Article in Energy Central, Colorado. http://www.energycentral.com/utilitybusiness/international/articles/2914/Can-India-Go-100-Renewable-by-2050-

90. Pleßmann G., Erdmann M., Hlusiak M., Breyer Ch., 2014. Global energy storage demand for a 100% renewable electricity supply. Energy Procedia 46, 22–31.

91. Komoto K., Ito M., Van der Vleuten P., Faiman D., Kurokawa K. (eds.), 2009. Energy from the desert—very large scale photovoltaic systems: socio-economic, financial, technical and environmental aspects. Earthscan, London.

92. Agora Energiewende, 2015. Current and Future Cost of Photovoltaics—Long-term Scenarios for Market Development System Prices and LCOE of Utility-Scale PV Systems. Report by Fraunhofer Institute for Solar Energy Systems on behalf of Agora Energiewende, Berlin. www.fvee.de/fileadmin/publikationen/weitere_publikationen/15_AgoraEnergiewende-ISE_Current_and_Future_Cost_of_PV.pdf

93. Urban W., Lohmann H., Girod K., 2009. Abschlussbericht für das BMBF-Verbundprojekt Biogaseinspeisung. Fraunhofer UMSICHT, Leipzig. [in German].

94. European Commission, 2014a. ETRI 2014—Energy technology reference indicator projections for 2010–2050. EC Joint Research Centre Institute for Energy and Transport, Petten, Netherlands.

Publication II

Gulagi, A., Bogdanov, D., and Breyer, C.
The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India

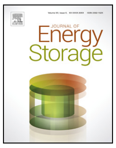
Reprinted with permission from
Journal of Energy Storage
Vol. 17, pp. 525-539, 2018

Journal of Energy Storage 17 (2018) 525–539

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est



The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India

Ashish Gulagi*, Dmitrii Bogdanov, Christian Breyer

Lappeenranta University of Technology, Skinnarilankatu 34, 53850, Lappeenranta, Finland

ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form 10 November 2017
Accepted 11 November 2017
Available online 26 November 2017

Keywords:
Energy transition
Storage technologies
India
100% renewable energy
Energy system optimization
Economics

ABSTRACT

In this work, a 100% renewable energy (RE) transition pathway based on an hourly resolved model till 2050 is simulated for India, covering demand by the power, desalination and non-energetic industrial gas sectors. Energy storage technologies: batteries, pumped hydro storage (PHS), adiabatic compressed air energy storage, thermal energy storage and power-to-gas technology are used in the modelling to provide flexibility to the system and balance demand. The optimisation for each time period (transition is modeled in 5 year steps) is carried out on an assumed costs and technological status of all energy technologies involved. Results indicate that a 100% renewable based energy system is achievable in 2050 with the levelised cost of electricity falling from a current level of 58 €/MWh$_e$ to 52 €/MWh$_e$ in 2050 in the power scenario. With large scale intermittent renewable energy sources in the system, the demand for storage technologies increases from the current level to 2050. Batteries provide 2596 TWh, PHS provides 12 TWh and gas storage provides 197 TWh of electricity to the total electricity demand. Most of the storage demand will be based on batteries, which provide as much as 42% of the total electricity demand. The synchronised discharging of batteries in the night time and charging of power-to-gas in the early summer and summer months reduces curtailment on the following day, and thus is a part of a least cost solution. The combination of solar photovoltaics (PV) and battery storage evolves as the low-cost backbone of Indian energy supply, resulting in 3.2–4.3 TWp of installed PV capacities, depending on the applied scenario in 2050. During the monsoon period, complementarity of storage technologies and the transmission grid help to achieve uninterrupted power supply. The above results clearly prove that renewable energy options are the most competitive and a least-cost solution for achieving a net zero emission energy system. This is the first study of its kind in full hourly resolution for India.

1. Introduction

In the next few decades, the role of India in transitioning to a net zero emission based energy system till 2050 as agreed in COP21 will be keenly observed by the world. In turn, its success will be a major step in restricting the global temperature rise to 2 °C. Working towards the COP21 agreement, various changes have been initiated by the government in the power generation sector, especially power generation from renewable energy sources [1]. India is endowed with an abundant renewable energy potential, especially solar, with average solar radiation varying from 1460 kWh/(m^2·a) to 2555 kWh/(m^2·a) over India [2]. The cost of power produced from solar energy dropped drastically in the last decade to 2.44 INR/kWh (0.035 €/kWh[1]) in May 2017 [3]. Realising the abundant potential of low cost solar, the government has set an ambitious target of installing 100 GW of solar by 2022 and further up to 250 GW by 2030 [4,5]. With a rapid decrease in solar cost, producing power from a new solar plant is cheaper than a new coal fired power plant [6]. The recent trends in installed capacities of solar photovoltaics (PV) validate the initiatives taken by the government to harness the massive solar potential in the country, with an installed capacity reaching 13 GW as of June 2017 [7]. Also during COP21, India launched the International Solar Alliance, which is a coalition of the countries located between the Tropic of Cancer and the Tropic of Capricorn, to help transfer and collaborate on solar energy [8].

In India, population growth, access to modern services, increasing electrification rates and a rapid growth in gross domestic product (GDP) in the last decade have driven a large increase in energy demand and put pressure on the security, reliability and affordability of energy supply, all of which are strongly linked to economic stability and development [9]. To keep

---

* Corresponding author.
E-mail address: Ashish.Gulagi@lut.fi (A. Gulagi).

[1] 1€ = 70 INR.

https://doi.org/10.1016/j.est.2017.11.012
2352-152X/

up with increasing electricity consumption, the electricity generation in India has grown at a 6% compound annual growth rate (CAGR) from 2012 to 2016 [4]. As of today, imports of oil, gas and coal form a substantial part in meeting the energy demand, and high dependence on imports of fossil fuels has created a serious threat to the energy security and environment of the country [10]. To keep up with economic development and improve the living conditions of the poor, a rapid increase in installed capacities of power generation sources would be needed without additional greenhouse gas emissions [11]. Coal has been the dominating fossil fuel in the energy mix of India [12]. Coal-fired power plants are associated with high health costs and heavy metal emissions [13–16], which are rarely taken into account in optimising the societal cost of energy supply in a region. In 2014, 240 million people in India did not have access to electricity, while 840 million people relied on wood, crop waste, dung and biomass to cook in traditional cook stoves, which are the major causes of indoor air pollution and premature deaths [12]. Climate change will affect most Indians due to flooding, change in the monsoon cycle and water scarcity [17,18]. Therefore, in the future India will hold the key to minimizing the impacts of climate change.

The government is going in the right direction to curb the effects of climate change and provide electricity for all in a sustainable way by taking initiatives in renewable power generation and particularly utilizing the abundant solar potential. According to research by KPMG [19], electricity generation from solar power will find a breakeven to the price of electricity from imported coal in 2015 and domestic coal in 2019. However, large scale deployment of renewables in the future would require various storage solutions to balance intermittency and to create a more reliable and flexible electricity distribution system. According to the IEA [20], energy storage offers the required flexibility for the energy systems of the future as they are capable of overcoming the problem of intermittent supply of the resources. For India energy storage technologies could bring reliable and uninterrupted basic energy services to remote areas [21].

The Indian storage market is gearing up with large-scale pilot projects and has the potential to become one of the largest markets for energy storage technologies [22]. Energy storage will play an important role in achieving the ambitious renewable energy targets of the government by reducing the curtailment of the intermittent renewable resources. In the financial year 2016–17, India has already started about 46 MW of large-scale energy storage projects. The years 2017–18 have already seen the introduction of 64 MWh of new Request for proposals (RFPs) and about 100 MW of projects will be announced. Also, new project tenders by SECI (Solar Energy Corporation of India) that include solar + energy storage were launched for the states of Karnataka and Andhra Pradesh. The government is planning to set up solar PV power plants with energy storage at two sites in Andaman and Nicobar Islands to replace 47 MW of diesel-run generation capacity [22].

This work on the sustainable energy transition pathways towards 2050 integrates all aspects in the required manner, including storage technologies. The methodology used in this study is more comprehensive, such as an hourly based model that guarantees that the total power supply in a year in the sub-regions covers the local demand from all sectors (which is most relevant during the monsoon season); a transmission grid connecting different regions that is able to reduce the need of energy storage and total costs; and an integrated scenario that assumes demand by the power, water desalination and non-energetic industrial gas sectors.

2. Methodology

2.1. Overview of the model

The transition of the Indian power system from 2015 to 2050 in 5-year time steps was modelled with the LUT Energy System Transition modelling tool (LUT model). Bogdanov and Breyer [23] describe the model in detail, giving equations and constraints used in the modelling. The LUT model is based on a linear optimisation with hourly resolution for an entire year of the energy system parameters under previously defined constraints, applied to the system with the assumptions for the future RE power generation and demand. The flow diagram of the main input parameters and outputs of the model can be found in Fig. 1. All the technical and financial assumptions used in the modelling of the Indian energy transition can be found in the Supplementary Material (Table 1). The main aim of the system optimisation is to minimise the total annual energy system cost, which is calculated as the sum of the

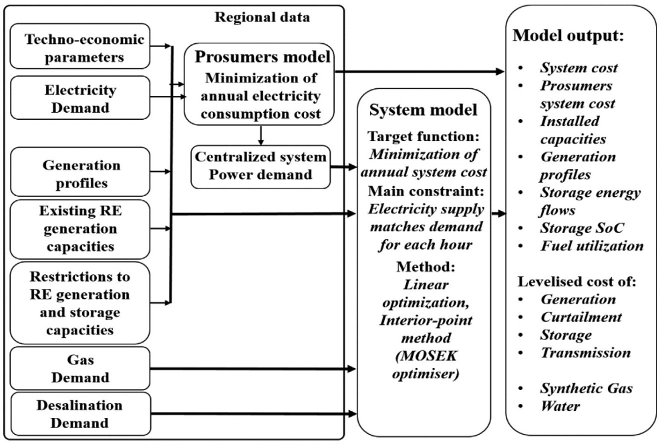


Fig. 1. The flow diagram of the LUT Energy System model from inputs parameters to outputs [24].

cost of installed capacities of the different technologies, energy generation and generation ramping. The energy system transition analysis also consists of self-generation and consumption of energy for residential, commercial and industrial consumers. A different model is used to describe PV prosumers and the development of battery capacity. The respective capacities of rooftop PV systems and Li-ion batteries can be installed by prosumers depending on the cost, and the prosumers also have an option to buy power from the grid to fulfil their demand. For prosumers, minimising the cost of consumed electricity is the target function. This cost is calculated as the sum of self-generation, annual cost and cost of electricity consumed from the grid. The excess electricity generated by prosumers is fed into the national grid and assumed to be sold for a price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before selling.

The target function described above was applied in 5-year time steps from 2015 to 2050. The two important constraints applied to the model were:

- No more than 20% growth in RE installed capacities compared to total power generation capacities could be achieved for each 5-year time step so as to avoid disruption to the power system.
- No new nuclear, coal and oil power plants could be installed after 2015, for strict sustainability reasons. However, installation of gas turbines was allowed as they are a highly efficient technology that can accommodate RE-based synthetic natural gas or bio-methane into the system [25].

The block diagram of the energy model is provided in Fig. 2.

2.2. Applied technologies

For India, technologies applied for the energy system optimization can be divided into four main categories:

- Technologies for electricity generation
- Energy storage technologies
- Energy sector bridging technologies such as gas from the Power-to-Gas (PtG) process and Seawater Reverse Osmosis (SWRO) desalination
- Electricity transmission technologies

3. Assumptions for the region of India

3.1. Subdivision of the region and grid structure

India was divided into 10 sub-regions based on the population distribution, consumption of electricity and grid structure. Fig. 3 shows the different sub-regions of India. The interconnection between the regions can also be seen in Fig. 3.

3.2. Applied scenarios

For the energy transition of India, two scenarios were studied for the energy system analysis:

- Power scenario, in which the energy systems of the regions are interconnected
- Integrated scenario, which is the power scenario plus SWRO desalination and industrial gas demand, and PtG technology is used not only as a storage option but also covers non-energetic industrial gas demand.

3.3. Financial and technical assumptions

The optimization of the model is carried out on an assumed cost basis and the state of technology from the year 2015 to 2050. The financial and technical assumptions for all the energy system components are tabulated in the Supplementary Material (Table 1). The weighted average cost of capital (WACC) is set to 7% for all scenarios, but is set to 4% for residential PV prosumers due to lower financial return requirements. Electricity prices (2015) for residential, commercial and industrial consumers for all the countries are taken from various state tariff annual reports. The electricity prices till 2050 were calculated according to the assumptions from Gerlach et al. [26] and Breyer and Gerlach [27]. The electricity prices for all the sub-regions in India are provided in the Supplementary Material (Table 3).

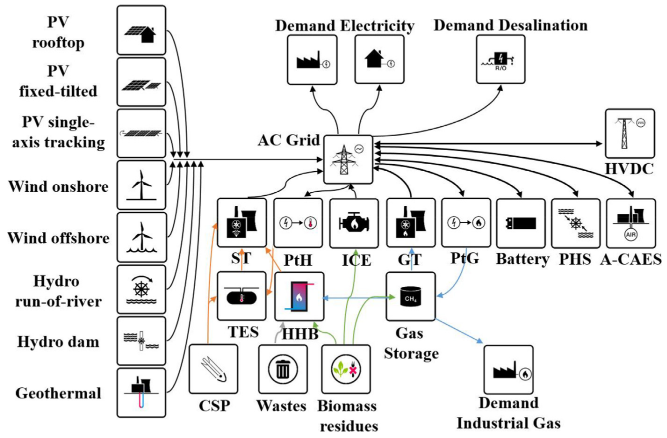


Fig. 2. Block diagram of the LUT Energy System Transition model [24]. This is made up of major renewable energy sources, transmission options, various storage technologies and various demands.

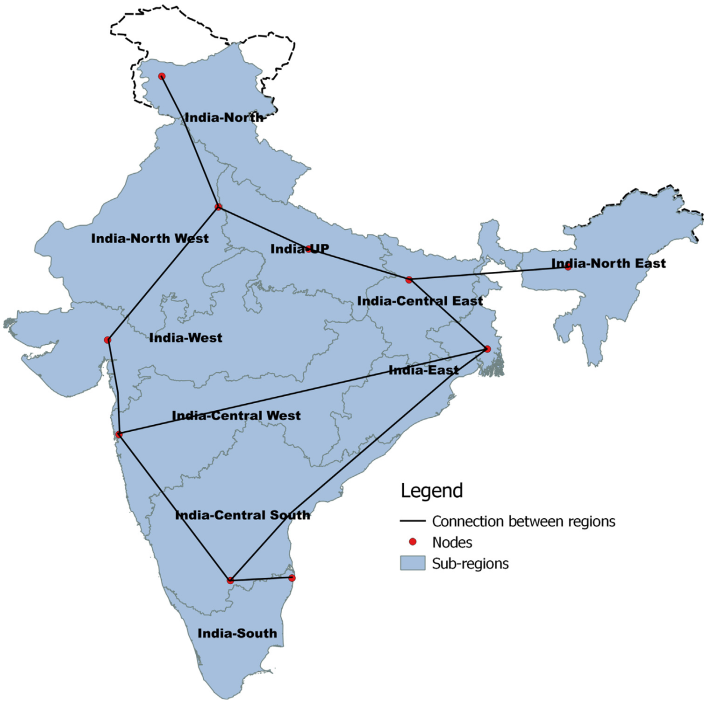


Fig. 3. The different sub-regions of India and the grid configuration.

3.4. Resource potential for renewable technologies

The generation profiles for single-axis tracking, optimally tilted PV, solar CSP and wind energy were calculated according to Bogdanov and Breyer [23]. For hydro power, feed-in profiles for all the regions were calculated based on the monthly resolved precipitation data for the year 2005 as a normalized sum of precipitation in the regions. The potentials for biomass and waste for India are taken from [28] and divided into three categories: solid wastes, solid residues and biogas. The cost calculations for all the biomass categories described above were performed using data from the International Energy Agency [29] and Intergovernmental Panel on Climate Change [30]. For solid fuels a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for

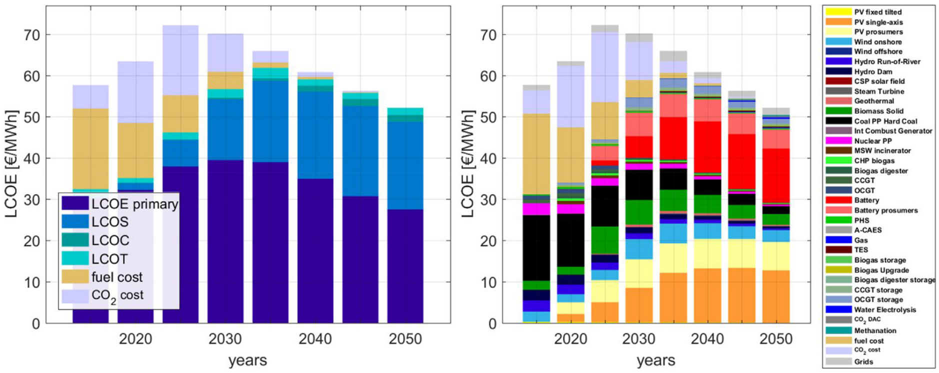


Fig. 4. Contribution of levelized cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost and carbon emission cost to total LCOE (left), and contribution of all technologies to LCOE (right) from 2015 to 2050 for the power scenario.

waste incineration plants, and this is reflected in the negative cost for solid waste. The method for calculating geothermal energy potential in the sub-regions can be found in Gulagi et al. [31]. For seawater desalination, detailed calculations for the technical constraints and financial cost of seawater reverse osmosis (SWRO) desalination are described in Caldera et al. [32]. The non-energetic industrial gas demand data are taken from IEA statistics [33] and extrapolated till the year 2050 from IEA assumptions of non-energetic industrial gas demand growth rate [12]. The electricity demand is taken from the Power System Operation Corporation Limited, National Load Dispatch Center [34] and extrapolated till 2050 from IEA assumptions [12]. The electricity demand till 2050 is given in the Supplementary Material (Table 3). The lower and upper limits of renewables and fossil fuels are given in the Supplementary Material (Tables 6 and 7, respectively).

4. Results

4.1. Levelized cost of electricity

The levelized cost of electricity (LCOE) for the power scenario (Fig. 4) in 2050 is 42 €/MWh, which is 26% lower than the current (2015) LCOE. As seen from Fig. 4, LCOE in 2050 is made up of the costs of primary generation and storage technologies and the minor costs of curtailment and transmission. By comparison, in the current fossil based system more than 50% of the cost is due to fuel and CO_2 emission cost. The LCOE shows first an increasing trend till 2025 and then decreasing trend from 2025 to 2050. The same is observed for the integrated scenario (Fig. 5). This is due to the higher cost of coal based generation and its associated fuel and CO_2 emission costs from 2015 to 2025 being replaced by lower cost solar and wind based generation from 2030 – 2050. The increase in LCOE till 2025 is due to the high fuel and CO_2 emission costs related to coal usage as the share of coal in the system in 2025 is 40%. As the demand is rising and the system has to satisfy this demand, till 2025 coal based generation is the cheapest option and renewables plus storage technologies are not cost competitive against fossil fuels. However, the decrease in LCOE after 2025 is due to an increase in the share of renewables, especially solar PV and batteries, which are now more cost competitive compared to coal based generation and further decrease the associated costs of CO_2 emissions and fuel costs of fossil based generation. The integrated scenario shows a decrease of 12% in the total LCOE for the year 2050 in comparison to the power scenario due to the decrease in the costs of curtailment and storage. The integrated scenario provides the system with the required flexibility due to the bridging technologies of non-energetic industrial gas and desalination demand. The fuel costs for all the fossil fuel technologies are shown in the Supplementary Material (Fig. 5).

4.2. Installed capacities and electricity generation

The cost optimal installed capacities of the different power plant technologies are shown in Fig. 6 and Fig. 8 and for electricity generation from these technologies shown in Fig. 7 and Fig. 9 for the energy transition period for the power scenario and for integrated scenario respectively. The absolute numbers of installed capacities can be found in the Supplementary Material (Table 4). For the year 2015, fossil fuels dominate the installed capacities, with coal contributing about 69% to the total installed capacities. However, after 2015 the renewables, particularly solar PV, start to dominate the installed capacities to overcome the deficit created by the phasing out of fossil fuel plants, particularly coal. For the year 2050, PV single-axis contributes 59% and prosumers contribute 29% to the total installed capacity in the power scenario.

As the prices of solar PV and batteries decrease in the transition years, electricity generation (Figs. 7 and 9) is more competitive than from coal fired power plants, which also have additional CO_2 emission costs associated with every kWh of power generated. For both the scenarios (Figs. 7 and 9), electricity generation from wind remains constant from the year 2035, as wind energy is important in the monsoon season when solar PV output is low.

The role of storage technologies increases with the rising share of renewable energy in the system. From Fig. 6 for the power scenario and Fig. 8 for the integrated scenario, installed storage capacities are dominated by gas storage for the years 2045 and 2050, when the share of renewables crosses 80%. Till the year 2020, already installed PHS is the most cost effective storage and balances the demand for the system (Figs. 7 and 9). By 2025, prosumer and system batteries have an effect due to the increasing influence of solar PV on the system. These batteries provide the system with the required flexibility and a more cost effective option than utilizing the thermal power plants. In the year 2025, the solar PV generation share is 55% of the total electricity generated, and this is the time when battery storage comes into the system for the power scenario (Fig. 7). The increase in share of electricity generated from solar PV (Figs. 7 and 9) corresponds to the increase in the share of batteries, as hybrid solar PV-battery

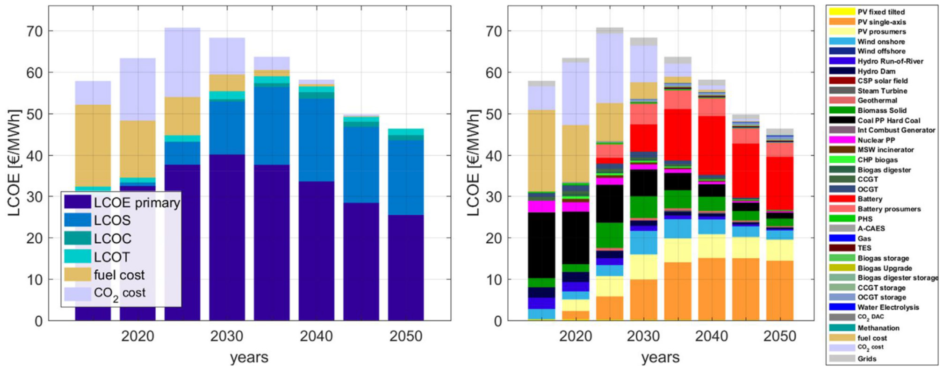


Fig. 5. Contribution of levelized cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost and carbon emission cost to total LCOE (left), and contribution of all technologies to LCOE (right) from 2015 to 2050 for integrated scenario.

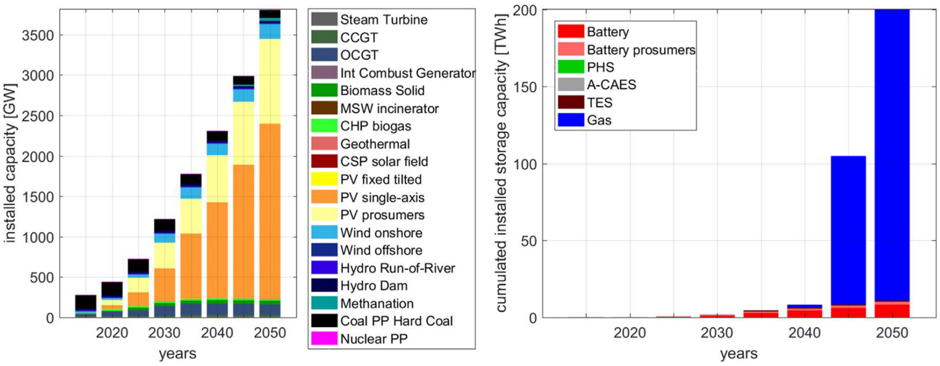


Fig. 6. Cumulative installed capacity for all generation (left) and storage (right) technologies from 2015 to 2050 (right) for the power scenario.

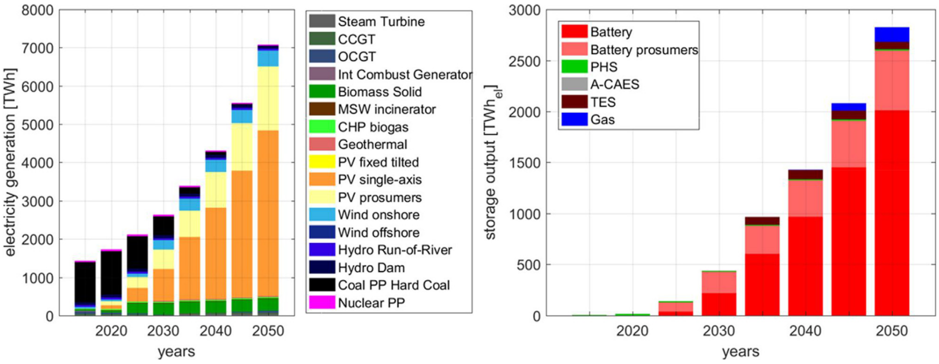


Fig. 7. Total annual generation (left) and storage output (right) of all technologies from 2015 to 2050 (right) for the power scenario.

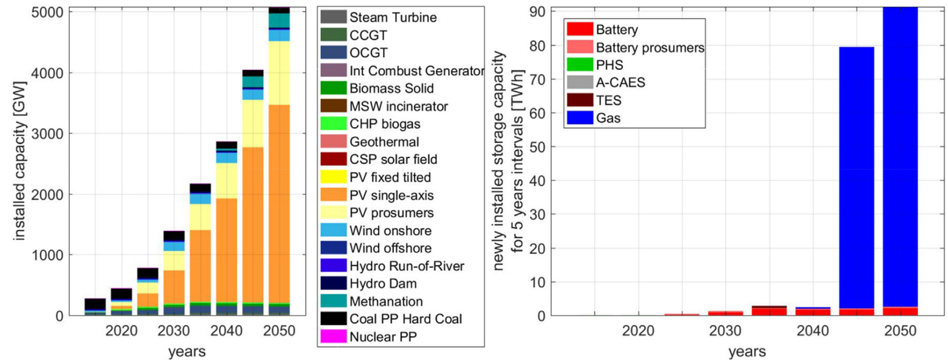


Fig. 8. Cumulative installed capacity for all generation (left) and storage (right) technologies from 2015 to 2050 (right) for the integrated scenario.

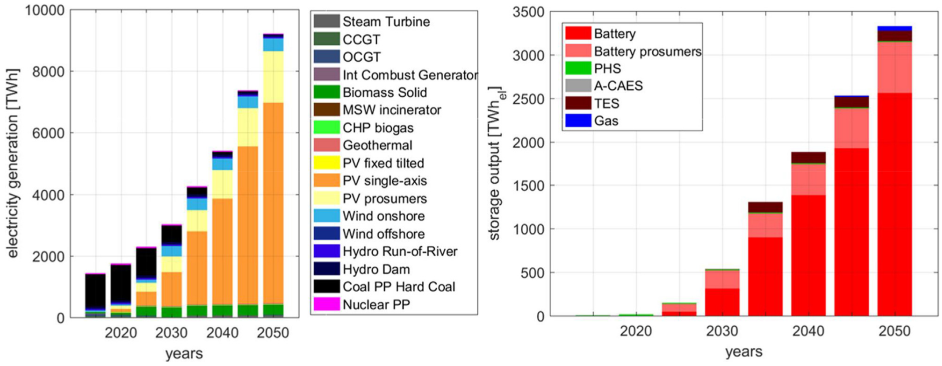


Fig. 9. Total annual generation (left) and storage output (right) of all technologies from 2015 to 2050 (right) for the integrated scenario.

Table 1
Installed capacities and throughput of storage technologies from 2015 to 2050–power scenario.

	Storage Capacities					Throughput of storage				
	Gas	Battery total	TES	PHS	A-CAES	Gas	Battery total	TES	PHS	A-CAES
	[GWh$_{th}$]	[GWh$_e$]	[GWh$_e$]	[GWh$_e$]	[GWh$_e$]	[TWh$_{th}$]	[TWh$_e$]	[TWh$_e$]	[TWh$_e$]	[TWh$_e$]
2015	5.2	0.0	3.4	23.7	0.0	0.0	0.0	0.6	4.2	0.0
2020	151.3	0.0	3.4	44.0	0.0	38.4	0.0	0.9	14.6	0.0
2025	416.6	407.7	3.5	44.0	0.1	39.9	127.9	0.7	11.0	0.0
2030	1613.3	1376.2	6.3	44.0	0.1	39.9	427.6	1.3	8.4	0.0
2035	7069.7	2817.2	416.8	44.0	0.2	39.9	878.6	77.8	9.6	0.0
2040	16310.8	4350.9	525.2	44.0	0.2	45.6	1323.8	91.9	9.1	0.0
2045	66187.3	6153.5	521.9	44.0	0.3	118.2	1908.4	87.3	12.6	0.0
2050	131694.1	8258.8	521.9	44.0	0.3	196.7	2596.0	73.2	12.5	0.0

systems evolve as the least cost combination to provide electricity in India [35]. Batteries help electricity generated by solar PV to be used in the night time. The batteries provide a total output of 2596 TWh and 3145 TWh in the year 2050 for the power and integrated scenarios, respectively. Tables 1 and 2 give the respective installed capacities and electricity generation from all the storage technologies utilized in the modelling for the transition years for the power and the integrated scenario, respectively. The increase observed in the installed capacities of gas storage for the integrated scenario is due to non-energetic industrial SNG demand. However, storage output from gas rather decreases in the integrated scenario, as now SNG is used for non-energetic industrial demand rather than for electricity generation. As a consequence, throughput of batteries is increased in the integrated scenario to overcome the gap created by gas output for electricity generation.

The additional demand created in the integrated scenario by non-energetic industrial gas and seawater desalination is satisfied by the installation of additional solar PV plants (Fig. 8). For the year 2050, 25% more solar PV and 19% additional battery capacities are installed in the integrated scenario when compared to the power scenario. The installed capacities for coal in the year 2050 are due to technical lifetime assumptions, as these plants do not contribute to any power generation [36]. Solar PV plants develop quickly after 2025 and wind power develops gradually after 2015. Installed

Table 2
Installed capacities and throughput of storage technologies from 2015 to 2050–integrated scenario.

	Storage Capacities					Throughput of storage				
	Gas	Battery total	TES	PHS	A-CAES	Gas	Battery total	TES	PHS	A-CAES
	[GWh$_{th}$]	[GWh$_e$]	[GWh$_e$]	[GWh$_e$]	[GWh$_e$]	[TWh$_{th}$]	[TWh$_e$]	[TWh$_e$]	[TWh$_e$]	[TWh$_e$]
2015	63.7	0.0	3.5	23.7	0.5	0.0	0.0	0.6	4.2	0.0
2020	64.1	0.0	3.5	44.1	0.5	7.6	0.0	0.9	14.6	0.0
2025	66.6	433.2	3.5	44.1	0.5	7.8	136.0	0.7	10.8	0.0
2030	67.7	1655.9	24.3	44.1	0.6	0.5	521.2	5.1	9.8	0.0
2035	67.7	3767.5	675.9	44.1	0.6	0.9	1175.7	121.6	10.4	0.0
2040	1798.4	5655.8	720.5	44.1	0.6	1.0	1742.5	129.1	10.2	0.0
2045	96508.1	7646.8	717.0	44.1	0.6	18.6	2382.1	123.1	9.9	0.0
2050	189318.3	10166.4	717.0	44.1	0.6	56.4	3145.3	119.5	9.7	0.0

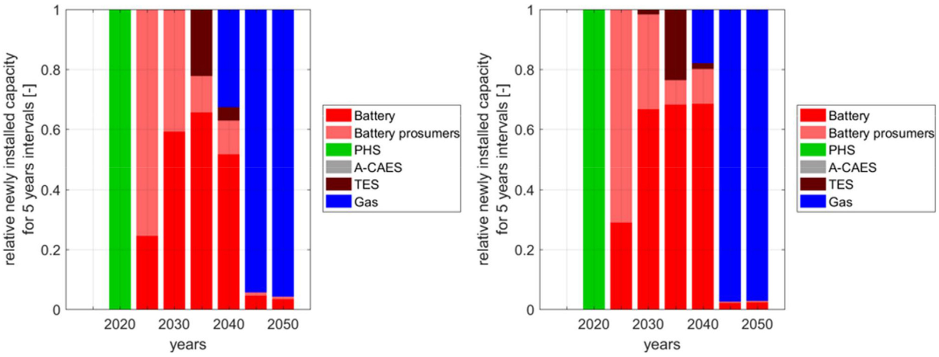


Fig. 10. Newly installed capacities in relative terms for 5-year intervals for power (left) and integrated (right) scenarios.

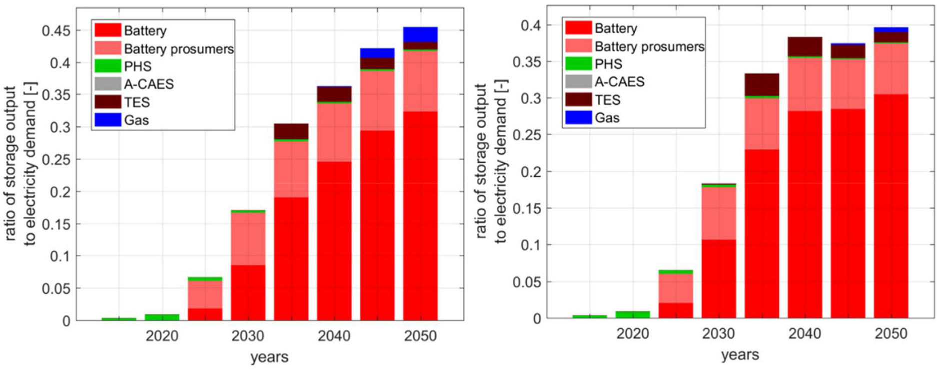


Fig. 11. Ratio of storage output to electricity demand for the power (left) and integrated (right) scenarios.

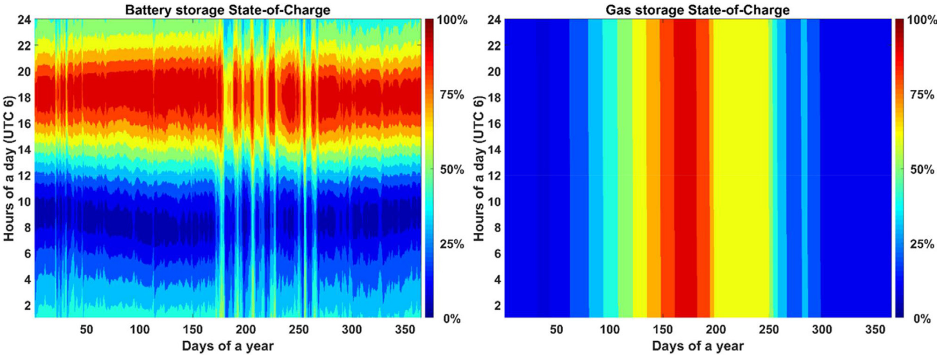


Fig. 12. Aggregated yearly state-of-charge for storage technologies for the integrated scenario in 2050, battery (left) and gas storage (right).

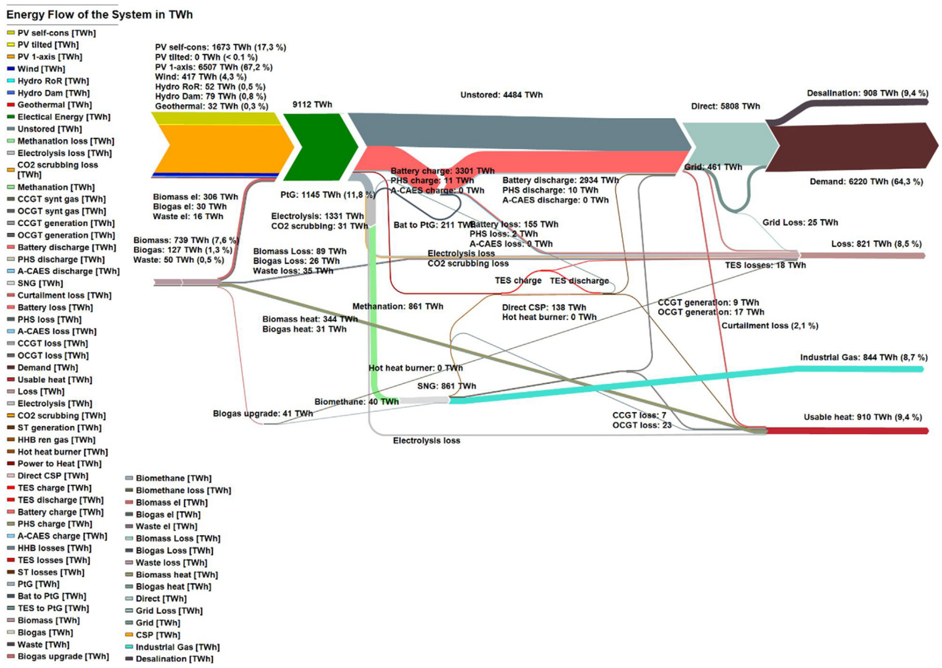


Fig. 13. Energy flow of the system in the integrated scenario for 2050.

capacities of renewables grow at a constant rate for all the years. In comparison to solar PV plants, electricity generation from wind energy does not increase significantly from 2035 to 2050 in both the scenarios. By 2050, PV single-axis contributes 6000 TWh and 8180 TWh of electricity, and PV prosumers contribute 1673 TWh of the total electricity generation in the power and integrated scenarios, respectively. The full load hours (FLh) for solar PV in the power scenario reached a peak of 2081 in the year 2025 and decreases slightly year by year till 2050. This can be explained by the higher installed capacities of solar PV after 2025, also in regions with slightly lower irradiation. PtG technology creates an additional demand of 157 $\mathrm{TWh_{el}}$ in the power scenario and 860 $\mathrm{TWh_{el}}$ in the integrated scenario in the year 2050, which is observed in increased generation capacity. The FLh for all the technologies in the power scenario can be found in the Supplementary Material (Table 5). As the share of renewables increases, curtailment increases due to the intermittency of the renewables (Supplementary Material Fig. 6).

The newly installed capacities for the storage technologies are mainly based on PHS for the year 2015, as the influence of renewables on the system is low and fossil fuels dominate the system. However, after 2020 the newly installed capacities are mainly based on prosumer batteries in 2025 and later replaced by system batteries in the next years. Gas storage is required as a seasonal storage from 2040 onwards and can be observed from Fig. 10. There are huge capacities installed in 2045 and 2050.

From Fig. 11 it can be seen that almost all of the electricity demand is satisfied by the prosumer and system batteries for the transition years for both the scenarios. The gas storage output for electricity generation contributes when the demand for seasonal storage increases and the penetration of the intermittent renewables increases. In the initial years, PHS is the least cost storage option and can manage the night time load. However, when the penetration of the intermittent renewables increase from 2025 and when batteries are cost competitive against PHS, batteries replace PHS as the main electricity storage and are used on a daily basis to satisfy the night time demand.

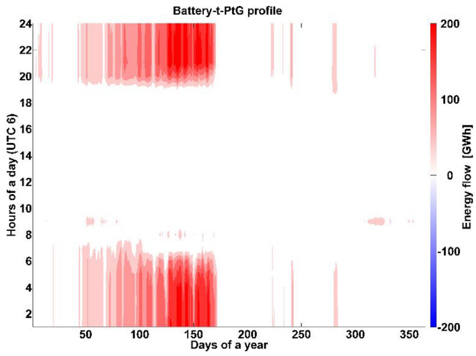


Fig. 14. Flow of energy from batteries discharging to power-to-gas for the integrated scenario in the year 2050.

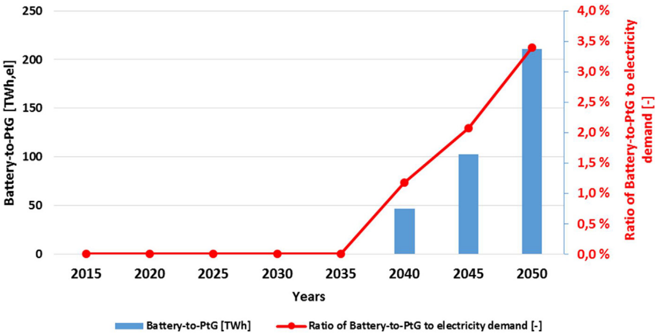


Fig. 15. The transfer of electricity from battery discharge going to the charging of gas storage and the contribution of this electricity to total electricity demand for the transition years.

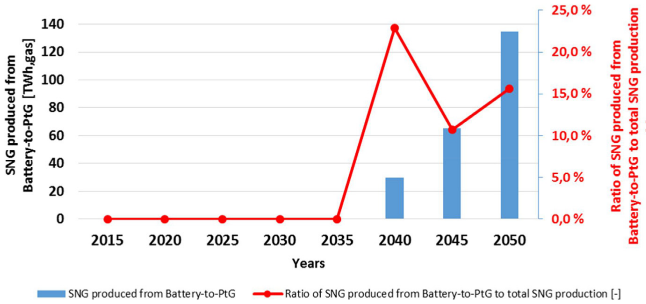


Fig. 16. SNG produced from electricity transferred from battery discharge going to gas charging of the gas storage and the contribution of the produced SNG to total SNG production.

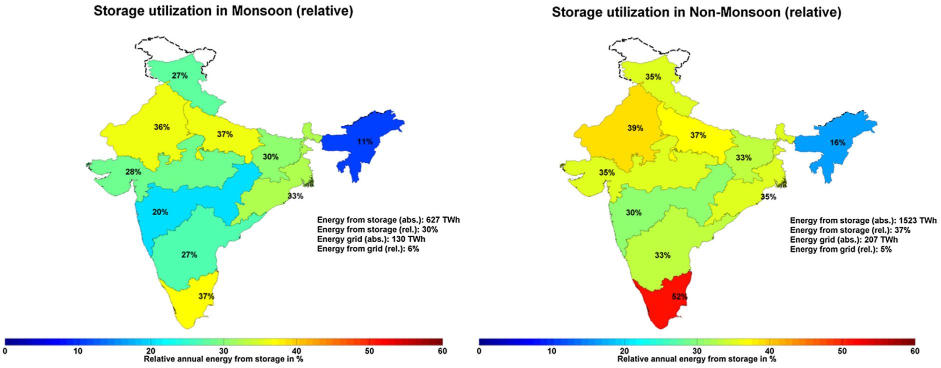


Fig. 17. Utilization of storage technologies in the monsoon (left) and non-monsoon (right) months for the power scenario in 2050 [39].

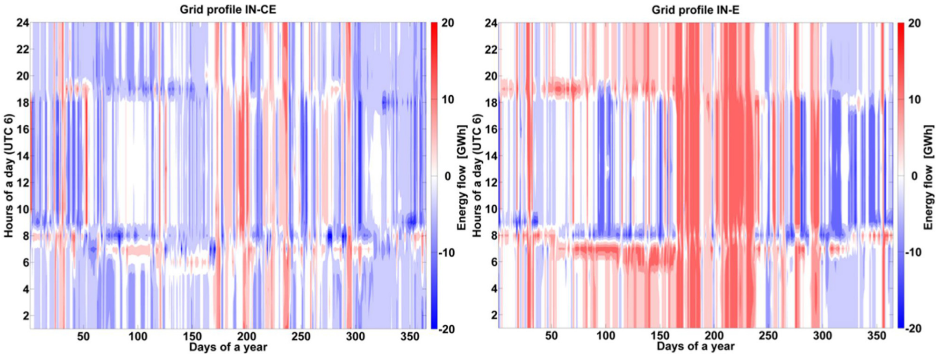


Fig. 18. Grid profile for the power scenario for year 2050 for IN-CE (left) and IN-E (right). Import (+) and Export (−).

4.3. State of charge of battery and gas storage

Solar PV and batteries will form the backbone of a fully renewable Indian power system. With the solar resource well distributed all over India for most of the days of the year, batteries are required on a daily basis to store this energy for the evening and night time demand. From Fig. 12, it can be seen that the batteries are fully charged by the end of the day on a daily basis, and start discharging to satisfy the evening, night time and early morning loads. A slight aberration can be observed in the daily cycle of charging and discharging of batteries in the monsoon months, when the solar resource in some parts of India is not the best and the batteries are not fully charged on some days. However, gas storage helps to satisfy the peak demand in the monsoon season, as it discharges from the beginning of the monsoon season and is fully discharged by the end. In the summer months, when excess solar is available in all the parts of India, gas storage is fully charged. Gas storage helps to balance the seasonal variation of monsoon. State of charge profiles for other storage technologies can be found in the Supplementary Material (Fig. 3).

4.4. Role of battery discharge for PtG for a least cost energy system

In the case of the excellent solar resource which is available from the start of March to the end of June, batteries are fully charged, and the discharge from the batteries can be used for the charging of the gas storage. This phenomenon can be seen from Fig. 13, in which an energy stream goes from battery discharge to the PtG process.

During the early summer and peak summer months, the overall electricity demand is lower than in the festival months of September and October, when the peak load for India is observed. During the summer months, as the solar resource availability is excellent in all parts of India in addition to the lower demand, a significant amount of energy is stored in batteries and gas storage. As the night time demand is lower than the energy stored in the batteries, batteries start discharging electricity to the electrolyser units to produce gas to be stored over a longer term (Fig. 14). It can be observed from Fig. 14 that the battery discharge increases in the peak summer months (darker red color). From Fig. 12, the charging of the gas storage can be seen in the summer and early summer months, becoming fully charged by the end of the summer. This effect has already been reported by Breyer et al. [37] for the case of South Korea and Japan, and by Solomon et al. [38] for the case of Israel.

The discharging from the batteries and charging of the gas storage starts from the year 2040, when the share of renewables is around 98%. This is also the period when gas storage is utilised by the system. The amount of electricity transferred from battery discharge to PtG charging is 211 TWh_{el} for the year 2050. From Fig. 15, a gradual increase in the battery discharge to PtG charging can be observed from the year 2040 onwards. Also, it can be observed that for 2050, this electricity transferred is about 3.4% of the total electricity demand for India. Since the contribution reaches a level of more than 3% of the total demand, it plays a vital role in the overall cost optimisation and in obtaining a least cost system.

The amount of SNG produced from the discharged electricity from batteries increases gradually from 2040 onwards. In the year 2050, 135.5 TWh_{th} of SNG is produced from the discharged electricity from batteries, which goes into the PtG processes. From Fig. 16, a gradual increase in SNG production is observed. However, it can be observed that the contribution of battery discharged electricity to SNG production is highest in the year 2040 and lower in the year 2045. The contribution of battery discharged electricity to SNG production is about 16% in the year 2050.

4.5. Role of storage technologies and transmission grids in the monsoon season

In the monsoon period (June-September), the total battery output is 85% of the total storage output, in comparison to 92% in the non-monsoon period. The reduced solar resource availability contributes to less energy stored in the batteries, as batteries are utilised as short-term storage, which complements perfectly with the solar availability and discharge in the night time. However, an increase of almost 10% is observed in the monsoon period in the output of stored gas to produce electricity via combined cycle gas turbines (CCGT). The CCGT plants can be ramped up to provide electricity in the night time and in periods of low solar radiation. The relative utilization of the storage technologies in the monsoon period was 30% in comparison to the non-monsoon period, when it was 37%. Fig. 17 gives the relative storage utilisation in all the sub-regions of India [39]

The transmission grids help to balance the power demand in different regions and decrease the need of storage technologies since energy shifted in time can be cost effectively substituted by energy shifted in location. The grid utilisation increases in the monsoon period in comparison to storage technologies. In the monsoon period grid utilisation was 6.2% in comparison to 4.9% in

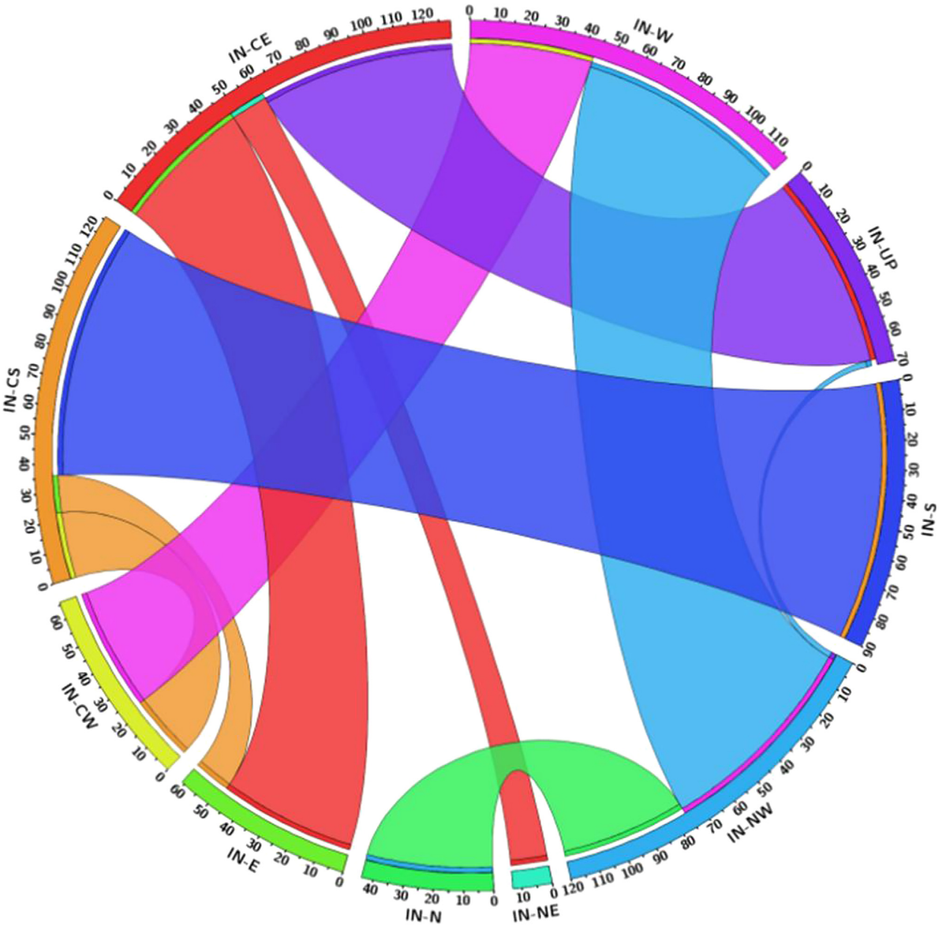


Fig. 19. Electricity exchange among the 10 Indian regions in the year 2050 for the power scenario [39].

the non-monsoon period of the respective total power demand. The Eastern (IN-E) region imports electricity mainly from the Central-East (IN-CE) region and the energy flow in the grid for the two regions is shown in Fig. 18. The positive numbers indicate import and negative export of electricity in the transmission line. In the monsoon period, export of electricity takes place for most hours in a day from the region IN-CE due to solar resource unavailability in the region IN-E, as over 90% of the power generated is by solar and this region does not have good wind resources. This exported electricity is used directly to satisfy the day time demand or stored to satisfy the night time load. During the non-monsoon months, electricity is exported during the daytime by IN-CE, and is consumed directly or stored in gas storage in the IN-E region. So, to satisfy the demand the IN-E region has to import electricity from IN-CE. This example shows how a system balances itself due to transmission grids in the monsoon months.

The net electricity exchange between the 10 regions for a fully renewable energy system in 2050 is 698 TWh (11.2% of total demand) for the power scenario. In Fig. 19, the thickness of the flow indicates the amount of electricity exchanged between the regions in TWh. The exporter region ribbons and the importing region flows have the same color. For example, the blue ribbon of India-South (IN-S), an exporting region, extends a blue flow of import to India-Central South (IN-CS), a net importing region. It can be seen that the major importing regions are IN-CW, IN-W and IN-CS and the major exporting regions are IN-S, IN-UP and IN-NW.

4.6. Annual CO_2 emissions in the transition period

The annual CO_2 emissions during the energy transition are illustrated in Fig. 20 for the power and integrated scenarios. The annual CO_2 emissions are reduced to zero by 2050. The increase in

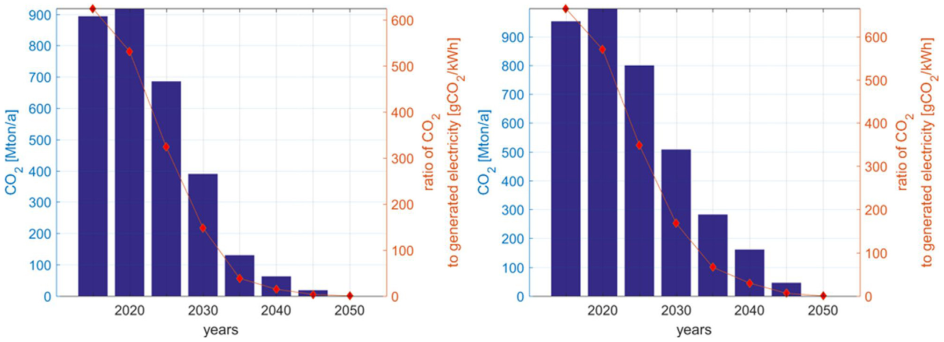


Fig. 20. Total annual CO_2 emissions and ratio of CO_2 emissions to electricity generation during the transition period for the power (left) and integrated (right) scenarios.

annual emissions in 2020 is due to an increase in the electricity generated from coal power plants to satisfy increased electricity demand as solar PV and other renewables are not yet cost competitive against the marginal cost of coal plants, and since existing capacities generate more electricity due to higher full load hours. But even more relevant is the set limit to not change the installed RE capacity share by a higher growth rate than 20% for each 5-year time step. However, a substantial decrease in emissions from 2025 is observed due to an increase in the generation share of the renewables. The red lines in Fig. 20 represent the ratio of CO_2 emitted for every kWh of electricity produced. In 2015, this value is at about 900 g of CO_2 per kWh and drops to zero by 2050. The energy system in India is completely decarbonised by 2050.

5. Discussion

A 100% renewable based energy system is technically possible and economically viable for India by 2050 with an assumptions used in this study. These results represent a first of its kind energy transition integrating the applied sectors on an hourly basis towards achieving a 100% renewable energy based system. The energy system will be mainly based on solar PV, with batteries supplying electricity in the night and early morning hours. The LCOE obtained for a fully sustainable energy system for India in the year 2050 is 52 €/MWh and 46 €/MWh for the power and integrated scenarios, respectively. The price of electricity would go down further if subsidy schemes from the government were taken into account. The main aim of this research is to show that a fully sustainable energy system is lower in cost than the current system without any subsidies.

The role of storage technologies is very important to achieve a 100% renewable energy based power system. In terms of cumulative installed capacities, gas storage dominates the power system as PtG is utilised as a seasonal storage after 2040, when the penetration level of renewables exceeds 80%. However, batteries are already utilised from 2025, when the share of renewables exceeds 50%. The above results are in agreement with others that show the utilisation of storage technologies at different renewable penetration levels [40,41]. For the year 2015 and 2020, the current installed capacity of PHS is sufficient to balance the system, which is dominated by electricity generation from coal in these years. As the influence of solar and wind increases, the relevance of storage increases, particularly batteries. After 2035, battery output contributes approximately 14% to the total electricity demand, increasing to 42% by 2050 in the power scenario. The fast decline in cost of batteries in the transition years and solar PV as a major electricity generation source mainly contribute to the utilisation of batteries. Electricity storage technologies play a key role in maintaining the balance between supply and demand. On a daily basis, batteries and PHS play a vital role in maintaining balance between supply and demand. Power-to-gas provides the system with a long-term storage option, and acts as seasonal storage. For the total electricity demand in 2050 for the power and integrated scenarios, 46% and 40% come from storage technologies, respectively.

In the monsoon period, the decrease in electricity output of batteries due to the decrease in solar resource availability is effectively managed by an increase in gas storage discharge to produce electricity and satisfy the power demand. However, utilisation of storage is not enough to overcome the monsoon obstacle, as in some regions storage of electricity is not cost competitive. In such cases transmission grids are important to transfer electricity from regions which are least affected by monsoon.

The synchronised discharging of batteries in the night time and charging of PtG in the early summer and summer months reduce the possibility of curtailment during the following day. If the batteries were not fully discharged the next day, the generated primary energy would have to be curtailed due to limited total capacities of batteries and electrolyser units of power-to-gas storage. Installation of additional battery capacity would be required to store the excess energy if the batteries were not fully discharged. The observed synchronised battery discharge to PtG charging process is thus part of a least cost solution.

In the year 2050, PV single-axis tracking power plants and PV prosumers dominate the system with 2169 GW and 1048 GW, respectively, in the power scenario, which represent 59% and 29%, respectively, of the total installed capacities. This can be attributed to the fast decline in the capex of solar PV and batteries, and excellent solar conditions all year around in all parts of India. The solar PV electricity generation share, of about 86% for 2050, is substantially higher than the world average of 40% found for a 100% RE overnight scenarios based on the year 2030 assumptions [42]. It is also higher than the obtained PV electricity share of 50% based on the same 2030 overnight scenario assumptions for the region India/SAARC [31]. Prosumers contribute significantly to the power generation and can play a significant role as they are immune to the risk of power cuts, which is a big problem in India. According to Ram et al., [43] PV prosumers in India can benefit greatly in terms of considerably reducing electricity costs annually by maximising their self-consumption. Solar PV and batteries will form the backbone of a fully sustainable electricity based system in India. The high solar PV share in the generation is possible only due to the (low-cost) support of batteries. The wind conditions in India are not the best, and this can be observed in the installed capacities of wind energy during the transition period in both scenarios (Fig. 6 and 7). However, installed wind capacities are utilized in the period of low solar radiation and monsoon, when the wind conditions are excellent in some parts of India [31]. A 100% RE-based system can be visualized for the year 2030, understanding the effects of monsoon and how the system reacts to its effect [44]. For the year 2050, wind contributes 36% to the total generated electricity.

The results obtained show a low LCOE for a fully renewable energy system for the transition till 2050 in the power and integrated scenarios. The recent growth in policies regarding renewables in India has been remarkable, with many ambitious projects and targets from the Ministry of New and Renewable Energy [45,46] and the formation of the International Solar Alliance at COP 21 [8]. These initiatives will support the development of a fully sustainable energy system for the future. The LCOE obtained from this study can be compared with the LCOE of the alternatives of clean energy such as a new nuclear plant (assumed for 2023 in the UK and Czech Republic) and gas CCS (assumed for 2019 in the UK) with LCOE of 112 €/MWh, and 126 €/MWh for coal CCS (assumed for 2019 in the UK) [47]. Some reports [48] even indicate that CCS technology will not be available until 2030, and a report by Citigroup questions whether it will ever be profitable at all [49]. The results obtained for a 100% renewable energy based system show the available least cost RE electricity generation options, which would help achieve the goal of net zero GHG emissions set at COP 21 [50].

The results of this paper indicate scenarios where a 100% RE-based system is possible and lower in cost than the high risk options which have disadvantages related to proliferation risk, nuclear melt down, unsolved nuclear waste disposal, CO_2 emissions from power plants with CCS technology, health risks due to heavy metal emissions from coal fired power plants and diminishing fossil fuel reserves. Also, nuclear fission has limitations similar to those mentioned above. As well, the associated financial and human research and development resources spent will not solve the energy problems in the world [51]. The criteria for a low cost, fully sustainable energy system are not satisfied by the above mentioned alternative options.

6. Conclusion

A 100% RE-based system is achievable and the real policy option for India. The RE sources can cover the electricity demand in 2050 of the power, seawater desalination and synthetic natural gas sectors. The future energy system for India will be mainly based on solar PV and batteries, with other technologies complementing. The proposed energy system configuration can handle the hurdle due to the monsoon season quite effectively by utilising gas storage and transmission grids. The LCOE obtained for a fully renewable energy system for the year 2050 was 52 €/MWh for the power scenario and 46 €/MWh for the integrated scenario. The obtained price range for electricity is lower than the current system based on coal while matching climate change targets plus a huge co-benefit from reduced health cost due to eliminated toxic heavy metal emission from coal-fired power plants. The high PV share is only possible due to the (low-cost) support of batteries. The storage requirements will be mainly based on batteries from the year 2025, when the share of renewables is more than 50%, and from 2045 gas storage is utilized, when the share of renewables is more than 90%. A 100% renewable energy system for India is highly attractive, in particular due to the fact that it costs less than only the subsidies for a coal-based energy system.

Acknowledgements

The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14 and support for Finnish Solar Revolution project under the number 880/31/2016. The first author would like to thank Fortum Foundation for the valuable scholarship. The authors would like to thank Michael Child for proofreading.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.est.2017.11.012.

References

[1] T. Buckley, J. Sharda, India's Electricity-Sector Transformation, Institute of Energy Economics and Financial Analysis, Ohio, 2015. (Available online:) http://ieefa.org/wp-content/uploads/2015/08/IEEFA-Indian-Electricity-Sector-Transformation-August-2015. pdf.
[2] N.K. Sharma, P.K. Tiwari, Y.R. Sood, Solar energy in India: strategies, policies, perspectives and future potential, Renew. Sustain. Energy Rev. 16 (no. 1) (2012) 933–941.
[3] M. Patil, How India's Sunny, Solar Forecast Could Become Reality, article in IndiaSpend, Mumbai, 2017.
[4] CEA, Central Electricity Authority, Draft National Electricity Plan, Ministry of Power, Government of India, New Delhi, 2016.
[5] N. Sethi, India's Energy Mix to Have 40% Renewable Sources by 2030, article in Business standard, New Delhi, 2015.
[6] E. King, Solar Is Now Cheaper than Coal, Says India Energy Minister, ClimateChangeNews, London, 2016. (Available online:) www.climatechangenews.com/2016/04/18/solar-is-now-cheaper-than-coal-says-india-energy-minister/.
[7] CEA, Central Electricity Authority, All India Installed Capacity of Power Stations, New Delhi, 2017. (Available Online:) http://www.cea.nic.in/reports/monthly/installedcapacity/2016/installed_capacity-06. pdf.
[8] ISA, International Solar Alliance. Working Paper on International Solar Alliance, Ministry of New and Renewable Energy, Govt. of India, Gurgoan, 2015. (Available online:) http://isolaralliance.com/pdf/ISA-Working-Paper.pdf.
[9] IEA, International Energy Agency, Energy transition for industry: India and the global context, Paris (2011).
[10] TIFAC, Technology Information, Forecasting and Assessment Council, Solar PV Technology and Foresight For India, Report, New Delhi, 2015. (Available online :) http://tifac.org.in/images/publication/TIFAC%20Solar%20PV%20TF%20Report%20final%20version.pdf.
[11] S. Teske, T. Pregger, S. Simon, T. Naegler, M. O'Sullivan, et al., Energy Revolution: A Sustainable ASEAN Energy Outlook. Technical Report, Greenpeace International and European Renewable Energy Council (EREC), Amsterdam, 2013.
[12] IEA, International Energy Agency. India Energy Outlook, IEA publications, Paris, 2015.
[13] Ontario's Long-Term Energy Plan, in: B. Duguid (Ed.), Ontario Ministry of Energy, Toronto, 2010. (Available online:) www.nexteraenergycanada.com/pdf/ontario_ltep.pdf.
[14] J.J. Buonocore, P. Luckow, G. Norris, J.D. Spengler, B. Biewald, J. Fisher, J.I. Levy, Health and climate benefits of different energy-efficiency and renewable energy choices, Nat. Clim. Change 6 (2016) 100–105.
[15] P. Epstein, J. Buonocore, Full cost accounting for the life cycle of coal, 1219, Annals of the New York Academy of Sciences, 2011, pp. 73–98.
[16] IMF, How Large Are Global Energy Subsidies? IMF Working Paper, International Monetary Fund, Washington, 2015. (WP/15/105, IMF) www.imf.org.
[17] WBGU, German Advisory Council on Global Change, Climate Change as a Security Risk, Berlin, Earthscan, London, 2007. (Available online:) www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2007/wbgu_jg2007_engl.pdf.
[18] IPCC, Intergovernmental Panel on Climate Change. Special Report on Impacts, Adaption and Vulnerability, Intergovernmental panel on climate change, Geneva, 2014.
[19] KPMG, The rising sun – disruption on the horizon, Report Published in ENRich ?KPMG Energy Conference, India, 2015. (Available online:) www.kpmg.com/IN/en/IssuesAndInsights/ArticlesPublications/Documents/ENRich2015. pdf.
[20] IEA, International Energy Agency, Technology Roadmap, Energy storage, Paris, 2014.

[21] R. Pode, Solution to enhance the acceptability of solar-powered LED lighting technology, Renew. Sustain. Energy Rev. 14 (2010) 1096–1103.

[22] IESA, Indian Energy Storage Alliance, Energy Storage in India, A fast developing landscape, Pune, 2017.

[23] D. Bogdanov, C. Breyer, North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options, Energy Convers. Manage. 112 (2016) 176–190.

[24] L. Barbosa, D. Bogdanov, P. Vainikka, C. Breyer, Hydro, Wind and Solar Power as a Base for a 100% Renewable Energy Supply for South and Central America, World Climate and Energy Event, 2015, 2017. (Available online:) https://goo.gl/9DjAIZ.

[25] M. Fasihi, D. Bogdanov, C.H. Breyer, Economics of global LNG trading based on hybrid PV-Wind power plants, 31 st European Photovoltaic Solar Energy Conference, Hamburg, September 14–18, 2015. (Available at:) https://goo.gl/3kCcPQ.

[26] A. Gerlach, C. Breyer, C. Werner, Impact of financing cost on global grid-parity dynamics till 2030, 29th European Photovoltaic Solar Energy Conference, Amsteradam, 2014. (Available online:) https://goo.gl/dv75Py.

[27] C. Breyer, A. Gerlach, Global overview on grid-parity, Prog. Photovolt: Res. Appl. 21 (2013) 121–136.

[28] K. Bunzel, V. Zeller, M. Buchhorn, F. Griem, D. Thrän, Regionale Und Globale räumliche Verteilung Von Biomassepotenzialen, German Biomass Research Center, Leipzig, 2009.

[29] IEA, International Energy Agency. Technology Roadmap ?Bioenergy for Heat and Power, IEA Publishing, Paris, 2012.

[30] IPCC, Intergovernmental Panel on Climate Change. Special Report on Renewable Energy Sources and Climate Change Mitigation, Intergovernmental Panel on Climate Change, Geneva, 2011.

[31] A.D. Gulagi Bogdanov, P. Choudhary, C. Breyer, Electricity system based on 100% renewable energy for India and SAARC, PLoS ONE 12 (2017) e0180611.

[32] U. Caldera, D. Bogdanov, Ch. Breyer, Local cost of seawater RO desalination based on solar PV and wind energy: a global estimate, Desalination 385 (2016) 207–216.

[33] IEA, Energy Balances of OECD and Non-OECD Countries, International Energy Agency, Paris, 2014.

[34] POSCO, Power System Operation Corporation Limited, National Load Dispatch Center, Government of India, New Delhi, 2015. https://posoco.in/.

[35] D. Bogdanov, C. Breyer, PV generation share in the energy system and battery utilisation correlation in a net zero emission world, 6th Solar Integration Workshop, Vienna November 14–15, 2016. (Available at:) https://goo.gl/ZT1foq.

[36] J. Farfan, C. Breyer, Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator, J. Clean. Prod. 141 (2017) 370–384.

[37] C. Breyer, D. Bogdanov, K. Komoto, T. Ehara, J. Song, N. Enebish, North-East asian super grid: renewable energy mix and economics, Jpn. J. Appl. Phys. 54 (2015) (08KJ01).

[38] A.A. Solomon, D. Bodganov, Ch. Breyer, Solar Driven Net Zero Emission Electricity Supply with Negligible Carbon Cost: Israel as a Case Study for Sun Belt Countries, (2017) (submitted).

[39] A. Gulagi, M. Ram, C. Breyer, Solar-Wind complementarity with optimal storage and transmission in mitigating the monsoon effect in achieving a fully sustainable electricity system for India, 1st International Conference on Large-Scale Grid Integration of Renewable Energy in India, 6–8 September, New Delhi, 2017.

[40] D. Bogdanov, C. Breyer, The role of solar energy towards 100% renewable power supply for Israel: integrating solar PV, wind energy, CSP and storages, Proceedings of the 19th Sede Boqer Symposium on Solar Electricity Production (2015). (Available online:) https://goo.gl/6hojuf.

[41] S. Weitemeyer, D. Kleinhans, T. Vogt, C. Agert, Integration of Renewable Energy Sources in future power systems: the role of storage, Renew. Energy 75 (2015) 14–20.

[42] Ch. Breyer, D. Bogdanov, A. Gulagi, A. Aghahosseini, L.S.N.S. Barbosa, O. Koskinen, M. Barasa, U. Caldera, S. Afanasyeva, M. Child, J. Farfan, P. Vainikka, On the role of solar photovoltaics in global energy transition scenarios, Prog. Photovolt: Res. Appl. 25 (2017) 727–745.

[43] D. Ram, A. Keiner, C. Gulagi, Role of Solar PV Prosumers in Enabling the Energy Transition Towards a Fully Renewables Based Power System for India, 1st International Conference on Large-Scale Grid Integration of Renewable Energy, New Delhi, 2017. 6–8 September http://bit.ly/2xaP2Ab.

[44] Neo-Carbon Energy, Internet of Energy -Online Visualization Too, Lappeenranta University of Technology, Lappeenranta, 2016. http://neocarbonenergy.fi/internetofenergy/#.

[45] JNNSM, Jawaharlal Nehru National Solar Mission, Initiative by Gov. of India, New Delhi, 2011. (Available online:) http://mnre.gov.in/filemanager/UserFiles/jnnsm_gridconnected_24082011. pdf.

[46] GOI, Government of India, Report on India's Renewable Electricity Roadmap : Towards Accelerated Renewable Electricity Deployment Available online:, NITI Aayog, Govt. of India, New Delhi, 2015 (Report on India's Renewable Electricity Roadmap 2030: Towards Accelerated Renewable Electricity Deployment).

[47] Agora Energiewende, Comparing the Cost of Low-carbon Technologies: What Is the Cheapest Option? report by Prognos AG on behalf of Agora Energiewende, Berlin, 2014, pp. 10–13. (Available online:) www.prognos.com/fileadmin/pdf/publikationsdatenbank/140417_Prognos_Agora_Analysis_Decarbonisationtechnologies_EN.pdf.

[48] European Commission, Integration of Renewable Energy in Europe, Study Prepared by KEMA Consulting, DNV GL ?Energy, Imperial College and NERA Economic Consulting on behalf of DG Energy, Brussels, 2014 (p. 7–8 and 54).

[49] Citi Research Equities, Paris Climate Change Agreement, Citi Research Equities, Sydney, 2015.

[50] UNFCCC, United Nations Framework Convention on Climate Change, Adoption of the Paris Agreement ?Proposal by the President, UNFCCC, Paris, 2015. (Available online:) http://unfccc.int/resource/docs/2015/cop21/eng/l09. pdf.

[51] M. Dittmar, Nuclear energy: status and future limitations, Energy 37 (2012) 35–40.

Publication III

Gulagi, A., Ram, M., and Breyer, C.

Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India

Reprinted with permission from
IET Renewable Power Generation
Vol. 14(2), pp. 254-262, 2020

IET Renewable Power Generation

Research Article

Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India

ISSN 1752-1416
Received on 21st May 2019
Revised 17th October 2019
Accepted on 5th November 2019
E-First on 16th January 2020
doi: 10.1049/iet-rpg.2019.0603
www.ietdl.org

Ashish Gulagi[1] ✉, *Manish Ram*[1], *Christian Breyer*[1]

[1]*School of Energy Systems, LUT University, Yliopistonkatu 34, Lappeenranta, Finland*

✉ *E-mail: Ashish.Gulagi@lut.fi*

Abstract: Various assessments have shown abundant renewable energy (RE) potential for India, especially solar. For a fully sustainable power system, monsoon presents an obstacle with the resultant decrease in solar resource availability. In this study, India is subdivided into ten regions, and these regions are interconnected via power lines. A 100% RE transition pathway in hourly resolution, until 2050, is simulated. The results from this paper indicate that the power system can overcome the monsoon hurdle by solar–wind complementarity and grid utilisation. Wind energy output increases in regions that have the best wind conditions with 62% of the total wind energy generated in monsoon. Solar photovoltaic (PV) and grids can manage the unavailability of wind resources in some of the regions. There is a clear indication that imports increase during the monsoon period. The least affected regions such as India-Northwest (IN-NW) can transmit PV electricity to other regions via transmission grids. In the monsoon period, grid utilisation increases by 1.3% from the non-monsoon period to satisfy the respective demand. The two major exporters of electricity, IN-NW and India-South export about 43% of electricity in the monsoon period. These results indicate that no fossil-based balancing is required in the monsoon period.

1 Introduction

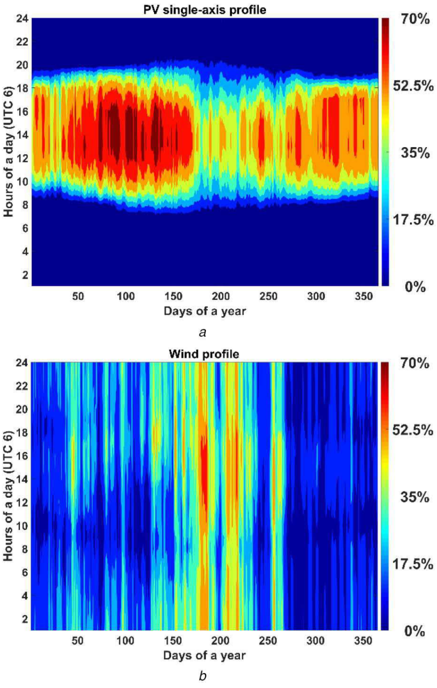
The Indian power sector is evolving rapidly to keep up with the economic growth and fast-changing socio-economic status of the country [1]. The increasing electricity consumption due to the growth in gross domestic product and government's aim to provide reliable electricity to every individual has put tremendous pressure on the power sector. Currently, electricity generation is largely based on fossil fuels, particularly coal. Consequently, increased use of coal has consequently contributed to rapid growth in greenhouse gas (GHG) emissions in the past decades [2]. The power sector in India is one of the major contributors to GHG emissions [3]. The major dilemma that India faces today is prioritising its energy goals of a low carbon economy with reduced dependence on coal and increasing renewable energy (RE) usage [2]. The power sector needs to evolve rapidly to keep up with local and global goals.

In the past few years, India has woken up to the issue of climate change and pollution and its devastating effects [4]. In its Intended Nationally Determined Contribution (INDC) commitment at COP21, India pledged to reduce GHG emissions by 33–35% until 2030 in comparison with 2005 and 40% of the country's electricity would be generated from renewables such as wind and solar [5]. Commitment to the Paris Agreement will require utilising the available RE resources to achieve the required targets. Assessments [6, 7, 8] have shown that India has abundant RE potential, especially solar. With, 250–300 clear sunny days and average solar radiation varying from 1460 to 2555 kWh/(m^2 a) across the country [9], the government has taken steps to utilise this solar potential with an installed capacity of 28 GW, until end of March 2019 and aggressive future targets [10, 11, 12]. The vast coastline of India provides perfect conditions for wind power installations, with the potential mainly concentrated in the states of Tamil Nadu, Gujarat, Karnataka, Maharashtra and Rajasthan. While the current total wind capacity is around 34 GW [10], the potential is estimated at around 2000 GW [13, 14]. Tamil Nadu is the leading state in terms of wind power installations [10].

However, the major drawback of the above technologies is that electricity can be produced only during certain intervals. For example, when the Sun is shining during the day and strong winds in the evening and night or the monsoon season for the specific case of India. Hybrid projects may reduce variability to some extent and power can be generated at night and even in the monsoon months [15]. The Ministry of New and RE has released a draft policy for hybrid solar and wind energy projects [16]. While, at a lower penetration of variable renewable resources, the variability of power generation can be effectively managed by ramping up conventional fossil fuel generators, but for a fully RE-based system having a major share of solar and wind energies, this presents a huge hindrance [17, 18, 19, 20].

On the other hand, increasing flexibility of the transmission lines [21], adding storage capacity and power-to-gas flexibility to the energy system [22, 23] and complementarity of wind and solar [22], would help mitigate the variability of solar and wind resources. Various studies have shown that a 100% RE-based system is possible for India. While The Energy and Resources Institute (TERI) [24] puts forward that such a scenario is desirable for India; however, it maintains that financial and technical policies should be in proper order to make such a scenario realistic. On the other hand, according to Röben and Köhler [25], a 100% RE scenario is feasible and more efficient than the current energy system, while Lawrenz *et al.* [26] conclude that it is technically possible to supply energy for the power, heat and transportation sector entirely by renewables. According to Gulagi *et al.* [27], a 100% RE-based system is technically and economically feasible on an hourly resolution [19, 27, 28] and also for countries in the South Asian Association for Regional Cooperation [29], with the cost structure less than the current system based on fossil fuels. According to these studies, a fully renewable electricity system for India will be based mainly on solar photovoltaic (PV) complemented by other RE technologies. However, these studies do not address in detail an important question: ‘How will a solar PV-dominated electricity system perform during the monsoon season’?

The onset of monsoon is from the southwest of India, and then it travels into the western, eastern, northeastern and northern regions. The increase in cloud cover follows this path; as a result, solar resource availability varies between the different regions based on the position of the monsoon. Strong southwesterly winds



a

b

Fig. 1 *Solar PV generation*
(a) Solar profile on an hourly basis for India, ***(b)*** Wind profile on hourly basis for India

accompany the arrival of the monsoon, giving rise to peak wind resources, particularly in the southern and western regions. On the other hand, solar resource is low during the monsoon season, due to the presence of cloudy weather [30]. The decrease in power production from solar PV in a particular region affected by the monsoon can pose considerable challenges for the stability of the power grid. To balance the monsoon effect in a 100% RE system, wind energy will play a vital role in complementing the deficit in solar PV generation (Figs. 1*a* and *b*), along with additional flexibility options provided by transmission grids, storage technologies in particular batteries and hydropower.

Not many studies have shown a fully RE-based scenario for India on an hourly resolution with storage technologies and transmission grids. Furthermore, none of them has a special focus on the energy system analysis during the monsoon season. A study by the National RE Laboratory [31] touches on the aspect of monsoon season and transmission grid utilisation, but does not dwell into the impacts in detail. Also, the study is limited to the year 2022, taking into account the government's RE targets. According to this paper, curtailment is highest in the monsoon months compared with non-monsoon months, and curtailment can be reduced in the regions generating highest RE by evacuating the power generated via additional transmission grids and integrating the different regions.

This paper is a first of its kind to analyse the effects of the monsoon season on a fully RE system. In the first step, this paper analyses the complementarity provided by wind energy to the decrease in solar PV. In the second step, we analyse the role of the transmission grid in evacuating power from different regions to the monsoon-affected regions. Thus, reducing curtailment in these regions. It is acknowledged that hydropower and storage technologies provide some level of flexibility to the system. However, these are not discussed in this paper as Gulagi *et al.* [32] describe the role of hydropower and storage technologies in the monsoon period in greater detail. Historically, India has relied on coal and hydropower for supplying electricity to most of its regions and the monsoon season had less impact on the supply side. However, a rapidly evolving power sector with increasing shares of renewables compels energy planners and other stakeholders to consider the impacts of seasonal variations such as the monsoon on power systems with high shares of renewables.

This paper is organised as follows: Section 2 provides the methodology, the input data and the technologies used for the simulations. This is followed by the assumptions and description of the power scenario used for the simulations in Section 3. All the technical and financial assumptions are provided in Section 4. Section 5 presents the results and discussion. Finally, conclusions are drawn in Section 6.

2 Methods and input data

The model with its equations and constrains used for this paper have been described in detail previously by Bogdanov *et al.* [28] and Gulagi *et al.* [19]. The following section gives a brief description of the main optimisation function and the constraints.

The model is based on linear optimisation and the main constraint is that total power generation should be equal to the total power demand in that particular hour for the selected year, whereas the main objective function is to minimise the total annual energy system costs, calculated as a sum of the costs of installed capacities, energy generation and generation ramping of the different technologies. For every 5 year intervals from 2015 to 2050, the model optimises the least-cost solution. The equations for the objective function (1) and the main constraint are given below (2):

$$\min\left(\sum_{r=1}^{\text{reg}}\sum_{t=1}^{\text{tech}}(\text{CAPEX}_t\,\text{crf}_t+\text{OPEXfix}_t)\,\text{instCap}_{t,r} + \text{OPEXvar}_t\,E_{\text{gen},t,r}+\text{rampCost}_t\,\text{totRamp}_{t,r}\right) \qquad (1)$$

CAPEX_t is the capital cost of each technology, crf_t is the capital recovery factor for each technology, OPEXfix_t is the fixed operational cost for each technology, OPEXvar_t is the variable operational cost for each technology, $\text{instCap}_\text{t,r}$ is the installed capacity in a region, $E_\text{gen,t,r}$ is the electricity generation by each technology, rampCost_t is the ramping cost of each technology and $\text{totRamp}_\text{t,r}$ is the annual total power ramping values for each technology. The target function was applied in time steps of 5 year from 2015 to 2050

$$\forall h\in[1,\ 8760]\left(\sum_{t}^{\text{tech}}E_{\text{gen},t}\right)_h+\left(\sum_{r}^{\text{reg}}E_{\text{imp},r}\right)_h+\left(\sum_{t}^{\text{stor}}E_{\text{stor, disch}}\right)_h = (E_{\text{demand}})_h+\left(\sum_{r}^{\text{reg}}E_{\text{exp},r}\right)_h+\left(\sum_{t}^{\text{stor}}E_{\text{stor, ch}}\right)_h+(E_{\text{curt}})_h \qquad (2)$$

It is defined for every hour of a year in a particular region, electricity generation from all the technologies ($E_\text{gen,t}$), imported electricity from the regions ($E_\text{imp,r}$) and electricity from storage discharge ($E_\text{stor,disch}$) should be equal to the total demand for an hour (E_demand), electricity exported to other regions ($E_\text{exp,r}$), electricity for charging storage technologies ($E_\text{stor,ch}$) and curtailed electricity (E_curt). The other abbreviations used in this equation are hours (h), technology (t), all technologies used in modelling (tech), sub-region (r) and all sub-regions (reg).

The other two important constraints applied were:

- The RE-installed capacity cannot grow by more than 20% of the total power generation capacities for each 5 year time step to avoid the disruption of the power system.
- No new nuclear or fossil fuel capacities can be installed after 2015, except gas turbines, which can utilise synthetic gas or bio-methane.

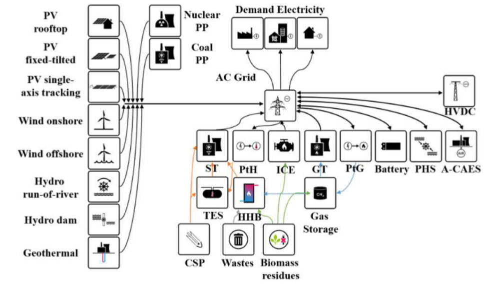


Fig. 2 *Block diagram of the LUT Energy System model [17]*

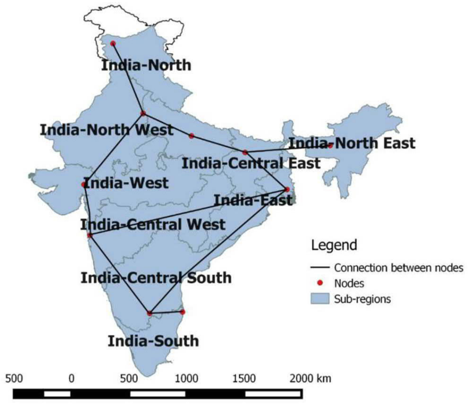


Fig. 3 *Ten sub-regions of India and grid interconnection between them*

All the applied technologies from electricity generation, storage options used, bridging technologies and transmission of electricity can be seen in Fig. 2.

3 Grid structure and scenario

India was divided into ten sub-regions based on the population distribution, consumption of electricity and the grid structure as in Fig. 3.

The power scenario [19] was studied for the analysis of the Indian energy system during the monsoon period. In this scenario, the energy systems of the different regions are interconnected.

4 Assumptions

All the technical and financial assumptions related to the model can be found in the supplementary material of Gulagi *et al.* [19].

5 Results and discussion

According to Gulagi *et al.* [19, 27], a power system based on fully RE is the least-cost solution, and the system can overcome hindrances created during the monsoon months.

The structure of the system concerning power generation technologies, storage technologies and transmission grids was analysed in detail, and the following sub-sections will explain in detail the roles of power generation, storage technologies and transmission grids in the monsoon and non-monsoon periods.

5.1 Complementarity of solar and wind generation in 2050

The total annual electricity generation from solar PV and wind in 2050 are 6000 and 415 TWh, respectively. These two RE sources contribute to almost 92% of the total electricity generation. Fig. 4 shows the monthly solar and wind generation in the year 2050 for the power scenario. Solar generation is highest during March, April and May, which are also the summer months. While generation is at its lowest during the monsoon months of June, July, August and September. On the contrary, wind generation is seasonal, and the peak generation is observed during the monsoon period. The lowest generation of electricity from solar is seen in July when the monsoon is at its peak in most parts of India. The highest generation from solar is observed in March, April and May when summer is at its peak in most parts of India.

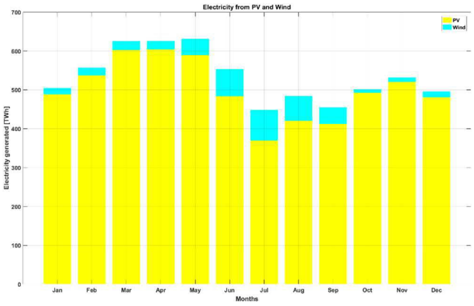


Fig. 4 *Monthly electricity generation from solar PV and wind in 2050 across India for the power scenario*

Owing to cloudy and rainy weather in the monsoon period (June–September), a decrease in the solar energy output was observed for all the regions. The decrease in solar energy output is dependent on a particular region; some regions that were affected the most by the monsoon saw a steep decrease in solar energy output and vice versa. The total power generation in the monsoon months from solar PV decreases by almost 14% in comparison with non-monsoon months. The regions India-West (IN-W), India-Central West (IN-CW) and India-Central South (IN-CS) are the most affected by the monsoon season with a decrease of 19, 34 and 23%, respectively. On the other hand, regions India-Northwest (IN-NW), India-South (IN-S) and India-Central-East (IN-CE) seem to be least affected by monsoon season with a decrease of 4, 5 and 5%, respectively.

It was observed that the monsoon months (June–September) produce 62% of the total wind energy generated in India while representing only one-third period of the year. The regions of IN-W, Central West, Central South and the South regions produce more than 95% of the total wind energy generated. The electricity generated from wind energy particularly picks up in the regions of Central West and Central South. The coastal and some inland regions of Gujarat, Maharashtra, Kerala and Tamil Nadu have the best wind potential of all the sites available across India. The above findings are in agreement with Solomon *et al.* [22, 33], wherein the solar–wind complementarity analyses were done for Israel and California, and Gerlach *et al.* [34] for global–local resolution. Here, the authors conclude that complementarity has multiple benefits such as stable high share RE system and grid. Complementarity provides a fully RE system to function without hindrances.

5.1.1 Analysis on a regional level: Significant variation of wind generation exists across the regions in India. The southern and western regions are expected to install and generate most of the wind energy in India due to the availability of excellent wind resources. This can be observed in the current-installed capacities of wind, which are concentrated in these regions. In comparison, the solar resource is well-distributed all over India, except the Northeast region. For regional analysis, two regions are selected that have the following characteristics:

- A region where PV generation decreases the most and where wind generation is the highest in the monsoon period: IN-CW.

- A region where PV generation is least affected by the monsoon period: IN-S.

The dispatches of IN-CW and IN-S in a monsoon week can be observed from Figs. 5 and 6, respectively.

It can be observed for the region Central West that the decrease in the solar PV output in the initial hours of the week is effectively complemented by an increase in electricity generation from wind. If solar is available, wind generation decreases as seen from the later hours of the week. As solar PV is the least-cost generation source, the system first utilises all the available energy from solar, and if wind is available in those hours it utilises wind, and the remaining energy is imported from neighbouring regions to satisfy the demand. Wind overcomes the decrease in solar PV output for the Central West region in the monsoon period.

For the region IN-S, which is least affected by the monsoon period, it is observed that the solar PV output is constant for all hours of the week with even export of excess electricity in these hours. Such regions help to balance the demand of the neighbouring regions with whom they are connected by transmission lines via electricity exports in the monsoon season.

Solar being the major energy source for India in 2050, curtailment is reduced in all the regions during the monsoon period with an overall decrease in solar generation in most parts of India. The highest curtailment is observed in the summer months as this is the peak duration for solar generation. From the onset of the monsoon season, curtailment decreases drastically in most of the regions and goes down to zero in almost all the regions, except IN-S. As seen earlier, this is the region that is least affected by monsoon and the decrease in solar PV generation is the lowest. In the monsoon months, increase in electricity generated by wind supports the system even when the electricity generated from solar PV decreases.

5.2 Role of storage technologies

A fully RE system for India is based on a solar PV–battery hybrid, with batteries (prosumer and system) contributing to almost 90% of the total storage output and the remaining 10% from other storage technologies [19]. Gas storage, which is utilised as long-term storage, contributes 7% of the total storage output [19].

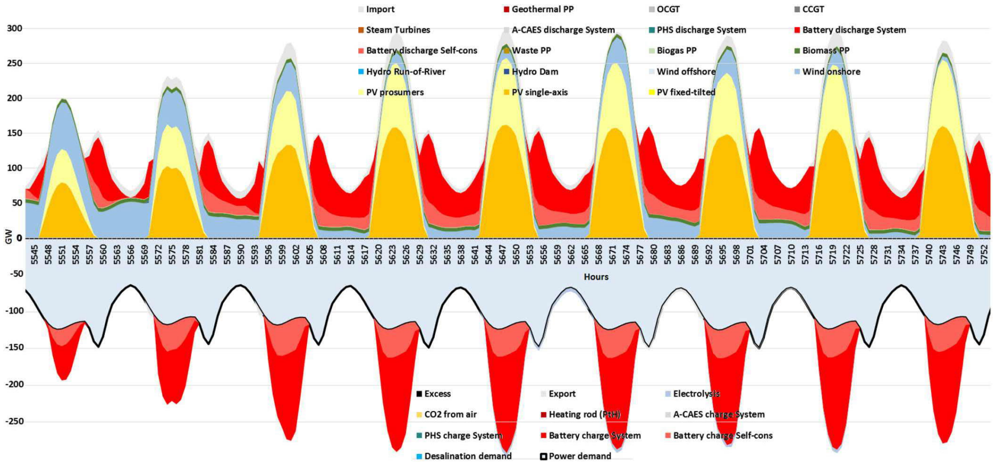


Fig. 5 *Dispatch for the region IN-CW in a monsoon week in 2050*

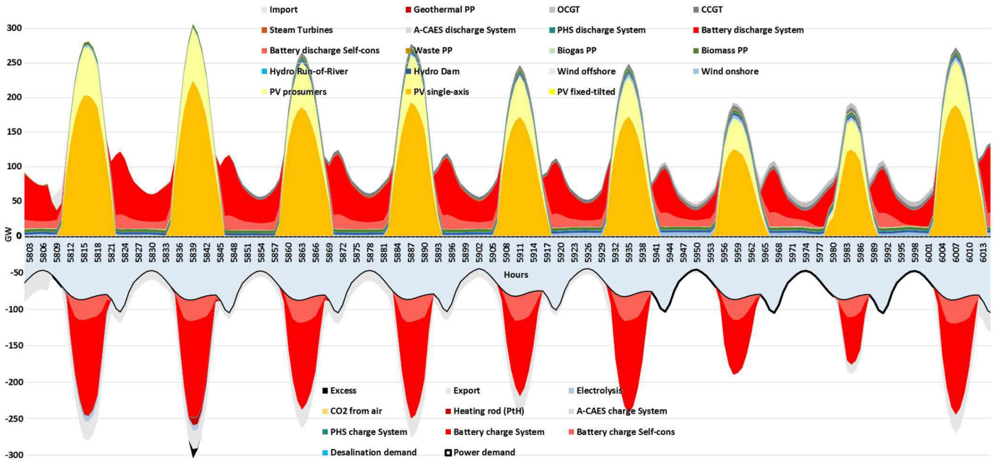


Fig. 6 *Dispatch for the region IN-S in a monsoon week in 2050*

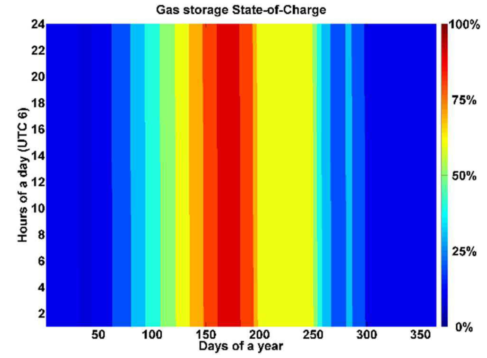


Fig. 7 *Hourly state-of-charge profile of gas storage for India in 2050, for the power scenario [19]*

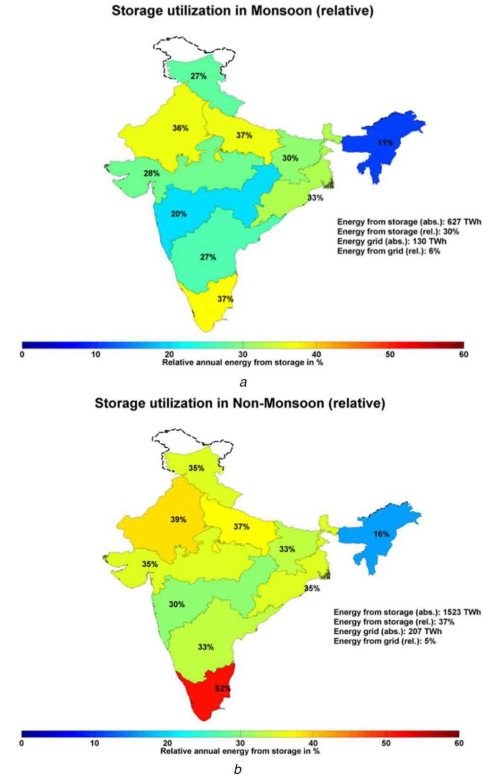


Fig. 8 *Relative storage utilisation*
(a) Utilisation of storage technologies in the monsoon months for the power scenario in 2050 [19], ***(b)*** Utilisation of storage technologies in the non-monsoon months for the power scenario in 2050 [19]

In the monsoon period, battery output is 85% of the total storage output in comparison with 92% in the non-monsoon period. The reduced solar resource availability contributes to less energy stored in the batteries since it is utilised as short-term storage that perfectly complements solar availability and discharge in the night-times.

One interesting observation, which was made, is the increase in output of stored gas to produce electricity via combined cycle gas turbines (CCGTs). An increase of almost 10% is observed in the gas output in the monsoon period. CCGT plants can be ramped up to provide electricity in the night-times and periods of low solar radiation. From Fig. 7, it can be observed that gas storage is fully charged before the start of the monsoon season and starts discharging to cover demand in the monsoon months and fully discharged until the monsoon is over. The relative utilisation of the storage technologies in the monsoon period was 30% in comparison with the non-monsoon period, where it was 37%. Figs. 8*a* and *b* give the relative storage utilisation in all the sub-regions of India. While in the monsoon season, the utilisation of storage technologies decreases, still, storage technologies play an important role in a 100% RE system in India, as found by Lawrenz *et al.* [26].

5.3 Role of transmission grids

In a fully RE system, there are a lot of import and export of electricity between the regions. Some regions act as net importers of electricity due to huge demands that cannot be satisfied by local generation, higher costs of primary generation and flexibility provided by different renewable power generation sources in other regions. Transmission grids are important as they help to balance the power demands in the different regions and decrease the need for storing electricity since it can be cost-effective to import electricity rather than storing it for later usage.

The net electricity is drawn from the grid to satisfy the respective demand increases in the monsoon period. In the monsoon period, the net electricity utilised from the grid was 6.2% in comparison with 4.9% in the non-monsoon period. The net imports and exports for all regions in India are 338 and 360 TWh, respectively. However, some regions are importing more than the others are, for example, IN-CW, IN-W and IN-CS are the largest importers of electricity. For these regions, the costs of primary generation are higher than the neighbouring regions with which they are connected and have high electricity demand. From Fig. 9, the imports and exports for all regions according to months of the year can be observed.

In the monsoon period, the net import and export are 130 and 137 TWh, respectively, representing about 38% of the total net electricity transfer. It can be seen that during the monsoon period, which represents only one-third of a year, there is a lot of transfer of electricity between the regions due to overall reduction in the major source of electricity generation for India, which is solar.

5.3.1 Analysis on a regional level: From Fig. 9, it is seen that the imports and exports increase in some regions during the months of the monsoon. The region of IN-W has its peak imports in June and overall higher imports in the monsoon months than the non-monsoon months. As this region is one of the most affected by the monsoon with a decrease in solar PV output of 19%. This region has good potential for wind energy generation. However, the increase in wind output is not enough to satisfy the total electricity demand in the region. Therefore, importing electricity from neighbouring regions benefits the IN-W region and decreases overall cost of the system.

The region of IN-S is a net exporting region, and it can be seen with the increase of exports in the monsoon period. This region is blessed with good solar as well as wind resources. As this region is not affected by the monsoon and the decrease in solar PV output is one of the lowest in the country. The wind output is increased considerably so that the excess electricity is exported to IN-CS. The energy flow in one of the transmission lines is shown in Fig. 10. The India-Eastern (IN-E) region imports electricity mainly from the Central-East (IN-CE) region.

The positive numbers indicate imports and negative exports of electricity in the transmission lines. In the monsoon period, export of electricity takes place for most hours in a day from the region IN-CE due to solar resource unavailability in the region IN-E. This is also observed in Fig. 9 (imports). In the region IN-E, over 90% of the power generated is by solar, and this region does not have good wind resource. Therefore, the exported electricity is used directly to satisfy the daytime demand or stored to satisfy the night-time load. During the non-monsoon months, electricity is exported during the daytime by IN-CE, which is consumed directly or stored in gas storage in the IN-E region.

To satisfy its demand, the IN-E region has to import electricity from IN-CE. This example shows how the system balances itself due to transmission grids in the monsoon months. The grid utilisation of the region IN-W increases in the monsoon period. This region has solar PV as the major power generation source and complemented by wind power, as this region is situated in one of the best wind sites in India having good wind potential all year round. However, in the monsoon months, the demand cannot be fulfilled by the available renewable resources due to the decrease in solar resource availability. Therefore, this region imports electricity from the IN-CW region, where wind energy is available, which can be seen from Fig. 11. From 4000 to 6500 h, the IN-W region imports wind energy from IN-CW to satisfy its power demand in the monsoon period.

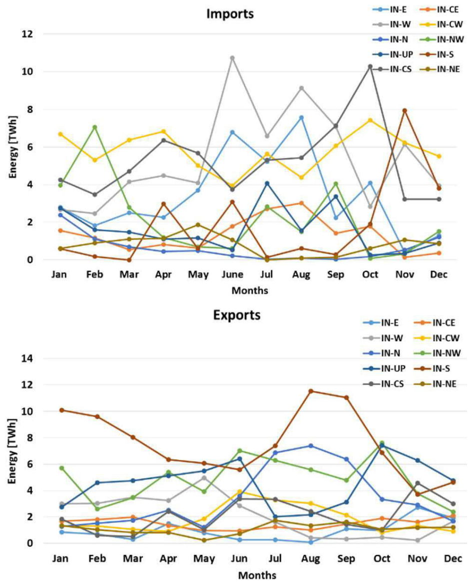


Fig. 9 *Imports (top) and exports (bottom) for the ten regions in India on a monthly scale in 2050*

The regions that are least affected by the monsoon and with a slight decrease in solar PV electricity production support the other regions that are strongly affected, through transmitting electricity via interconnected grids. A perfect example of this is the regions of IN-NW and IN-W, as shown in Fig. 12. The region IN-NW is least affected by the monsoon, as major parts of the area consist of the desert, where the solar conditions are almost constant all year round with a slight decrease during the monsoon period. In comparison, IN-W is most affected by the monsoon with electricity from solar PV decreasing by almost 19% in comparison with the non-monsoon period. The region IN-W imports electricity generated by solar PV directly daily from IN-NW and more so in the monsoon period with the absolute value of imports increasing (see Fig. 12). The same can be observed for the region IN-S, which is least affected by the monsoon and is one of the largest exporters of electricity. The export of solar PV-generated electricity to IN-CS is daily in the noon and afternoon hours. For the regions, IN-NW and IN-S batteries are charged daily in the daytime and discharged to satisfy the local demand or sometimes transmitting electricity via grids to the other regions.

The regions of IN-NW and IN-S are the top two exporters of electricity amongst the ten regions. In the monsoon period, these two regions combined export about 43% of the total electricity in 2050. The exported electricity is mainly solar PV generated, as it is the cheapest source for electricity and is abundantly available. To minimise the overall cost of the system, it is more cost-effective to export electricity from PV than wind. For IN-NW, the electricity generated from wind is negligible, and this further proves that electricity from solar PV is exported. Also, by utilising batteries to export power even during the night-times to other regions for balancing the load in the monsoon period in a cost-effective way.

The net energy transfer between the ten regions for a fully RE system in 2050 is 678 TWh. For the monsoon period, the net energy transfer is 250 TWh and for the non-monsoon period it is 428 TWh. Fig. 13 gives an overview of the imports and exports between the different regions in the monsoon and non-monsoon periods. In Fig. 13, the thickness of the flow indicates the amount of electricity exchanged between the regions in TWh. The exporter region ribbons and the flows have the same colour. For example, the blue ribbon of IN-S, an exporting region, extends a blue flow of export to IN-CS, a net importing region. Interesting observations can be made from Fig. 13 in terms of major importing and exporting regions. IN-NW is a major exporting region in the monsoon period with exports to the regions of IN-W and IN-UP. As the effects of the monsoon on this region are the lowest in terms of solar power production, this region exports electricity to the regions impacted most by the monsoon. In the monsoon period, IN-W is a major importing region, importing from IN-CW and IN-

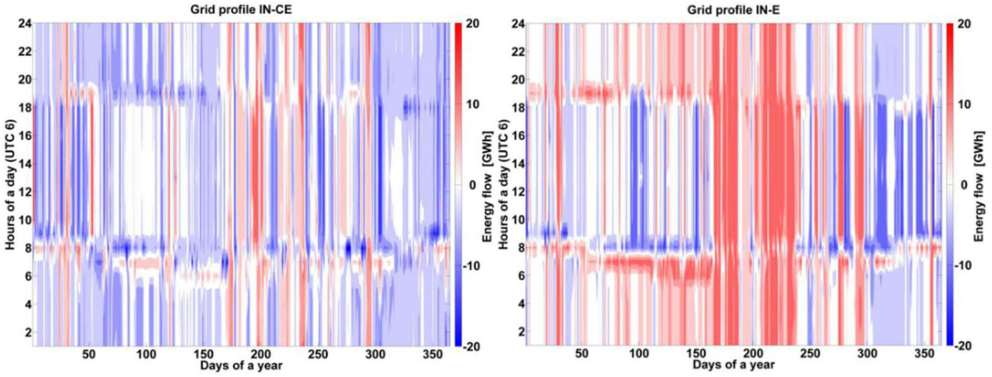


Fig. 10 *Grid profiles for the power scenario in 2050 for IN-CE (left) and IN-E (right). Import (+) and export (−)*

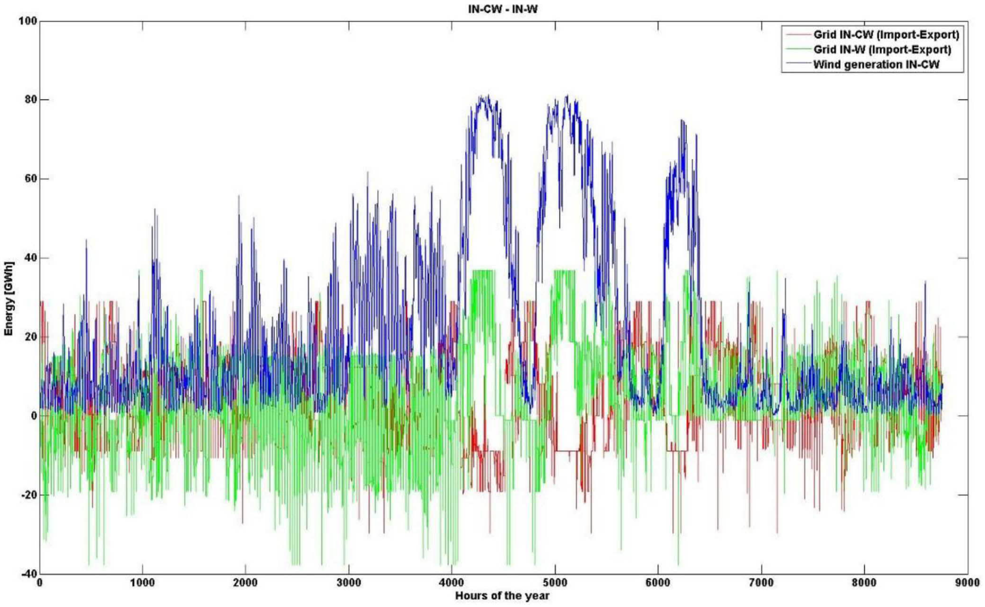


Fig. 11 *Grid energy flows and wind energy generation on an hourly basis for the power scenario in 2050. The blue line is wind energy generation in the IN-CW region. The red and green lines are the annual import and export by IN-CW and IN-W, respectively*

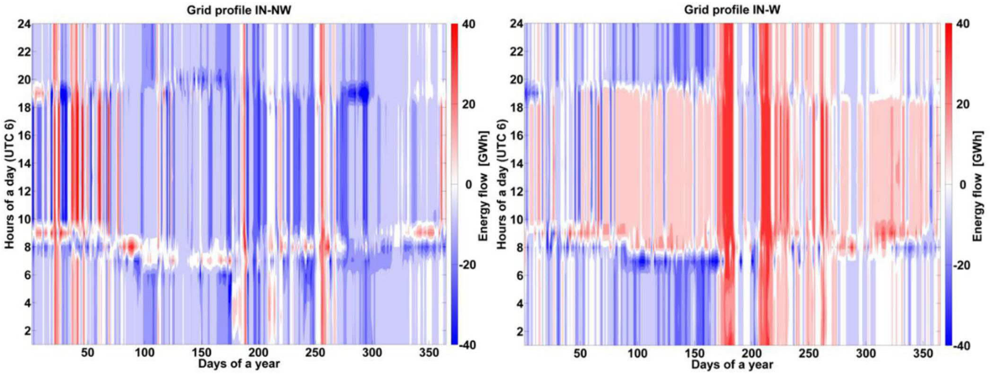


Fig. 12 *Grid profiles for the power scenario in 2050 for IN-NW (left) and IN-W (right). Import (+) and export (−)*

NW. However, in the non-monsoon period, IN-W exports electricity to IN-CW, while importing from IN-NW.

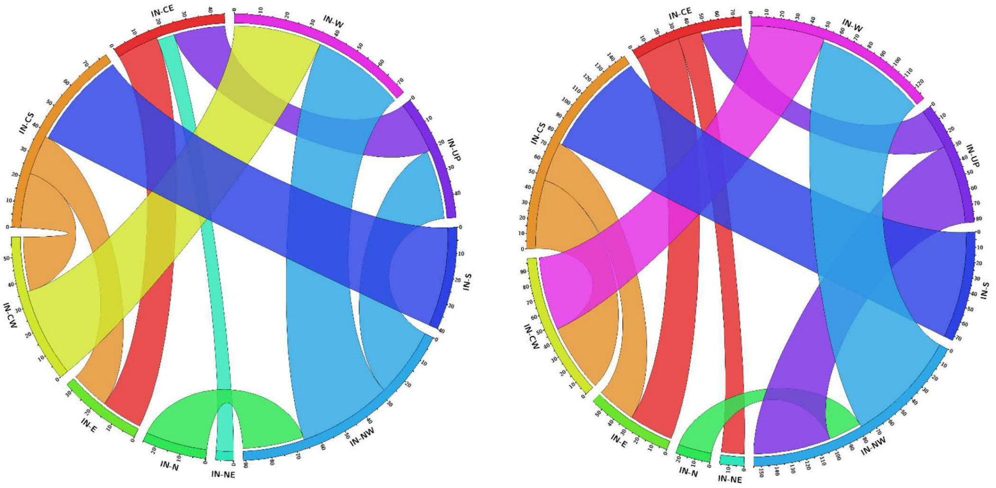
6 Conclusion

A fully renewable electricity system for India is possible in 2050 in an hourly resolution. Besides, the proposed system can effectively handle the decreased solar power generation during the monsoon season by effectively utilising transmission grids and increased wind power availability.

The reduced power generation from solar PV in the monsoon period can be effectively complemented by an increase in power generation from wind, in some regions. Total power generation from wind in the monsoon period is 62% of the total wind power generated in India. The region of IN-CW, where the wind generation increases considerably in comparison with the other regions, satisfies its demand and exports excess wind energy.

The interconnection of regions via transmission grids helps to balance the power demand in regions that are most cost-effectively affected by the monsoon. Total imports to satisfy the demand in the monsoon period increases by 1.3% in comparison with the non-monsoon period. It is observed that in the monsoon period, which represents only one-third of a year, the net electricity transfer happening in the grids is 38% of the annual net electricity transfer. The energy flow between the regions of IN-E and IN-CE clearly shows an increase in imports during the monsoon period by IN-E, due to the decrease in its solar energy production. The decrease in solar PV availability in the region IN-W is compensated by increasing its imports from IN-CW and IN-NW. The electricity exported from IN-CW mainly being wind and solar and from IN-NW.

These results prove that RE options are the most competitive and least-cost solution for achieving a zero GHG emission-based



a b

Fig. 13 *Electricity exchange among the ten regions in 2050 for the power scenario*
(a) For the monsoon period, ***(b)*** For the non-monsoon period. The thickness of the flow indicates the amount of electricity exchanged denoted as TWh

electricity system, even in the monsoon season without utilising balancing power based on fossil fuels.

7 Acknowledgments

The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the Finnish Solar Revolution project under the number 880/31/2016. The first thank Fortum Foundation for the valuable scholarship.

8 References

[1] [TERI] – The Energy and Resources Institute: 'Transitions in Indian Energy Sector 2017–2030, a report'. New Delhi, 2016
[2] Reddy, B.S.: 'Economic dynamics and technology diffusion in Indian power sector', *Energy Policy*, 2018, **120**, pp. 425–435
[3] Rathore, P.K.S., Chauhan, D.S., Singh, R.P.: 'Decentralized solar rooftop photovoltaic in India: on the path of sustainable energy security', *Renew. Energy*, 2019, **131**, pp. 297–307
[4] REN21: 'Renewables 2019 Global Status Report', Paris, 2019. Available at https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf, accessed: 10.05.2019
[5] [UNFCCC] – United Nations Framework Convention on Climate Change: 'India's intended nationally determined contribution: working towards climate justice'. Technical Report, Bonn, 2015
[6] Mahapatra, S.: 'India attracted $14 billion in renewable energy investment in 3 years'. Clean Technica, New Delhi, India, 2016. Available at: https://cleantechnica.com/2016/04/29/india-attracted-14-billion-renewable-energy-investment-3-years/, accessed 01.04.2019
[7] Pillai, I.R., Banerjee, R.: 'Renewable energy in India: status and potential', *Energy*, 2009, **34**, (8), pp. 970–980
[8] Kumar, A., Kumar, K., Kaushik, N., *et al.*: 'Renewable energy in India: current status and future potentials', *Renew. Sustain. Energy Rev.*, 2010, **14**, (8), pp. 2434–2442
[9] Bhattacharya, S.C., Jana, C.: 'Renewable energy in India: historical developments and prospects', *Energy*, 2009, **34**, pp. 981–991
[10] [MNRE] – Ministry of New and Renewable Energy: 'Physical Progress (Achievements)'. Government of India, New Delhi, 2019. Available at: https://mnre.gov.in/physical-progress-achievements
[11] [CEA] – Central Electricity Authority: 'Monthly report on installed capacity, Ministry of power'. Government of India, New Delhi, 2017, accessed 01.04.2019
[12] Sharma, N.K., Tiwari, P.K., Sood, Y.R.: 'Solar energy in India: strategies, policies, perspectives and future potential', *Renew. Sustain. Energy Rev.*, 2012, **16**, (1), pp. 933–941
[13] Sethi, N.: '*India's energy mix to have 40% renewable sources by 2030*' (Business Standard, New Delhi, 2015)
[14] Hossain, J., Deepshikha, S., Swamy, D., *et al.*: 'Report on India's Wind Power Potential, WinDForce, CSTEP, Shakti Foundation'. Report for Ministry of New and Renewable Energy, New Delhi, 2015
[15] Sinha, S., Chandel, S.S.: 'Prospects of solar photovoltaic–micro-wind based hybrid power systems in western Himalayan state of Himachal Pradesh in India', *Energy Convers. Manage.*, 2015, **105**, pp. 1340–1351
[16] [PIB] – Press Information Bureau: 'MNRE issues National Wind-solar Hybrid Policy'. Government of India, New Delhi, 2018
[17] Ram, M., Child, M., Aghahosseini, A., *et al.*: 'A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030', *J. Clean Prod.*, 2018, **199**, pp. 678–704
[18] Lau, W.K., Waliser, D., Goswami, B.: '*South Asian monsoon intraseasonal variability in the atmosphere-ocean climate system*' (Springer, Berlin, 2005), pp. 21–72
[19] Gulagi, A., Bogdanov, D., Breyer, C.: 'The demand for storage technologies in energy transition pathways towards 100% renewable energy for India', *Energy Proc.*, 2017, **135**, pp. 37–50
[20] Merchant, B.: 'How solar power could become the world's dominant energy source in 35 years'. Motherboard Tech By Vice, New York, 2014
[21] Zsiborács, H., Baranyai, N.H., Vincze, A., *et al.*: 'Intermittent renewable energy sources: the role of energy storage in the European power system of 2040', *Electronics (Basel)*, 2019, **8**, (7), p. 729
[22] Solomon, A.A., Faiman, D., Meron, G.: 'Grid matching of large-scale wind energy conversion systems, alone and in tandem with large-scale photovoltaic systems: an Israeli case study', *Energy Policy*, 2010, **38**, pp. 7070–7081
[23] Pursiheimo, E., Holttinen, H., Koljonen, T.: 'Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries', *IET Renew. Power Gener.*, 2017, **11**, (13), pp. 1695–1706
[24] TERI and WWF: 'The energy report – India 100% renewable energy by 2050, report'. TERI and WWF, New Delhi, 2013
[25] Röben, F., Köhler, M.: '*India's pathway to 100% renewable power generation – exploring capacity mix, costs and innovative financing tools*' (Policy Brief, Greenwerk, Hamburg, 2016)
[26] Lawrenz, L., Xiong, B., Lorenz, L., *et al.*: 'Exploring energy pathways for the low-carbon transformation in India – a model-based analysis', *Energies*, 3001, **11**, (11), p. 2018
[27] Gulagi, A., Bogdanov, D., Breyer, C.: 'The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India', *J. Energy Storage*, 2018, **17**, pp. 525–539
[28] Bogdanov, D., Farfan, J., Sadovskaia, K., *et al.*: 'Radical transformation pathway towards sustainable electricity via evolutionary steps', *Nat. Commun.*, 2019, **10**, (1), p. 1077
[29] Gulagi, A., Bogdanov, D., Breyer, C.: 'Electricity system based on 100% renewable energy for India and SAARC', *PLoS ONE*, 2017, **12**, (7), p. e0180611
[30] Lolla, S., Roy, S.B., Chowdhury, S.: 'Wind and solar energy resources in India', *Energy Proc.*, 2015, **76**, pp. 187–192
[31] USAID and Ministry of Power: 'Greening the grid: pathways to integrate 175 GW of renewable energy into India's electric grid, National Study, Report'. New Delhi, 2017, vol. **1**
[32] Gulagi, A., Ram, M., Breyer, C.: 'Solar–wind complementarity with optimal storage and transmission in mitigating the monsoon effect in achieving a fully sustainable electricity system for India'. First Int. Conf. Large-Scale Grid Integration of Renewable Energy in India, New Delhi, 2017. Available at: https://goo.gl/gNa5kD, accessed 01.04.2019
[33] Solomon, A.A., Kammen, D.M., Callaway, D.: 'Investigating the impact of wind–solar complementarities on energy storage requirement and the

corresponding supply reliability criteria', *Appl. Energy*, 2016, **168**, pp. 130–145

[34] Gerlach, A.-K., Stetter, D., Schmid, J., *et al.*: 'PV and wind power – complementary technologies'. ISES Solar World Congress 2011, Kassel, 28 August–2 September 2011

Publication IV

Gulagi, A., Ram, M., Solomon, A. A., Khan, M., and Breyer, C.
Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh

Reprinted with permission from
Renewable Energy
Vol. 155, pp. 899-920, 2020

Renewable Energy 155 (2020) 899–920

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh

Ashish Gulagi [*], Manish Ram , A.A. Solomon , Musharof Khan , Christian Breyer

LUT University, Yliopistonkatu 34, 53850, Lappeenranta, Finland

ARTICLE INFO

Article history:
Received 8 April 2019
Received in revised form
15 January 2020
Accepted 20 March 2020
Available online 26 March 2020

Keywords:
Bangladesh
Energy transition
100% renewable Energy
Energy economics
Storage technologies

ABSTRACT

This study analyses energy transition pathways for the case of Bangladesh. The LUT Energy System Transition model, a high temporal - spatial resolution linear optimisation tool, is used to model an energy system transition from 2015 to 2050 for the case of Bangladesh. Four scenarios aimed at analysing different energy policies were created in order to replicate the present and alternative renewable energy based policies, with and without greenhouse gas emissions costs. The results show that emissions costs accelerate the transition towards a fully renewable energy system, however, removing these costs does not significantly affect the energy system, as renewables would still contribute 94% of the electricity generation by 2050. The Current Policy Scenario increases electricity and greenhouse gas emissions costs significantly especially, starting in 2025. The results indicate that countries like Bangladesh are prone to serious and complicated national risks that lead to several vulnerabilities like high electricity costs, increase in greenhouse gas emissions, energy insecurity and poor political trust, if present energy policies are pursued. However, focusing on indigenous renewable resources could help mitigate this vulnerability and bring about socioeconomic benefits.

1. Introduction

In the past years, industrial development, rise in population and an increase in living standards led to significant increase in global primary energy consumption [1]. While, this trend is expected to continue in the future, global energy consumption could double by 2100 [2]. Maintaining a fast-paced economic growth at the same level as population increase, particularly in developing countries, together with climate change mitigation targets, have put tremendous pressure on governments to supply stable, uninterrupted and sustainable power [3]. High dependence on domestic or imported fossil fuels have environmental consequences of their own, in addition to risks related to long term energy security and cost competitiveness of electricity production. Therefore, governments around the world are revisiting their energy strategies to enable transition towards increased adoption of renewable energy sources [4,5]. This has resulted in the addition of around 160 GW of renewables, globally in 2017, which is far more than the installed capacities of fossil fuels and nuclear power. However, most countries are still taking cautious steps towards embracing renewables [5]. Recent studies have shown that these cautious steps carry significant risks for countries that plan to rely on fossil fuels [6]. The level of risk and vulnerability could be more significant for developing countries, who do not revise their policies frequently and those depending on fossil fuel imports. Bangladesh is one of the countries that appear to be prone to such risks.

Bangladesh is one of the rapidly developing countries in South Asia [7]. It is also one of the most densely populated countries, having a population density of around 1079 per km^2 [8]. The average annual GDP growth rate was 5.7% between 1996 to 2016, with a peak of 7.1% observed in 2016 [9]. According to the Government of Bangladesh (GoB), GDP is expected to grow at an average annual growth rate of 6.1% from 2016 to 2041 [8]. On the other hand, electricity demand grew at an average annual growth rate of 9.7% between 2004 to 2015 [10]. The historical growth in GDP and electricity demand are correlated because rise in electricity demand is often associated with improving standards of living and national economic activity. This was observed in the growth of electricity access from 40.6% in 2004 to 68.2% in 2015 [11]. However, it should be noted that Bangladesh has a per capita electricity consumption of just 387 kWh, which is amongst the lowest in the world [8].

---

[*] Corresponding author.
E-mail address: Ashish.Gulagi@lut.fi (A. Gulagi).

https://doi.org/10.1016/j.renene.2020.03.119
0960-1481/

Nomenclature

A-CAES	Adiabatic compressed air energy storage
AC	Alternating Current
BAU	Business-as-usual
BERC	Bangladesh Energy Regulatory Commission
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CSP	Concentrating solar thermal power
FLH	Full load hours
GoB	Government of Bangladesh
GHG	Greenhouse gases
HVDC	High-voltage direct current
IEA	International Energy Agency
INDC	Intended Nationally Determined Contributions
LCOC	Levelised cost of curtailment
LCOE	Levelised cost of electricity
LCOG	Levelised cost of gas
LCOS	Levelised cost of storage
LCOT	Levelised cost of transmission
NCBD	National Committee Bangladesh
OCGT	Open cycle gas turbine
OPEX	Operational expenditures
PHES	Pumped hydro energy storage
PSMP	Power System Master Plan
PtG	Power-to-gas
QRPP	Quick Rental Power Plant
RE	Renewable energy
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
WACC	Weighted average cost of capital

Bangladesh has been dependent on fossil fuels for its electricity generation [12] and a continued reliance will require an increase in fossil fuel imports to satisfy the growing electricity demand, as domestic reserves a due to limited domestic reserves. A high contingency on imported gas, coal and oil will not only add economic pressure on Bangladesh, but also raise serious questions on its long-term energy security [13]. Moreover, as one of the world's most vulnerable countries to be impacted by the threats of rising sea level on its low-lying areas [14], burning fossil fuels puts Bangladesh in a more precarious position due to eroding trust towards its government's integrity and commitment to address its society's vulnerability. Specifically, studies show that about 1 m sea level rise will submerge one-fifth of the country's land mass, which might dramatically increase climate change refugees in the coming decades, displacing millions of individuals and communities from their homes [15–17]. In addition, PM 2.5 concentration is steeply rising since 2010 and about 100 thousand people die each year due to increasing air pollution [18]. The above facts obligate countries such as Bangladesh to take a leading role in working towards a renewable future.

Currently, renewable energy is gaining momentum in the global energy mix, which is seen as a low risk option in comparison to fossil fuels. This is mainly attributed to the expected cost decline [19], of the main renewable energy technologies, PV [20,21] wind [22] and batteries [23,24]. Additionally, the levelised cost of electricity production have become cost competitive with fossil fuels [25]. These factors have triggered a positive outlook towards renewable energy technologies all around the world. Several studies have reported the technical feasibility and economic viability of 100% renewable energy systems for various parts of the world, e.g. Finland [26], Denmark [27], Australia [28], Israel [6], India [29,30], Pakistan [31], Southeast Asia [32], Nigeria [33], Sub-Saharan Africa [34], etc. According to Brown et al. [35], 100% renewable energy systems are already technically feasible and economically viable with decreasing costs every year. Hansen et al. [36] present an overview on 100% RE studies and comment on the status and perspectives of the respective research. This suggests that achieving 100% RE by 2050 is possible but often hindered by political will. The above discussion clearly puts renewables in the forefront for achieving a lower levelised cost of electricity by 2050 than the present energy policies.

For Bangladesh, renewable energy sources can provide a viable alternative in tackling energy shortage, energy security and long-term energy planning with reduced GHG emissions, whilst complying with climate change targets. For these reasons, Bangladesh presents a good case study for developing countries: First, it is a developing country that is highly dependent on fossil fuels for its electricity generation and its future energy policy is inclined towards the imports of fossil fuels. Second, it lies in a region of high solar potential, hence its future energy supply will have a large share of solar PV. Third, presence of the monsoon season and few electricity generation options other than solar in a fully renewable energy system.

In addition, there is no research on future energy transition scenarios that are fully based on a broader potential of renewable energy (RE) resources for Bangladesh. Table 1 summarises various energy scenarios and their key findings. Unfortunately, none of them have considered broader RE resources and as a result achieved lower RE shares. Moreover, the modelling tools adopted lack a key requirement, such as, the ability to handle an hourly dynamics of storage and the needed hourly balance between demand and generation, in order to simulate high variable RE systems appropriately [37,38].

This study contributes to the various existing studies on the energy transition pathways for Bangladesh. However, it goes a few steps further by considering the multi-nodal approach with an hourly resolution for an entire transition year [29,30,42] in addition, to its broader power generation, storage and flexibility options including grid balancing among the regions. Further, it identifies the risks associated with future energy policies of the Government of Bangladesh, like energy security in this changing geo-political world, increasing greenhouse gas emissions, climate change and high electricity costs and the potential opportunities in embracing renewables. This paper shows how RE could solve energy security challenges of Bangladesh as well as meet the climate change goal of reducing its GHG emissions.

2. Methodology

This research assesses energy transition scenarios for Bangladesh from 2015 to 2050. The modelling was performed using LUT Energy System Transition model, which is summarised below. More detailed information about the model and its inputs can be found in Bogdanov and Breyer [42,43].

The LUT Energy System Transition model optimises energy systems under a set of linear constraints and assumptions for future RE power generation and demand for a particular area. The transition is modelled starting from the energy system in 2015 towards a fully RE system in 2050, in 5-year time steps. The model ensures that all technologies, which are built in the transition period, are

Table 1
Various studies on future electricity demand and renewable energy system for Bangladesh.

Study	Scope	Key findings
Mondal M. A. H. et al., 2014 [39]	Bangladesh	Different scenarios analysed from 2010 to 2035 using MARKAL. Different policy scenarios developed for the analyses of the power sector. The analyses show that energy imports are needed to satify the growing energy demand in the future. However, imports can be reduced by having CO_2 reduction targets or fast increase in renewable energy deployment. Additionally, this would also improve energy security and reduce environmental impacts without increase in discounted total energy system cost. The highest installed capacities of solar PV is observed in the Null Coal Import scenario of about 41 GW and electricity generation is 84 TWh. The renewables share in total installed capacity in 2035 is about 41%.
Power System Master Plan (PSMP), 2016 [40]	Bangladesh	In 2041, the total electricity demand would be 335 TWh, which would be supplied by coal (35%), gas (35%), imports/renewable (15%), nuclear (10%), and oil (5%). Approximate generation costs would be in the range of 97–124 €/MWh.
IEEFA, 2016 [10]	Bangladesh	Total electricity demand will be 92.5 TWh by 2024/2025. Renewable energy will have the highest share in electricity production around 50%, followed by gas 26% and oil 12%. 62% of the total renewable electricity will be provided by various solar energy technologies.
National Committee Bangladesh (NCBD), 2017 [13]	Bangladesh	By 2041, the approximate electricity demand would be 490 TWh in which renewable energy contributes 55%, natural gas 37%, and others have 8% share. Batteries would be used as storage technologies with a capacity of 78 TWh.
Das A. et al., 2018 [41]	Bangladesh	Four scenarios were explored till 2045: Power System Master Plan scenario, a high power import scenario, a higher use of renewable scenario and a combined scenario with high power imports and high renewable energy use. The results were optimised using a TIMES model and indicated that the combined scenario with high renewable energy and high imports lead to a least cost system. The maximum installed capacity for PV and wind in the high renewable energy scenario is 10 GW and 4.6 GW respectively and total generation from renewables is around 22.7 TWh in 2045. The maximum imports for the combined scenario is around 100 TWh. Due to the modelling strategy, this study leads to significant fossil fuel consumption even under the best policy scenario.

fully amortised. The model is comprised of a clearly defined objective function, which optimises for every 5-year time step, so that all constraints and assumptions are satisfied, resulting in a least cost energy system. The optimisation is currently carried out using a third party solver, MOSEK ver. 8. The post processing of the optimisation results and model compilation is done using Matlab. The target function for the optimisation is given in Eq. (1).

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t) \cdot instCap_{t,r} + OPEXvar_t \cdot E_{gen,t,r} + rampCost_t \cdot totRamp_{t,r}\right) \tag{1}$$

where the abbreviations stand for Capital cost of each technology, $CAPEX_{t;}$ capital recovery factor for each technology, $crf_{t;}$ fixed operational cost for each technology, $OPEXfix_{t;}$ variable operational cost each technology, $OPEXvar_{t;}$ installed capacity in a region, $instCap_{t,r;}$ electricity generation by each technology, $E_{gen,t,r;}$ ramping cost of each technology, $rampCost_{t;}$ annual total power ramping values for each technology, $totRamp_{t,r;}$ each and every region, *reg;* and each and every technology, *tech*.

The LUT Energy System Transition model has the following important features among other things:

- Hourly resolution for an entire year depicting an accurate synergy between different system components utilised, guaranteeing an energy system much closer to reality, including energy supply security.
- A transition of an energy system can be modelled until any given year in the future, as long as data is available.
- Utilisation of different storage technologies.
- A multi-nodal approach of the model enables a country or a region to be divided into different sub-regions, each sub-region can act as a different node and the nodes can be interconnected to form a transmission network.

Fig. 1 presents a simplified representation of the model input data, optimisation and results.

Electricity is generated using a mix of fossil fuels and renewable generation technologies. Additionally, intermittency of renewables is balanced by deploying appropriate storage technologies and flexibility options. The supply of electricity to the nodes is secured by utilising the assumed network of High Voltage Alternating Current (HVAC) transmission lines. The list of various technologies is given in Table 2 and Fig. 2.

3. Scenario development for the energy system analysis of Bangladesh

In this section, we briefly explore the energy system of Bangladesh and present the scenarios designed to perform this study and the related baseline assumptions.

3.1. Current and future energy policies in Bangladesh

In 2016, nearly 92% of the total electricity generated in Bangladesh was sourced from fossil fuels, with major contribution from natural gas (60%) and the remaining from expensive furnace oil and diesel (32%) [10,46]. In future, electricity generation will be dependent on imported natural gas as its domestic natural gas fields are fast depleting. According to Ahmed et al. [47], natural gas fields in the country will be empty within 15 years and running an energy system that will be entirely depend on imported fuels, will undermine the energy security of the country.

The power sector in Bangladesh is entirely managed by the Bangladesh Power Development Board (BPDP), which is

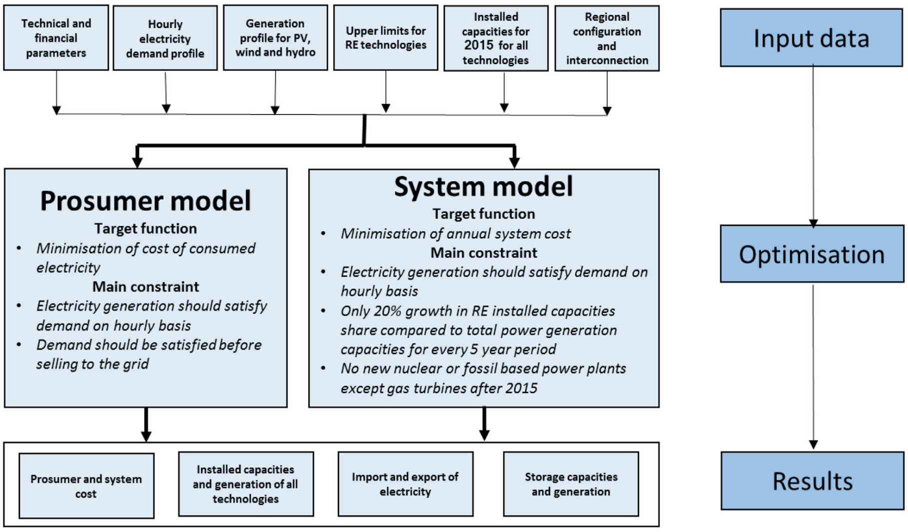


Fig. 1. A simplified version of the LUT Energy System Transition model flowchart from input parameters to results.

Table 2
The list of technologies utilised for the energy system transition.

	Technologies utilised
Generation	**Renewables:** PV rooftop for prosumers, PV fixed-tilted, PV single-axis tracking [44], wind onshore, hydropower, geothermal, biomass and waste-to-energy **Fossil:** coal, gas and oil Nuclear power
Storage	Batteries, pumped hydro energy storage (PHES), adiabatic compressed air energy storage (A-CAES) [45], gas storage and thermal energy storage (TES).
Transmission	High Voltage Alternating Current (HVAC)

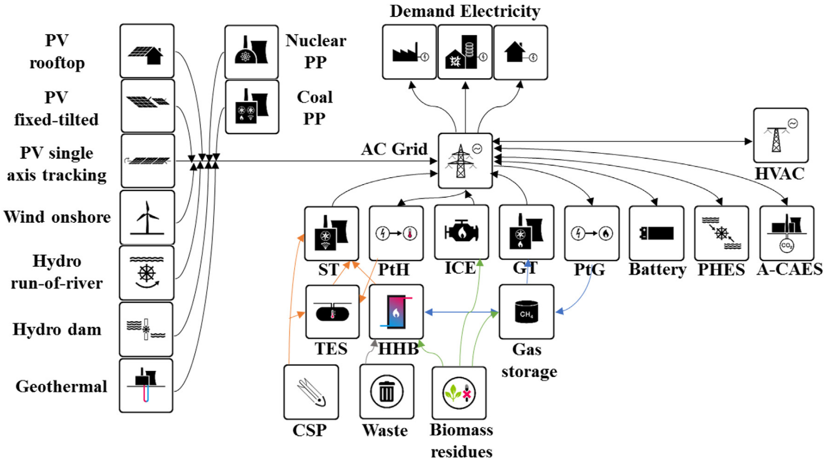


Fig. 2. The LUT Energy System Transition model [31].

responsible for electricity generation, transmission and distribution. The current installed capacity is around 18 GW, which includes 2 GW of renewable energy [46,48]. Due to the persistent problems of under generation, transmission and distribution losses [49], current installed capacity is not enough to satisfy the ever-growing demand. To overcome the power shortage problem, the government has undertaken Quick Rental Power Plant (QRPP) project based on oil. However, price fluctuations of crude oil in the international market have increased the costs of electricity from these power plants. Even if the government is committed to purchase electricity at the cost of production, the effect failed to provide the aspired least cost electricity to the society [50].

According to the future policy of the Government of Bangladesh, coal and natural gas are expected to be the main fuel sources for power generation until 2041 [40]. However, local reserves of these resources are limited and therefore the nation will rely on increasing fuel imports regardless of further risks associated with GHG emissions increase [50]. It should be noted that the power sector alone contributes to 40% of the GHG emisisons in Bangladesh [51]. The target (until 2030) for example, aspires to increase the capacity of coal power plants: 11.5 GW from domestic coal and 8.4 GW from imported coal [51].

3.2. Renewable energy and GHG emissions abatement strategy in Bangladesh

Bangladesh is amongst the developing countries with a small share of GHG emissions on the global level [52]. However, it is one of the most vulnerable countries in the world to climate change. The Government of Bangladesh has ratified the United Nations framework for climate change mitigation on 22nd April 2016 [53]. The submitted Intended Nationally Determined Contribution (INDC) includes emissions reduction goals in the power, transport and industry sectors with an additional clause of conditional and unconditional contributions. An unconditional contribution is to reduce the total GHG emissions by 5% from the business-as-usual (BAU) levels in 2030. However, with additional international support it plans to reduce its GHG emissions by 15% from the BAU levels by 2030. To support its commitment, Bangladesh has a number of activities and targets to reduce GHG emissions. Some of these activities include reducing the energy intensity (per GDP) by 20% by 2030 compared to 2013 levels, increasing the energy efficiency of new buildings, increasing penetration of renewables to 10% by 2020. The planned renewable energy increase is intended to utilise the abundant solar potential, by increasing the distribution of solar home systems, solar irrigation pumps, solar mini-grids and nano-grids [54], along with building utility-scale solar PV systems [52].

Bangladesh has good renewable energy potential, especially for solar energy. Fig. 3 shows the distribution of solar yield in Bangladesh. According to Ahamad and Tanin [55], Bangladesh receives an average solar irradiation of around 1095–1460 kWh/(m^2·a) and has the potential to generate 380 TWh of electricity, requiring about 10% of the total area of Bangladesh (excluding area under agricultural and forest cover) [10,56]. This potential is significantly higher than the present annual electricity demand and could satisfy the projected electricity needs. Bangladesh can follow suite of its neighbouring country India, where the cost of electricity generated from solar PV is currently amongst the lowest in the world, at about 35 €/MWh [57]. To realise the solar PV potential and cost competitiveness against fossil fuel power plants, India has set up target to install 100 GW by 2022 [58] and 227 GW by 2027 [59].

Similarly, the Government of Bangladesh has initiated a number of programs to take advantage of its renewable energy potential. The renewable energy policy was adopted in 2008 with an aim to boost renewable power generation [61]. In 2015, Bangladesh joined the International Solar Alliance to collaborate towards increased adoption of solar energy [62]. The installation of solar home systems in off-grid areas had been booming in the last decade [63]. So far, 218 MW of solar home systems have been installed [64]. There were about 5 million solar home system (SHS) installations in 2017, for the benefit of 30 million people and has created 140,000 new jobs [65]. Rooftop solar installations for commercial and residential buildings has been gaining popularity in recent years [66]. For utility-scale solar PV, non-agricultural land owned by the government is being used, mainly to develop solar parks [66]. Wind energy potential is around 340000 MW in Bangladesh with its nearly 740 km long coastline and many small islands, where strong winds are present during the monsoon season (May-October) [67]. Municipal waste has the potential to become a good energy resource for Bangladesh. In 2015, 27 million tons of municipal solid waste was produced in different municipalities [48]. Out of this, organic waste constitutes 78.9% [48], which can produce 10 TWh_{th} of biogas. Bangladesh also has a large potential of biomass due to its agricultural economy. Agricultural and forest residues form a major component in its biomass potential. According to Hossen et al. [68], agricultural, municipal waste, industries, animals and other sources of waste can generate >950 TWh_{th} of energy considering that all waste is recovered. In addition, 315 MW of small scale and large-scale hydropower plants can be installed in Bangladesh [61]. To ensure long term energy security without burdening the economy or the enviornment, Bangladesh will need to stress on policies that will exploit these RE potentials.

3.3. Parameters and assumptions in the modelling

3.3.1. Subdivision and grid structure of Bangladesh

For the purpose of this study, Bangladesh was sub-divided into seven sub-regions based on population distribution, consumption of electricity and the grid structure. The division of Bangladesh into seven regions enables a high spatial resolution of the power system, as shown in Fig. 4. The assumed grid structure is based on the current power grid, with Dhaka as the main consumption centre, which is connected with all the sub-regions. The inter-regional connections are via HVAC lines and intra-regional connections are based on existing AC grid structure of the country.

3.3.2. Potential and feed-in profiles for generation technologies

The generation profiles for single-axis tracking and optimally tilted PV, solar CSP, wind energy and hydropower were provided as an input data to the model. The feed-in profiles were calculated according to Bogdanov and Breyer [42], whereas single-axis tracking PV was modelled according to Afanasyeva et al. [44]. For the base year 2015, installed capacities of solar PV, wind and hydro were taken from Farfan and Breyer [69]. Upper limits of the RE capacities were added after evaluating the potential. The potential of wind and hydro power are limited [66,70]. On the other hand, Bangladesh has one of the best solar resource availability [10], but a criteria was set so that the total land area availability for solar PV installations does not exceed more than 6% of the total area of a sub-region. It should be noted that solar resource variation over an area such as the sub-regions in Bangladesh, is negligible [71,72]. Thus, one selected site in each sub-region can give a good representation of the resource availability in that particular sub-region, and the respective algorithm from Bogdanov and Breyer had been applied [42]. The variable solar resource characteristic data was according to real weather year 2005. The overall wind energy potential in Bangladesh is limited to the coastal areas and mainly available during the monsoon season [66,73,74]. Additionally, due

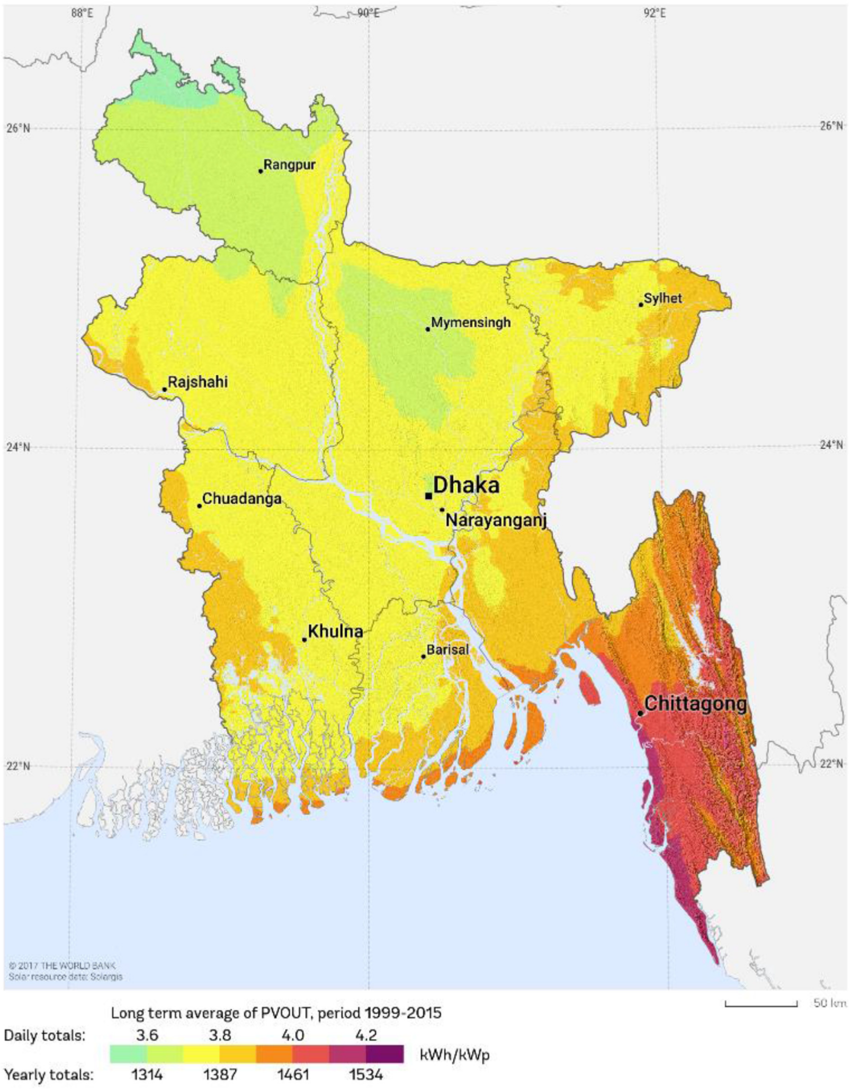


Fig. 3. The photovoltaic power generation potential for an optimally fixed tilted 1 kWp system for Bangladesh [60].

to the spatial resolution of wind data, there could be some spots with good wind speed profiles that may not have been captured, especially in the coastal areas. The impact of such data limitations should be assessed when better data are available.

Additionally, the model utilises the potential of storage technologies in each of the regions. The Energy-to-Power ratios and the efficiencies of the storage technologies are given in Ref. [31]. The installed capacity of each storage technology is based on the requirement of energy-to-power ratio and the economic performance.

Biomass was divided into three categories: solid wastes, solid residues and biogas. The potential of biomass for Bangladesh was obtained from Ref. [75] and divided into different sub-regions, according to the area and population of each region. The cost

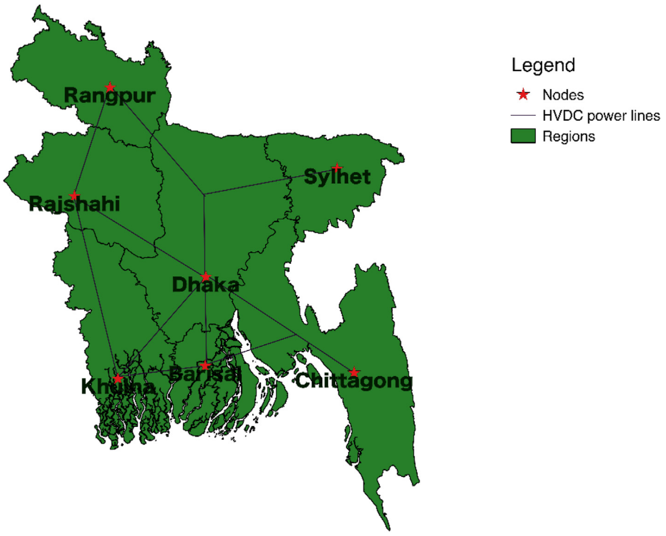


Fig. 4. The seven sub-regions in Bangladesh and the grid connections.

calculations for the three biomass categories were done according to the data from International Energy Agency [76] and Intergovernmental Panel on Climate Change [77]. For solid fuels a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for waste incineration plants and this is reflected in the negative costs for solid waste [31].

At present, geothermal energy does not play a critical role in Bangladesh. However, the model input consists future geothermal potential for all the seven sub-regions, which is calculated according to the method described in Ref. [30].

The lower and upper limits for renewables are given in the Supplementary Material (Table S3).

3.3.3. Financial and technical assumptions

The weighted average cost of capital (WACC) for Bangladesh is set at 7% in real terms for the investments considering the stability and the potential of renewable energy in the country. For residential rooftop PV installations, WACC of 4% was used due to lower financial return requirements. The increase or decrease in WACC does not alter the costs of electricity considerably [19].

The economic assumptions for capital expenditures (CAPEX) and operating expenditures (OPEX fixed and variable) and the technical assumptions for efficiency and lifetimes of the different technologies utilised in the energy transition of Bangladesh are tabulated in the Appendix Table A1 and A2 Due to absence of country specific cost projection data, a global average of the financial cost projections were assumed. The financial assumptions of important renewable technologies are based on the steady cost decline from around the world and the expected fast cost decline with faster capacity additions in the future. This is reported in a number of established studies [23,78,79]. It is assumed that with the ongoing improvements in technology and production processes, the costs of materials and installations will fall considerably from their current values until 2050. For example, the cost of power produced from solar PV has gone down to 14.9 €/MWh in 2017 from around 70–80 €/MWh in 2014 [80,81]. It should be noted that 14.9 €/MWh is globally the least cost observed, but a range of 20–25 €/MWh is regularly achieved worldwide. In addition, globally the cost of batteries have decreased by 77% in the last 7 years [23,82,83]. The cost of onshore and offshore wind power plants, particularly offshore wind plants are expected to decline sharply in the future [84]. The sharp decline in cost is possible due to the expected learning curves [85].

The price of electricity for 2015 for the three prosumer categories were assumed from Dhaka Electric Supply Company Limited [86] and future prices until 2050 were calculated according to the methodology described in Breyer and Gerlach [87]. The electricity prices for Bangladesh are provided in the Supplementary Material (Table S1).

3.3.4. Electricity demand

The electricity demand is taken from Power System Master Plan report 2010 [88] and 2016 [40] and extrapolated until 2050 with the provided growth rate. The hourly load profile for electricity for each sub-region is calculated as a fraction of the total demand in Bangladesh based on synthetic load data according to Toktarova et al. [89], weighted by the sub-region's population.

3.4. Description of the scenarios

For this study, four scenarios were developed after reviewing the local energy policies and future energy planning. The scenarios help to focus on the policy options leading to a transition towards 100% RE system taking into account the GHG emissions reduction and the overall system cost. The description of the scenarios and the assumptions are given in Table 3.

3.5. Model calibration

The model was calibrated using the 2015 generation and

Table 3
Detailed description of the four scenarios.

Scenario	Detailed description
Best Policy Scenario (BPS)	This scenario focusses on achieving a 100% renewable energy system by 2050. To achieve the stated target, three main assumptions were considered. First, no new fossil fuel capacities are allowed to be installed after 2015, except gas fired power plants, and the phased out capacities can only be replaced by renewables and storage, also imports were restricted from the neighbouring countries after 2015. Second, the model assumes a carbon cost of 9 € in 2015, which increases in 5-year time steps to 28, 53, 61, 68, 75, 100 and 150 € per ton till 2050, respectively. Third, no more than 20% growth in RE installed capacities share compared to total power generation capacities can be achieved for each 5-year time step, to avoid meaningless increase in capacities. The BPS scenario incorporates the potential role of prosumers (rooftop PV, optionally with batteries) during the system transition using an exogenously estimated prosumer capacity. The prosumer potential calculation is performed using an hourly optimisation model, which installs rooftop PV and optionally battery systems for residential, commercial and industrial customers. The target function for prosumers is cost minimisation of the consumed electricity, calculated as a sum of generation, annual costs and cost of electricity consumed from the grid. The prosumers have an option to sell the excess generation to the grid at an assumed price of 0.02 €/kWh, after fulfilling their own demand, but not more than 50% of their own generation. The limit on prosumer installations is 20% of the total electricity demand in 2050.
Best Policy Scenario with no carbon cost (BPS-NCC)	This scenario is similar to the BPS scenario. The only difference is the removal of the assumed GHG emissions costs throughout the transition period. Currently, Bangladesh does not have any GHG emissions costs. There is no evidence that any costs will be applied in the future as well. Thus, a scenario without GHG emissions costs will show the potential role of renewables as derived by their cost competitiveness. In addition, this scenario does not limit fossil fuels by 2050, as in the BPS scenario.
Current Policy Scenario (CPS)	This scenario is based on the national 'Power System Master Plan 2016' [40]. This plan was developed to diversify the power generation sources and transform the country into a high-income country by 2041. As the current domestic natural gas supply is diminishing, the increasing electricity demand is expected to be satisfied by importing fossil fuels. In addition, electricity imports will play a significant part in satisfying the growing demand. While, local renewables are expected to play a minor role in the overall electricity generation mix of the country. However, for this scenario a GHG emissions costs similar to the BPS scenario is assumed. The levying of carbon tax would bring a huge monetary benefit annually to the Government of Bangladesh. The implementation of a carbon tax was previously discussed on a wide scale [90], however before the elections in 2017, it was scrapped citing various reasons [91]. The main reason being that a carbon tax would increase the price of electricity and raise living costs. The authors have not considered a scenario by the National Committee to Protect Oil, Gas, Mineral Resources Power and Ports (NCBD), a study that appears to show a possibility of more renewable alternative as opposed to the proposed PSMP plan [40]. Because the study analyses the case of 2041 without presenting any detail of what happens in between. Moreover, a high renewable future that was intended to be demonstrated by the NCBD report is investigated in much detail in the BPS and BPS-NCC scenarios. The masterplan by the Government of Bangladesh shows that electricity imports will be an important factor to satisfy the future demand growth, for stable base load supply and supply diversification [40]. In 2015, Bangladesh imported 500 MW of power from India. The 3.8 TWh of imported electricity contributed about 9.5% to the total consumption in that year [46,92]. In addition to an increasing capacity of imports from India, Bangladesh plans to import power from the neighbouring countries of Bhutan, Myanmar and Nepal. The future share of imports is expected to rise to around 15–25% of the total power generation until 2041 [39]. In order to account for electricity imports in the LUT modelling tool, a 'Deflated demand' approach was adopted. In this, the imported electricity is subtracted from the total demand and the new residual demand is used as the input for the simulation. This logic follows the prosumer approach, so that finally the domestic residual system demand is optimised. As the Government of Bangladesh wants to use the imported electricity to meet the base load, this methodology may be a better way to represent the role of imported electricity in the power system. As Bangladesh will have power purchase agreements with the respective neighbouring countries for imported electricity, assuming a constant hourly import is a simplified way to capture the hourly distribution.
Current policy scenario with no carbon costs (CPS-NCC)	This scenario is similar to the CPS scenario, except the consideration of GHG emissions costs, similar to the BPS-NCC scenario.

installed capacities for the different power technologies obtained from the Government of Bangladesh [40]. This was done by reproducing the 2015 results for each of the scenarios using the installed power plant capacities and demand data, the results for the energy generation by each technology is in agreement with the actual generation in 2015. All scenarios use this result as a starting point and continue to 2050 depending on the intended scenario constraints as discussed in Table 3.

4. Results

The optimised results with respect to the cost structure, installed capacities of generation and storage technologies and annual GHG emissions in the transition period will be presented as follows.

4.1. Cost structure of the transition

The results related to the levelised cost of electricity (LCOE) in the transition period for the BPS, BPS-NCC, CPS and CPS-NCC scenarios, respectively are presented in Fig. 5.

LCOE is highest for CPS and CPS-NCC scenarios for all the transition years. These two scenarios are primarily comprised of fossil fuels, particularly natural gas and oil in the initial years of the transition and later on supported by coal power plants. GHG emissions costs have a huge impact on the total LCOE in all the scenarios, particularly the CPS scenario, where the total LCOE in 2050 is higher by 69% in comparison to its LCOE in 2015. The combination of high GHG emissions costs and close to 90% fossil fuels in total electricity generation in 2050 are primary reasons for the high LCOE. Completely abolishing the GHG emissions costs (CPS-NCC scenario) during the transition, decreases the LCOE in comparison to the CPS scenario, however, the LCOE is still higher than the two BPS scenarios and has very high GHG emissions, which is to be explained in section 4.6.

Fossil fuels are associated with a 'fuel cost' i.e. cost of producing a unit of electricity from a particular fuel. For the year 2015, oil is associated with the highest fuel cost of 52.5 €/MWh (89.3 €/bbl) and natural gas of 21.8 €/MWh (0.23 €/Nm^3). The high fuel costs associated with natural gas and oil, contribute to about 80% of the

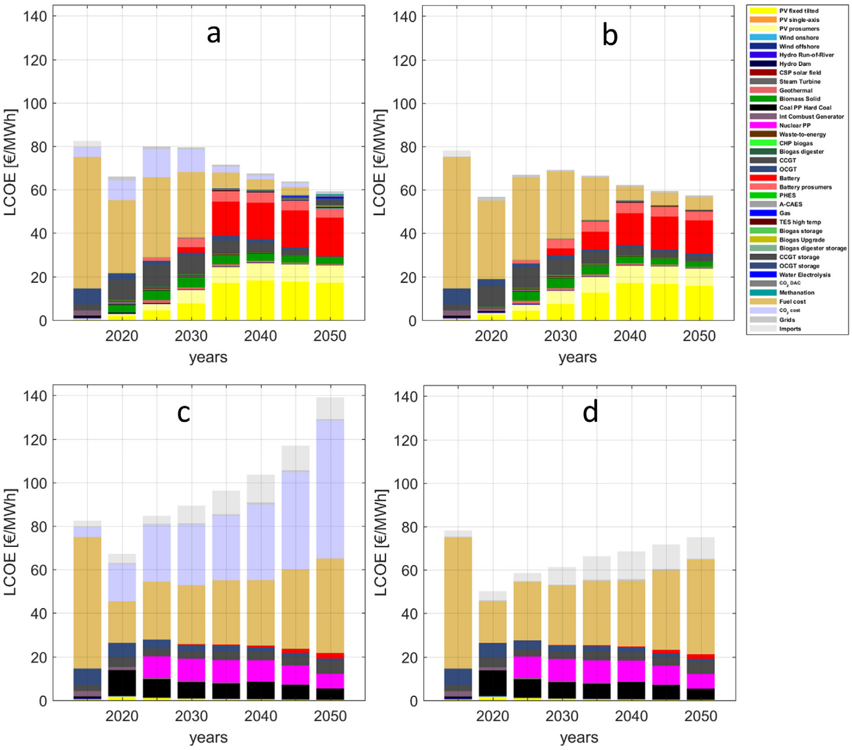


Fig. 5. The LCOE distribution according to each technology in the transition years from 2015 to 2050 for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

total generation, and the associated costs of emissions contribute to the LCOE in 2015. The fuel costs for all the fossil fuel technologies and the emissions costs assumed are provided in the Supplementary Material (Fig. S6 and Table S6 respectively). After 2015, the LCOE decreases in 2020 for all the scenarios, due to the influx of flexible power generation technologies, however, after 2020 the LCOE increases for the CPS scenarios.

For the BPS scenarios Fig. 5a and b, LCOE decreases by about 20–28% in 2020 compared to 2015, primary factors being the reduction in utilisation of expensive fossil fuels and the associated GHG emissions costs. The power generation from expensive, inefficient and inflexible oil and diesel based power plants reduced considerably from 15% in 2015 to almost 0% in 2020. This decrease is in agreement with the government's policy of not installing new oil and diesel based power plants in the transition years, though unlike their vision, these scenarios replace the created fossil fuel generation shortfall with an increased electricity production from renewables especially solar, biomass and municipal waste.

Specifically, the large biomass and municipal waste resource discussed in section 3.2, plays a major role in replacing the fossil fuel generation as observed from 2015 to 2020. With the falling cost of solar PV during the transition years, it becomes the main source of electricity generation in both BPS scenarios. Despite the similarity in cost trends between BPS and BPS-NCC scenarios, it can be seen that LCOE remains lower in the BPS-NCC scenarios. This is because of the avoided costs of GHG emissions in this scenario and the reduced costs of achieving a faster transition as observed in the BPS scenario. The impact of fast transition requirements of the BPS scenario has resulted in 100% RE in 2050, as compared to 94% for the BPS-NCC scenario for the same year. While the LCOE for BPS-NCC scenario presented in Fig. 5b shows the fossil fuel role, it can be inferred that Bangladesh could remove significant power sector GHG emissions by promoting solar and battery storage technologies (subject to be detailed later). Note that by 2050, emissions in the BPS scenario becomes zero. However, the relatively higher LCOE by 2050 of 4% is due to the increased investments in renewable capacities and the need to install storage technologies to arrive at 100% RE.

For the CPS scenarios with and without GHG emissions costs as given in Fig. 5c and d, LCOE decreases slightly in the year 2020 in comparison to 2015, due to the planned investments in relatively cheaper fossil fuel generators than oil-based power plants. In Fig. 5c and d, corresponding LCOE increases in the transition years from 2020 onwards. In comparison to BPS scenarios, LCOE for CPS scenarios are higher for all the years. In 2050, LCOE for CPS and CPS-NCC scenarios are 58% and 25% higher than the BPS scenario,

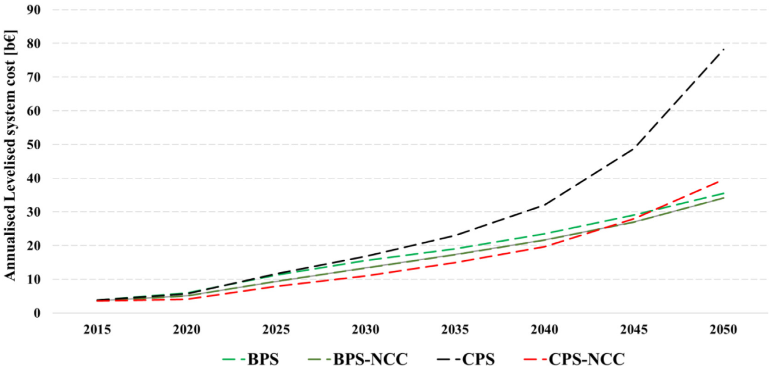


Fig. 6. Total annual costs of the system for all the scenarios in the transition years.

respectively. The low price of imported electricity may have reduced total LCOE in transition years, as compared to the expensive electricity generation options in Bangladesh. It can be concluded that a solar-based policy would provide Bangladesh the best transition option, as compared to the present fossil-based policy.

The total annual cost of the system in 2050 for all the scenarios is given in Fig. 6. The total cost is calculated as a sum of annual costs from all the power generation capacities, energy generation, generation ramping of the technologies, storage technologies and transmission costs of the generated electricity for each of the transition year. The BPS-NCC scenario shows the lowest cost, which suggests economically to be a favourable scenario, however this scenario does not give a 100% RE system. The CPS scenario has the highest cost due to the combination of high fuel and emissions costs followed by CPS-NCC scenario. On the other hand, BPS scenarios with and without GHG emissions costs show that a high share of renewables in the energy system does not increase the total cost of the system. The annual cost of the BPS-NCC scenario is lowest while, the BPS scenario costs about 4% more than the BPS-NCC scenario.

4.2. Primary electricity generation during the energy transition period

The previous section shows that Bangladesh obtains a better transition option if it emphasises on a solar-based policy by producing cheaper electricity for its customers. In this section, we will examine detailed electricity generation by each technology type in all the scenarios as presented in Fig. 7.

For the BPS scenarios, phasing out of fossil fuels, especially gas, is substituted by an increase in generation from solar PV and biomass for the year 2020. However, it should be noted that the share of biomass remains constant after 2025 because of full exploitation of the maximum resource potential assumed for the scenarios while, that of solar PV increases throughout the transition. The application of GHG emissions costs to the BPS scenario enforces a fast decrease in electricity generation from natural gas from 2035 onwards, which finally reaches zero in 2050 as compared to the BPS-NCC scenario that expects approximately 6% electricity generation from fossil gas in 2050.

On contrary, CPS scenarios rely on electricity generation from fossil fuels, including nuclear energy, and electricity imports from neighbouring countries. The primary electricity generation in 2015 is dominated by natural gas in the CPS scenarios, due to its vast domestic availability. However, due to forecasted depletion of the local natural gas reserves [41], electricity generation was planned to shift to coal in 2020, which is demonstrated in Fig. 7c and d. As a consequence, in 2020, coal and natural gas power plants contribute 75% and 19% of the electricity generation, respectively. After 2020, following the government plans, scenarios show an increased role of natural gas, nuclear and electricity imports. Evidently, the share of renewables in primary electricity generation is almost invisible.

4.3. Installed capacities of the technology mix in the transition

The installed capacities of different technologies in the transition period for the four scenarios is shown in Fig. 7 and absolute numbers can be found in the Supplementary Material (Table S2).

In the BPS scenarios, the fossil fuel dominated capacity mix gradually changes to renewables, dominated by solar PV in 2050. For the year 2015, total installed capacity is around 10 GW. For the BPS and BPS-NCC scenario, capacity increases to around 530 GW and 457 GW in the year 2050. The difference in installed capacities is due to the fact that in the BPS scenario, additional capacities are required for converting electricity to RE-based synthetic natural gas (SNG) via methanation plants (Fig. 7a), which is further utilised by CCGT and OCGT power plants to produce electricity [93,94]. This is further emphasised by the installed capacities of gas storage technologies (Fig. 8). However, for the BPS-NCC scenario, these extra capacities are not needed due to utilisation of fossil gas.

The BPS scenario places an additional financial constraint on the system to install renewables, particularly, solar PV which can be observed from relatively higher installed capacities in each of the transition years in comparison to the BPS-NCC scenario. To reduce the overall cost of the system, the BPS scenario invests at a faster rate in RE technologies, which aim at reducing GHG emissions. However, the BPS-NCC scenario still leads to very high penetration (94% of the annual generation) of renewables in 2050. The overall trend shows that the cost decline of solar PV with batteries (see section 4.4 for additional information) is the main factor for high penetration in both BPS scenarios. This finding is similar to the

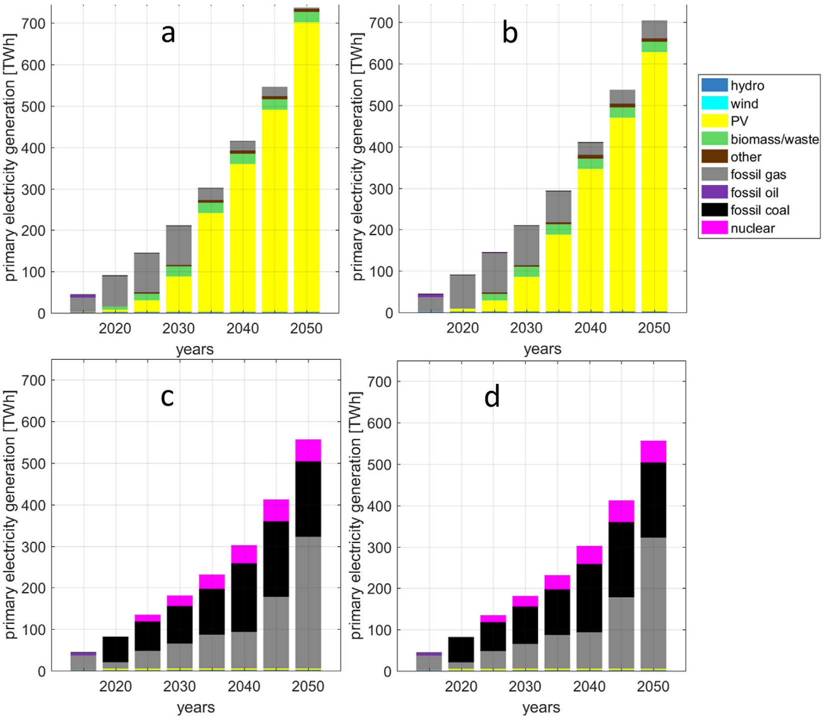


Fig. 7. Primary electricity generation in the transition years for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

results presented in Solomon et al. [6].

The technology mix for the CPS scenarios mirrors policy direction of the government to invest in fossil fuels (Fig. 8c and d). In comparison to the BPS scenarios, these pathways show an increasing trend in installations of coal, natural gas and nuclear capacities. With negligible renewable capacity addition, the share of solar PV remains constant during the transition, maintaining the current relatively small capacity mix throughout the transition period. Overall, it can be seen that Bangladesh pushes itself into a vulnerable position with respect to energy security by following a path that leads to significant dependence on fossil fuel imports.

For the BPS scenarios, Fig. 9a and b, in each region, installed share of solar PV is the highest. The PV share is between 20 and 83%, lowest being in the region of Barisal and highest in the region of Khulna. In the year 2050, it is observed that solar PV and battery provide low-cost electricity to power the increasing demand. The BPS-NCC scenario has a lower aggregated total installed capacity, however, some regions show an increase in their individual total capacities. The regions of Sylhet and Barisal show an increase in total installed capacities primarily due to utilisation of the existing installed gas turbines and further additional installations in 2050, as synthetic gas is not created, which can be later used to generate power, rather the system uses the available natural gas. This scenario does not enforce a transition to a fully renewable energy system in 2050.

For the CPS scenarios, in Fig. 9c and d, sub-region's installed capacities are based on coal, gas and nuclear. The region of Khulna has a share of around 77% and Chittagong accounts for 57% of the total coal capacity installed in Bangladesh. The nuclear power plant at Ruppur in the Rajshahi region is planned to be commissioned from 2023 to 24 and the government plans to install more capacities in the future. This is assumed to be constructed at the same location, therefore the installed capacities are located only in the Rajshahi region. The installed capacity of nuclear power plants is about 7 GW in 2050.

4.4. The role of energy storage technologies in the transition

This section shows that the need for energy storage technologies depend on scenarios as presented in Fig. 10. Scenarios emphasising on high shares of RE lead to a large scale energy storage as compared to the current policy direction of the country, which plans to rely heavily on fossil fuel generators. In the initial years, due to a lower share of renewables in the system, the model builds the most cost effective storage options, which can provide diurnal energy transfer depending on the scenarios. For the BPS scenarios, prosumer batteries appear first in 2025, due to higher penetration of prosumer PV in the system, which is followed by utility-scale batteries in 2030. The trend is similar for storage capacity installations and storage output for both BPS scenarios,

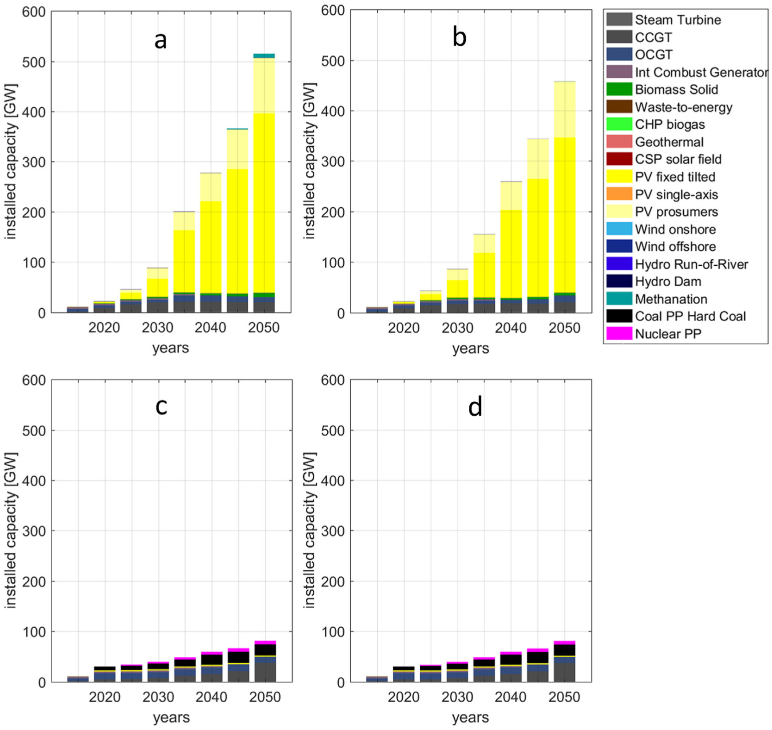


Fig. 8. Installed capacity mix in the transition years for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

except for gas storage, however, the absolute numbers differ significantly. As discussed before, the BPS scenario emphasises on faster transition through RE penetration in order to comply with the GHG emissions costs constraint. As a result, Fig. 10 shows a huge installation of gas storage for the BPS scenario and almost zero for the BPS-NCC scenario. The order of storage technology deployment observed in this study follows the requirement of the penetration-storage-curtailment nexus discussed in Ref. [95]. Batteries transfer daytime PV generation to the evening and night hours on a daily basis and disruption of this cycle or peak demand is taken care by CCGT and OCGT power plants, which run on fossil gas for the BPS-NCC scenario. Batteries provide the system with required flexibility and a cost effective option than utilising balancing from fossil fuel power plants for electricity generation. The share of electricity provided by batteries in total electricity demand is 50% and 55% in the year 2050, for the BPS and BPS-NCC scenario, respectively. The increasing share of solar PV (Fig. 7a and b) corresponds to the rising share of battery output (Fig. 10), as hybrid solar PV-battery systems evolve as a least cost combination to provide electricity until 2050. Gas storage for the BPS scenario is utilised from the year 2045 onwards, when the share of renewables crosses 96%, however huge installed capacities of the gas storage are observed in the year 2050. The electricity output from gas storage is very low in comparison to batteries as seen from Fig. 10a. Gas storage provides around 6% of electricity to the total electricity demand in the year 2050. It should be noted that the capex of gas storage is rather small compared to battery storage per unit stored energy, which is the reason why the LCOE of the entire energy system further declines (Fig. 5a).

Storage requirement in the CPS scenarios are very different in comparison to the BPS scenarios, as the storage requirements of fossil fuels are different. This is observed from the installed capacities of storage technologies and their outputs in Fig. 11a and b.

4.5. Effects of monsoon on a fully renewable energy system

Solar PV as a resource is well distributed in all the sub-regions of Bangladesh, for most parts of the year except for some months in the monsoon season. Batteries are used on a daily cycle to store solar electricity and satisfy the evening and night time demands in a fully renewable energy system. A slight change in the daily cycle of batteries is observed from days 175–275. This is due to onset of the monsoon season, where batteries are not charged to their full capacity. However, in summer months, excess electricity from the solar PV is converted to synthetic natural gas and stored in gas

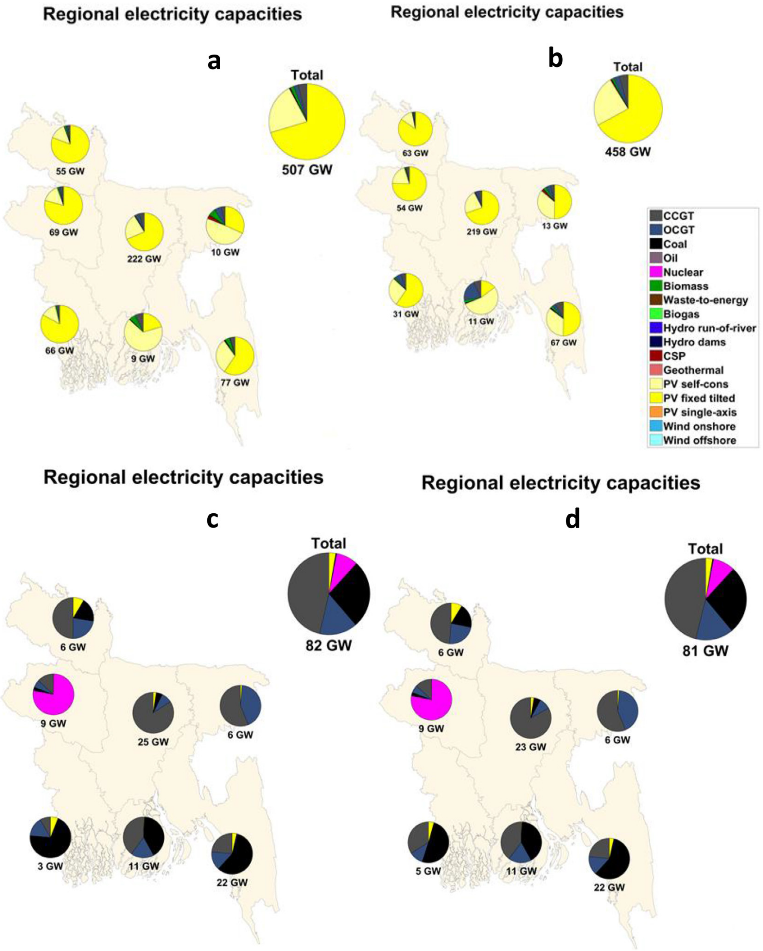


Fig. 9. Installed capacities according to the sub-regions of Bangladesh in 2050 for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

storage. It is observed from Fig. 12, that the gas storage is fully charged till the end of the summer season and slowly discharged around 175th day of the year, to compensate the decrease in solar electricity generation.

The hourly dispatch of electricity in a monsoon week for the capital region of Dhaka for the BPS scenario is shown in Fig. 13. Additionally, an hourly dispatch diagram for the non-monsoon week can be found in the Supplementary Material (Fig. S5), where it is observed that the solar resource is excellent to satisfy the daytime demand and also store excess electricity in batteries to satisfy the night time demand.

The monsoon affects electricity generation from solar and as a result batteries cannot provide electricity for the night time demand. The additional demand is met by PtG process utilising the combined gas turbines to produce electricity from synthetic natural gas. Additionally, at some hours, electricity is imported from neighbouring connected regions of Rangpur and Rajshahi to satisfy the demand as observed from Supplementary Material Fig. S6. In the period of low solar radiation, gas turbines and electricity transfer among sub-regions power the fully renewable energy system in Bangladesh.

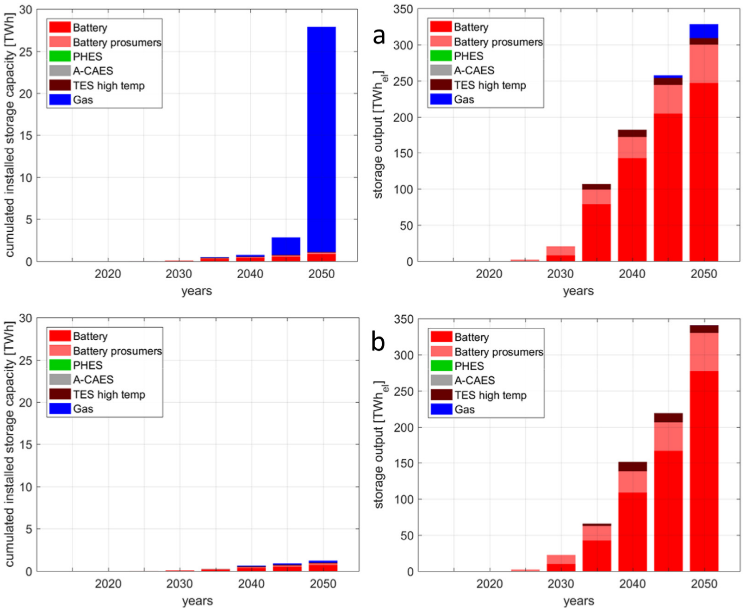


Fig. 10. Energy storage installed capacities and output by different storage technologies in the transition years for BPS (a) and BPS-NCC (b) scenarios.

4.6. Annual CO_2 emissions in the transition period

The annual net CO_2 emissions for the four scenarios in the transition period is illustrated in Fig. 14. The direct CO_2 emissions released to the atmosphere are considered in this study. Particulate matter (PM) and other GHG emissions such as methane, nitrous oxide, ozone, chlorofluorocarbons and hydrofluorocarbons are not considered. It can be inferred that proportional reduction is possible for other greenhouse gases and PM in the transition years for the BPS scenarios.

The two BPS scenarios follow the same path until 2030, but after 2030 the additional constraint of GHG emissions costs causes the BPS scenario to incorporate more RE in order to reduce the GHG emissions to zero in 2050. The remaining GHG emissions in 2050 for the BPS-NCC is due to the utilisation of fossil gas. The BPS scenarios show a slight increase in GHG emissions in 2025 due to the peak consumption of fossil gas in power generation, as the solar PV and battery hybrid are not yet cost competitive. It should be noted that, GHG emissions costs increases during the transition years from 9 €/t_{CO2eq} in 2015 to 150 €/t_{CO2eq} in 2050.

On the contrary, with the same starting point in 2015, emissions related to the CPS scenarios follow an upward trend due to negligible RE generation capacity in the transition years. The installation of coal and fossil gas based power plants release more and more GHG emissions into the atmosphere as the share of these technologies rises. The GHG emissions increase to 94.5 Mt_{CO2eq} in 2030 and after that increase linearly to 256 Mt_{CO2eq}, as the generation from fossil fuels increases considerably. The GHG emissions grow by 981% in 2050 in comparison to the emissions in 2015.

5. Discussion

This study presents various energy transition pathways for Bangladesh. The BPS scenarios, which are compatible with the Paris Agreement, lead to a least cost energy system in 2050 and are the best options for expanding the current energy system. Additionally, these scenarios avoid the risk of increase in GHG emissions and the likelihood for stranded investments in fossil fuel based capacities. On the contrary, it was shown that the government's plan emphasises on the most polluting and expensive options. Consequently, its present policies are a serious national risk that exposes it to several vulnerabilities, such as high costs of electricity, energy insecurity, and poor political trust. Similar risks were also reported in Solomon et al. [6]. However, the level of risk for Bangladesh appears to be much higher and more complicated due to its burgeoning population.

The first risk relates to domestically available resources. Domestically available natural gas will be exhausted around 2031, at the current rate of extraction [96]. On the other hand, government plans to install around 7 GW of coal capacities by 2020 and even more in the later years. With the coal capacity being at 0.2 GW in 2015, building new capacities would require huge mobilisation of all resources. Currently, no new coal power plants have been constructed. This is on top of the risks associated with the planned nuclear power plants, which have the associated high costs and other safety and environmental risks [97,98]. With these policies, Bangladesh not only imports the technology, but faces the need for an increased volume of fossil and nuclear fuels to be imported. The volatility of global fuel prices also makes the dependence on imported fossil fuels a high risk strategy. This

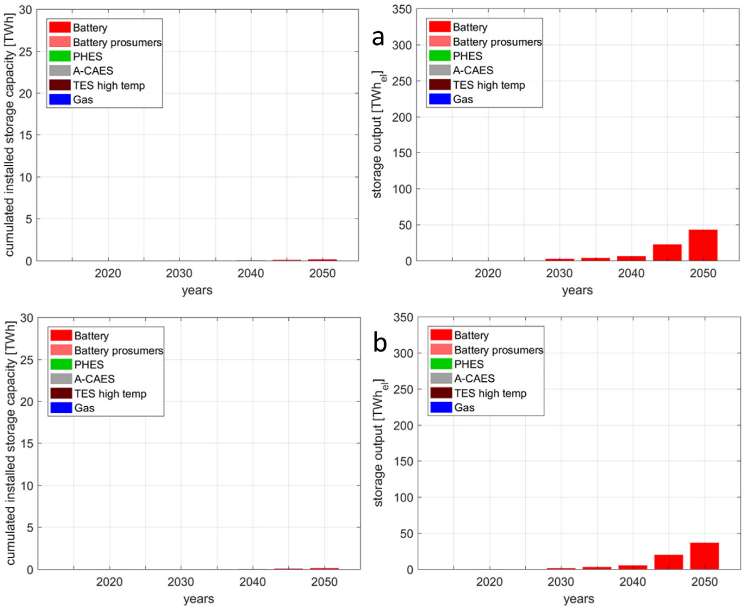


Fig. 11. Energy storage installed capacities and outputs by different storage technologies in the transition years for CPS (a) and CPS-NCC (b) scenarios.

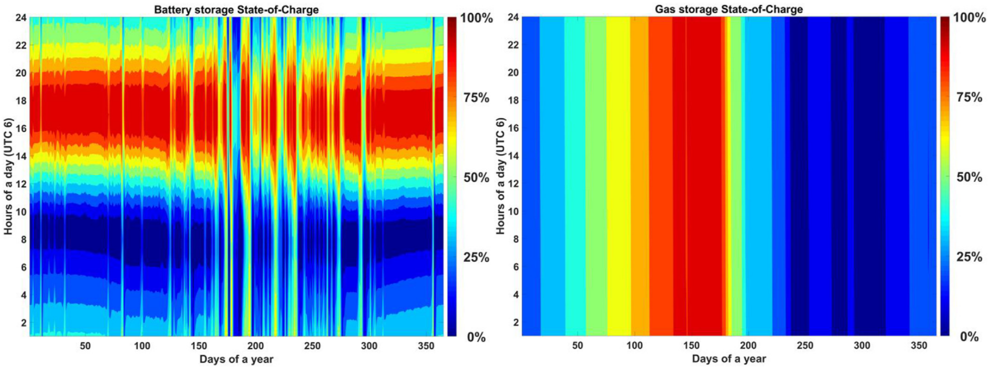


Fig. 12. State of charge of battery (left) and gas storage (right) in the BPS scenario in 2050.

compounds into a significant national risk in terms of trade and energy security. On the other hand, investing in locally available abundant renewable energy resources such as solar PV will not only decrease the GHG emissions, but also provide power to households living on remote islands, where grid extension has been an issue. A combination of centralised and decentralised solar PV systems will help achieve the government's aim to provide electricity to each and every individual in a cost effective way, moving away from expensive diesel generators. With low seasonal variability of solar resource, solar-based power generation is ideal for the demand and supply situation in Bangladesh. However, being one of the most densely populated countries, issues have been raised on the availability of land for huge utility-scale PV installations. The total land area of Bangladesh is

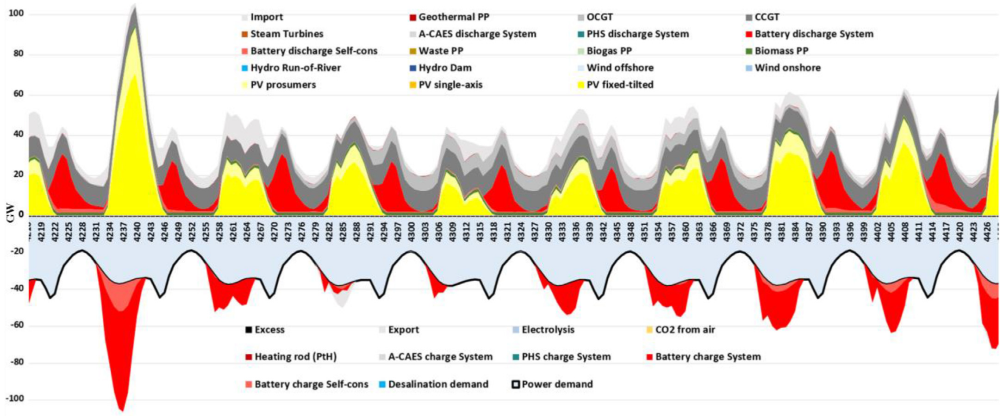


Fig. 13. Hourly dispatch of electricity in a monsoon week in the Dhaka region for the BPS scenario in 2050. The x-axis represents a particular hour in a year and the y-axis represents the capacity.

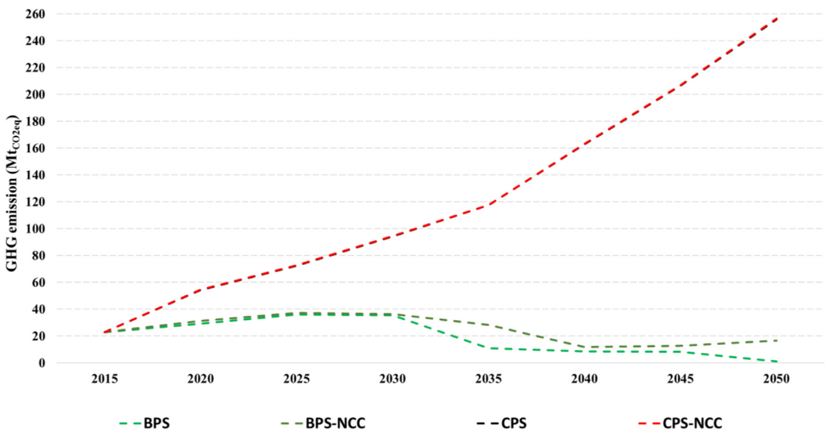


Fig. 14. GHG emission in the transition years from 2015 to 2050 for all the scenarios.

147,570 km^2 [56]. Currently, the land area suitable for agricultural purposes plus the portion covered by forests constitutes 81% of the total land area. Installing 357 GW of ground mounted solar PV (as in the BPS year 2050) would require about 10% of the land area from the remaining portion [56], assuming a PV module efficiency of 30% in 2050 [99] and the method of Bogdanov and Breyer [42], leading to 1.9% of required total land area. Rooftop PV systems are not considered since they can use the available roof area. The upper limit in the model is set to 6% of the total land area that would lead to a potential of about 1130 GW. It should be noted that water bodies, which could provide potential area for floating solar PV systems [100–103], cover about 12% of the area in Bangladesh. The government is considering the options to utilise Kaptai and other lakes, dams, beels, etc. which could provide electricity to remote locations [102]. Further, new designs of utility-scale power plants allowing crops to grown with them [103] and the various options of agricultural solar PV systems [104–106], can be explored to reduce stress on the land area requirements.

The other risk is related to the associated increase in GHG emissions. Bangladesh is one of the most climate vulnerable countries due to its low-lying areas, despite being a low emitter of GHG emissions per capita. Continuing these emissions trend with the underlying fact will make the government appear reluctant in protecting its citizens both locally and globally, leading to poor political trust.

The electricity sector in Bangladesh is grappling with various issues such as insufficient installed capacities, which are not able to satisfy the growing demand. Frequent blackouts and brown outs have become a daily part of the activities and incur huge losses to the GDP. Additionally, poor operational practices, inefficient technologies and inadequate maintenance add to the issues of the energy sector. These scenarios show that Bangladesh has important alternatives to its present strategy. The results of the BPS scenario show that, transition towards a 100% RE and zero emissions system is financially viable compared to the CPS scenario, due to rapidly declining renewable energy costs. The declining costs of renewables, especially, solar PV during the transition years provides better cost competitive options as shown in both BPS scenarios. Additionally, costs of the BPS scenarios would be even lower if the government's benchmark costs for solar PV is considered from neighbouring India [107]. Bangladesh should utilise the recent cost reductions in solar PV and tap into the growing market with local manufacturing and creating new jobs.

The technological mix, transition trends and typical RE future observed in these scenarios are also common to several other studies that investigate the case for other geographic regions [6,29,31]. Especially, recent studies on countries in the SAARC region, India [29] and Pakistan [31] grappling with similar issues as Bangladesh, show that a fully renewable energy future is possible with solar PV and batteries forming the backbone of the energy supply, subsequently with cost competitive electricity generation. With monsoon playing a big part in this region, the electricity system in India manages to overcome the decrease in solar PV with increase in generation from wind and hydropower plants, in addition to utilising the transmission line connections for electricity exchange between the different regions [29,108]. However, with limited availability of good wind conditions and hydropower, Bangladesh overcomes the decrease in solar PV output via increase in electricity production from synthetic natural gas storage via CCGT and OCGT turbines. This is a unique case for a country in the Sun Belt region and having a high share of solar PV in the system [20] and this presents a case for regions that will be highly dependent on solar PV, with no other resources to complement the decrease in solar electricity production. Gas storage will be an important technology in a fully renewable energy system. For Bangladesh, already existing infrastructure of gas turbines can be utilised with a fuel switch, i.e., utilising synthetic natural gas in place of fossil gas.

The stability and reliability of a fully renewable energy system on an hourly basis is provided by renewable technologies (mainly solar PV), batteries, the Power-to-Gas process and gas turbines utilising synthetic gas. Interaction of the above mentioned technologies can be observed from Figs. 12 and 13, showing the shifting of daily electricity by batteries to the night hours and when there is no electricity available from the batteries, the stored synthetic gas is utilised by gas turbines to produce electricity. Additionally, ancillary services are needed to stabilise and secure the electricity system, which are provided by conventional generators today. However, in a 100% RE-based system, synchronous condensers also called synchronous compensators, could provide all the ancillary services of conventional generators like fault current, inertia and voltage support, while active power can be provided by renewable generators and storage technologies [35]. According to Oyewo et al. [109], synthetic inertia provided by renewable technologies and batteries is extremely important for the stability of 100% RE systems. Additional flexibility options such as grid integration between countries would provide flexibility and stability to the power system in Bangladesh [30,110].

However, to implement the BPS scenario, Bangladesh needs to have appropriate policies, institutions and public awareness. Development of the Sustainable and Renewable Energy Development Authority (SREDA) in 2014 was a step in the right direction, but this organisation has to be developed and strengthened. One way to do this may be to collaborate with neighbouring countries that are leading in renewable energy development. For example, India, which has a similar energy situation as Bangladesh, has improved the growth of installed capacities of renewables with an establishment of an exclusive ministry for renewables. This together with its experience in successful implementation of solar home systems (SHS) deployment programme to electrify its rural population [111], Bangladesh could lead in prosumer and utility-scale PV. It is acknowledged that barriers do exist towards embracing renewables and moving away from the current fossil fuel mix. However, these barriers can be overcome by creating innovative policies by the government. Innovative financing mechanisms can be adopted from other countries that have a similar situation and are leading in large-scale RE deployment and adopted to local conditions. The government should encourage local manufacturing of renewable energy systems in order to reduce technology import costs and create new employment opportunities [112].

5.1. Limitations of this study and future research needs

This study tries to showcase techno-economic optimisation of the Bangladesh energy system through various scenarios, however, future policy decisions will be based on various other factors. So, the conclusion and findings of this study should not be seen as prediction of the future but rather one of the various ways to achieve a common goal of zero GHG emissions. We directly assume the electrification of the currently un-electrified population through being connected to the grid, however the growth in electrification will follow a different pathway. This is the next research focus to integrate rural electrification into the national energy transition modelling.

The assumptions concerning various parameters used in this study shape the results of the various scenarios. Sensitivity analysis of the input parameters will alter the results but not drastically, however this is recommended as future work. Higher spatial resolution of the data will provide more detailed insights and will better describe the regional variability. The results showcase only the power sector transition, however, addition of other sectors such as transport and industry will have a major impact on the results.

6. Conclusion

In this study, two scenarios (namely CPS) selected based on the government's policy direction and (BPS) created to study the possibility of achieving high RE shares in the future were devised to analyse the energy transition pathways for Bangladesh. One of the Current Policy and the Best Policy scenarios was with GHG emissions pricing. The key findings of the study are given below:

A 100% RE-based power system is possible for Bangladesh by 2050 with the cost of electricity lower than in 2015 for the BPS scenarios. However, policy approach from the government increases GHG emissions and electricity costs considerably in future years. This implies that Bangladesh needs to exploit indigenous renewable energy resources. It was observed that application of GHG emissions costs on the BPS scenario accelerates the transition towards zero emissions system, however, removing GHG emissions costs, does not drastically alter the capacity mix and generation by 2050. It was observed that the electricity generation was based on

94% renewables and the remaining was fossil gas. If the system was allowed to run until 2060–2070 with additional investments, it would be fully based on renewables. So, Bangladesh can think about the transition scenario even without enforcing GHG emissions costs, but based on a least cost pathway.

In the BPS scenarios, RE technologies produce enough electricity to cover the total electricity demand by 2050. The share of storage technologies, especially batteries increases simultaneously as the share of renewables increases, without increasing total cost of the system. Solar PV and batteries dominate the installed RE technologies due to their low costs and the excellent solar resource conditions available in Bangladesh. The fast declining costs of solar PV and batteries force the system to phase out fossil fuels including nuclear energy. Additionally, there is available land area for PV installations, along with new technologies such as floating PV and efficiency improvements in PV technology, utilising the huge resource potential would be beneficial for Bangladesh.

Overall, this study shows that Bangladesh entails serious national risks that lead to several vulnerabilities such as high costs of electricity, energy insecurity, and poor political trust due to its present policy direction. Similar risks are also observed for other developing countries. However, the level of risk for Bangladesh appears to be much higher and complicated. This study shows that RE solves the trilemma of security, reliability and cost effectiveness of energy services, which are hampering the growth of Bangladesh.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Ashish Gulagi: Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Manish Ram:** Methodology, Validation, Writing - original draft, Writing - review & editing. **A.A. Solomon:** Methodology, Validation, Writing - original draft, Writing - review & editing. **Musharof Khan:** Methodology, Investigation. **Christian Breyer:** Methodology, Supervision, Validation, Funding acquisition, Writing - review & editing.

Acknowledgements

The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14 which enabled the LUT Energy System Transition model. AG would like to thank Fortum Foundation for the valuable scholarship. MR and CB gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Finnish Solar Revolution' project under the number 880/31/2016. SAA and CB are also grateful for the LUT REFLEX internal finances. The authors would also acknowledge Arman Aghahosseini for the core set of diagrams, Dmitrii Bogdanov for the core LUT model and Francisco Javier Farfan Orozco for some input data.

Appendix A

Table A.1
Technical and financial assumptions of all energy system components used in the energy transition from 2015 to 2050 for Bangladesh. Assumptions are taken from Pleβmann et al. [113] and European Commission [114] and further references are individually mentioned.

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
PV rooftop - residential	Capex	€/kWp	1360	1169	966	826	725	650	589	537	[78]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kWp	1360	907	737	623	542	484	437	397	[78]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kWp	1360	682	548	459	397	353	318	289	[78]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally fixed-tilted	Capex	€/kWp	1000	580	466	390	337	300	270	246	[78]
	Opex fix	€/(kWp a)	15	13,2	11,8	10,6	9,6	8,8	8,0	7,4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kWp	1150	638	513	429	371	330	297	271	[78,115]
	Opex fix	€/(kWp a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW	1250	1150	1060	1000	965	940	915	900	[116]
	Opex fix	€/(kW a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/m^2	270	240	220	200	180	170	150	140	[117,118]
	Opex fix	%	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	
	Opex var	–	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	

Table A.1 (*continued*)

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
Geothermal power	Capex	€/kW	5250	4970	4720	4470	4245	4020	3815	3610	[114,119]
	Opex fix	€/(kW a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW	800	685	500	380	340	310	280	260	[120,121]
	Opex fix	€/(kW a)	32	27	20	15	14	12	11	10	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW	492	421	310	234	208	190	172	160	[120,122]
	Opex fix	€/(kW a)	10	8	6	5	4	4	3	3	
	Opex var	€/(kWh)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	
CO_2 direct air capture	Capex	€/kW	749	641	470	356	314	286	258	240	
	Opex fix	€/(kW a)	29.9	25.6	18.8	14.2	12.6	11.4	10.3	9.6	
	Opex var	€/(kWh)	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
	Lifetime	years	30	30	30	30	30	30	30	30	
CCGT	Capex	€/(kW$_{el}$)	775	775	775	775	775	775	775	775	[123]
	Opex fix	€/(kW$_{el}$ a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	58	58	58	58	59	60	60	60	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT	Capex	€/(kW$_{el}$)	475	475	475	475	475	475	475	475	[123]
	Opex fix	€/(kW$_{el}$ a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	43	43	43	43	43	43	43	43	
	Lifetime	years	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	Capex	€/(kW$_{el}$)	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW$_{el}$ a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	42	42	42	43	44	44	45	45	
	Lifetime	years	25	25	25	25	30t	30	30	30	
Steam turbine (coal-fired PP)	Capex	€/(kW$_{el}$)	1500	1500	1500	1500	1500	1500	1500	1500	[123,122]
	Opex fix	€/(kW$_{el}$ a)	20	20	20	20	20	20	20	20	
	Opex var		0	0	0	0	0	0	0	0	
	Efficiency	%	45	45	45	45	46	46	47	47	
	Lifetime	years	40	40	40	40	40	40	40	40	
Nuclear PP	Capex	€/(kW$_{el}$)	6210	6003	6003	5658	5658	5244	5244	5175	[114,124–126]
	Opex fix	€/(kW a)	162	157	157	137	137	116	116	109	
	Opex var	€/(kWh$_{,el}$)	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	
	Efficiency	%	37	37	37	38	38	38	38	38	
	Lifetime	years	40	40	40	40	40	40	40	40	
Biomass CHP	Capex	€/kW	3400	2900	2700	2500	2300	2200	2100	2000	
	Opex fix	€/(kW a)	238	203	189	175	161	154	147	140	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	36	37	40	43	45	47	47.5	48	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas CHP	Capex	€/kW	503	429	400	370	340	326	311	296	
	Opex fix	€/(kW a)	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	35	36	39	42	44	46	46	47	
	Lifetime	years	30	30	30	30	30	30	30	30	
Waste incinerator	Capex	€/kW	5940	5630	5440	5240	5030	4870	4690	4540	
	Opex fix	€/(kW a)	267.3	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
	Opex var	€/(kWh)	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Efficiency	%	27	31	32.5	34	35.5	37	29.5	42	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW	771	731	706	680	653	632	609	589	
	Opex fix	€/(kW a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW	340	290	270	250	230	220	210	200	[127]
	Opex fix	€/(kW a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	98	98	98	98	98	98	98	98	
	Lifetime	years	20	20	20	20	25	25	25	25	
Battery, Li-ion	Capex	€/(kWh$_{el}$)	600	300	200	150	120	100	85	75	[128]

(*continued on next page*)

Table A.1 (*continued*)

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
	Opex fix	€/(kWh$_{el}$ a)	24	12	8	6	4.8	4	3.4	3	
	Opex var	€/(kWh$_{throughput}$)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
Adiabatic compressed air energy storage (A-CAES)	Capex	€/kWh	35.0	35.0	33.0	31.1	30.4	29.8	28.0	26.3	
	Opex fix	€/(kWh a)	0.46	0.46	0.43	0.40	0.40	0.39	0.36	0.34	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh$_{th}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Table A.2
Energy to power ratio and self-discharge rates for storage technologies

Technology	Energy/Power Ratio (hrs)	Self-Discharge [%]	References
Battery	6	0	[113]
PHES	8	0	[113,114]
A-CAES	100	0.1	[114]
TES	8	0.2	[113]
Gas storage	80·24	0	[113]

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2020.03.119.

References

[1] [BP] - British Petroleum, Statistical Review of World Energy, British Petroleum, London, 2018. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html.

[2] D. Jason, Global Energy Demand Could Grow 124% by 2100: Even Fossil Fuels Won't Cut it, Greentech Media, Massachusetts, 2018. https://www.greentechmedia.com/articles/read/energy-needs-in-2100-even-fossil-fuels-will-not-cut-it.

[3] M. Kamaludin, Electricity consumption in developing countries, Asian J. Res. Soc. Sci. Humanit. 2 (2) (2013) 84–90.

[4] V. Cuming, L. Mills, D. Strahan, R. Boyle, K. Stopforth, S. Latimer, et al., Global Trends in Renewable Energy Investment 2015, UNEP and BNEF, Frankfurt am Main, 2015. http://fs-unep-centre.org/sites/default/files/attachments/key_findings.pdf.

[5] REN21, Renewables Global Futures Report: Great Debates toward 100% Renewable Energy, REN21 Secretariat, Paris, 2017. http://www.ren21.net/wp-content/uploads/2017/10/GFR-Full-Report-2017_webversion_3.pdf.

[6] A.A. Solomon, D. Bogdanov, C. Breyer, Solar driven net zero emission electricity supply with negligible carbon cost: Israel as a case study for Sun Belt countries, Energy 155 (2018) 87–104.

[7] [ADB] - Asian Development Bank, Booming South Asia Is Driving Economic Growth in Asia, Asian Development Bank, Manila, 2017. https://www.adb.org/news/features/booming-south-asia-driving-economic-growth-asia.

[8] [BBS] - Bangladesh Bureau of Statistics, Bangladesh Sample Vital Statistics 2016, Statistics and Informatics Division (SID), *Ministry Of Planning*, Government Of The People's Republic Of Bangladesh, Dhaka, 2017.

[9] Trading Economics, Bangladesh GDP Forecast, Trading economics, New York, 2015. http://www.tradingeconomics.com/south-korea/gdp.

[10] S.J. Ahmed, Tim Buckley, Simon Nicholas, Bangladesh Electricity Transition, Institute for Energy Economics Financial Analysis, Cleveland, 2016. http://ieefa.org/wp-content/uploads/2016/11/Bangladesh-Electricity-Transition_-NOVEMBER-2016.pdf.

[11] [WB] - World Bank, Access to Electricity, The World Bank, Washington DC, 2016. http://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS.

[12] M.A.H. Mondal, W. Boie, M. Denich, Future demand scenarios of Bangladesh power sector, Energy Pol. 38 (11) (2010) 7416–7426.

[13] [NCBD] – National Committee of Bangladesh, The Alternative Power and Energy Plan for Bangladesh, National Committee to Protect Oil Gas Mineral Resources Power and Ports, Dhaka, 2017. http://ncbd.org/wp-content/uploads/2018/01/The-Alternative-Power-and-Energy-Plan-for-Bangladesh-by-NCBD.pdf.

[14] [IPCC], in: Core Writing Team, R.K. Pachauri, L.A. Meyer (Eds.), Intergovernmental Panel on Climate Change, "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014. Geneva.

[15] [UNFCC], United Nations Framework for Climate Change, "Climate Displacement in Bangladesh, 2012. New York, https://unfccc.int/files/adaptation/groups_committees/loss_and_damage_executive_committee/application/pdf/ds_bangladesh_report.pdf.

[16] M.R. Dastagir, Modeling recent climate change induced extreme events in Bangladesh: a review, Weather Clim. Extrem. 7 (2015) 49–60.

[17] S. Nikitas, Haunting Photos Show Effects of Climate Change in Bangladesh, *Huffington Post*, New York, 2016.

[18] [HEI] - Health Effect Institute, State of Global Air-2017, Boston, 2017. https://www.stateofglobalair.org/sites/default/files/SOGA2017_report.pdf.

[19] C. Breyer, D. Bogdanov, A. Gulagi, A. Aghahosseini, L.S.N.S. Barbosa, O. Koskinen, et al., On the role of solar photovoltaics in global energy transition scenarios, Prog. Photovoltaics Res. Appl. 25 (8) (2017) 727–745.

[20] C. Breyer, D. Bogdanov, A. Aghahosseini, A. Gulagi, M. Child, A.S. Oyewo, et al., Solar photovoltaics demand for the global energy transition in the power sector, Prog. Photovoltaics Res. Appl. 26 (8) (2018) 505–523.

[21] N.M. Haegel, H. Atwater, T. Barnes, C. Breyer, A. Burrell, Y.M. Chiang, et al., Terawatt-scale photovoltaics: transform global energy, Science 364 (6443) (2019) 836–838.

[22] E. Williams, E. Hittinger, R. Carvalho, R. Williams, Wind power costs expected to decrease due to technological progress, Energy Pol. 106 (2017) 427–435.

[23] O. Schmidt, A. Hawkes, A. Gambhir, I. Staffell, The future cost of electrical energy storage based on experience rates, Nat. Energy 2 (8) (2017) 17110.

[24] Lazard, Lazard's Levelized Cost of Energy Analysis - Version 12.0, 2018. New York, https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf.

[25] [IRENA] – International Renewable Energy Agency, Renewable Power Generation Costs in 2017, 2017. Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.

[26] M. Child, C. Breyer, Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050, Renew. Sustain. Energy Rev. 66 (2016) 517–536.

[27] H. Lund, B.V. Mathiesen, Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050, Energy 34 (5) (2009) 524–531.

[28] A. Blakers, B. Lu, M. Stocks, 100% renewable electricity in Australia, Energy 133 (2017) 471–482.

[29] A. Gulagi, D. Bogdanov, C. Breyer, The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India, J. Energy Storage 17 (2018) 525–539.

[30] A. Gulagi, P. Choudhary, D. Bogdanov, C. Breyer, Electricity system based on 100% renewable energy for India and SAARC, PLoS One 12 (7) (2017).

[31] A. Sadiqa, A. Gulagi, C. Breyer, Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050, Energy 147 (2018) 518–533.

[32] A. Gulagi, D. Bogdanov, C. Breyer, A cost optimized fully sustainable power system for Southeast Asia and the Pacific Rim, Energies 10 (5) (2017).

[33] A.S. Oyewo, A. Aghahosseini, D. Bogdanov, C. Breyer, Pathways to a fully sustainable electricity supply for Nigeria in the mid-term future, Energy Convers. Manag. 178 (2018) 44–64.

[34] M. Barasa, D. Bogdanov, A.S. Oyewo, C. Breyer, A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030, Renew. Sustain. Energy Rev. 92 (2018) 440–457.

[35] T.W. Brown, T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, B.V. Mathiesen, "Response to 'Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems, Renew. Sustain. Energy Rev. 92 (2018) 834–847.

[36] H. Kenneth, C. Breyer, H. Lund, Status and perspectives on 100% renewable energy systems, Energy 175 (2019) 471–480.

[37] A.A. Solomon, D.M. Kammen, D. Callaway, The role of large-scale energy storage design and dispatch in the power grid: a study of very high grid penetration of variable renewable resources, Appl. Energy 134 (2014) 75–89.

[38] A.A. Solomon, D.M. Kammen, D. Callaway, Investigating the impact of wind-solar complementarities on energy storage requirement and the corresponding supply reliability criteria, Appl. Energy 168 (2016) 130–145.

[39] M.A.H. Mondal, M. Denich, T. Mezher, Deployment of renewable energy technologies in Bangladesh: long-term policy implications in power sector, Energy Strateg. Rev. 2 (3–4) (2014) 307–312.

[40] [PD] - Power Division Power System Master Plan, Energy and Mineral Resources, Government of the People's Republic of Bangladesh, Dhaka, 2016. http://powerdivision.portal.gov.bd/sites/default/files/files/powerdivision.portal.gov.bd/page/4f81bf4d_1180_4c53_b27c_8fa0eb11e2c1/(E)_FR_PSMP2016_Summary_revised.pdf.

[41] A. Das, A. Halder, R. Mazumder, V.K. Saini, J. Parikh, K.S. Parikh, Bangladesh power supply scenarios on renewables and electricity import, Energy 155 (2018) 651–667.

[42] D. Bogdanov, C. Breyer, North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options, Energy Convers. Manag. 112 (2016) 176–190.

[43] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, et al., Radical transformation pathway towards sustainable electricity via evolutionary steps, Nat. Commun. 10 (1) (2019) 1077.

[44] S. Afanasyeva, D. Bogdanov, C. Breyer, Relevance of PV with single-axis tracking for energy scenarios, Sol. Energy 173 (2018) 173–191.

[45] A. Aghahosseini, C. Breyer, Assessment of geological resource potential for compressed air energy storage in global electricity supply, Energy Convers. Manag. 169 (2018) 161–173.

[46] [BPDP] - Bangladesh Power Development Board, "Daily Generation Report," Bangladesh Power Development Board, 2017. Dhaka, www.bpdb.gov.bd/bpdb.

[47] S. Ahmed, M.T. Islam, M.A. Karim, N.M. Karim, Exploitation of renewable energy for sustainable development and overcoming power crisis in Bangladesh, Renew. Energy 72 (2014) 223–235.

[48] [SREDA] - Sustainable and Renewable Energy Development Authority, "Renewable Energy Master Database," Sustainable and Renewable Energy Development Authority, 2017. Dhaka, http://www.sreda.gov.bd/index.php/site/re_present_status.

[49] K. Sadovskaia, D. Bogdanov, S. Honkapuro, C. Breyer, "Power transmission and distributions losses – a model based on available empirical data and future trends for all countries globally, Int. J. Electr. Power Energy Syst. 107 (2019) 98–109.

[50] A. Islam, E.-S. Chan, Y.H. Taufiq-Yap, M.A.H. Mondal, M. Moniruzzaman, M. Mridha, Energy security in Bangladesh perspective - an assessment and implication, Renew. Sustain. Energy Rev. 32 (2014) 154–171.

[51] M.A. Habib, S. Chungpaibulpatana, Electricity generation expansion planning with environmental impact abatement: case study of Bangladesh, Energy Procedia 52 (2014) 410–420.

[52] [UNFCC], United Nations Framework Convention on Climate Change, "Intended Nationally Determined Contributions (INDC)," Paris, 2015. http://www4.unfccc.int/ndcregistry/PublishedDocuments/Bangladesh First/INDC_2015_of_Bangladesh.pdf.

[53] [UNFCC], United Nations Framework for Climate Change, "Bangladesh Signs Paris Agreement, 2016. United Nations, New York, https://www.un.int/bangladesh/sites/www.un.int/files/Bangladesh/Commiittees1516/press_release_29_on_bangladesh_signs_paris_agreement_.pdf.

[54] [IRENA] - International Renewable Energy Agency, Off-Grid Renewable Energy Systems: Status and Methodological Issues, 2015. Abu Dhabi, http://www.irena.org/documentdownloads/publications/irena_off-grid_renewable_systems_wp_2015.pdf.

[55] M. Ahamad, F. Tanin, Next power generation-mix for Bangladesh: outlook and policy priorities, Energy Pol. 60 (2013) 272–283.

[56] Trading Economics, "Bangladesh – Agricultural Land (% of Total Land Area), Trading economics, New York, 2015. https://tradingeconomics.com/bangladesh/agricultural-land-percent-of-land-area-wb-data.html.

[57] S. Shidore, J.W. Busby, What explains India's embrace of solar? State-led energy transition in a developmental polity, Energy Pol. 129 (2019) 1179–1189.

[58] P.K.S. Rathore, D.S. Chauhan, R.P. Singh, Decentralized solar rooftop photovoltaic in India: on the path of sustainable energy security, Renew. Energy 131 (2019) 297–307.

[59] D. Gielen, F. Boshell, D. Saygin, M.D. Bazilian, N. Wagner, R. Gorini, The role of renewable energy in the global energy transformation, Energy Strategy Rev. 24 (2019) 38–50.

[60] Solargis, Solar Resource Maps of Bangladesh, ESMAP and The World Bank, Washington DC, 2017. https://solargis.com/maps-and-gis-data/download/bangladesh/.

[61] [PD] – Power Division, Renewable Energy Policy of Bangladesh, Ministry of Power, Energy and Mineral Resources, Government of Bangladesh, Dhaka, 2008. https://www.iea.org/media/pams/bangladesh/Bangladesh_RenewableEnergyPolicy_2008.pdf.

[62] M.E. Karim, F. Azim, B. Bangladesh, Yearbk. Int. Environ. Law 27 (2016) 346–352.

[63] M. Kurata, N. Matsui, Y. Ikemoto, H. Tsuboi, Do determinants of adopting solar home systems differ between households and micro-enterprises? Evidence from rural Bangladesh, Renew. Energy 129 (2018) 309–316.

[64] REN21, "Renewables 2018 global status report REN 21," REN21 secretariat, Paris. http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_-1.pdf, 2018.

[65] REN21, "Renewables 2017 global status report REN 21," REN21 secretariat, Paris. www.ren21.net/gsr, 2017.

[66] M.A.H. Baky, M.M. Rahman, A.S. Islam, Development of renewable energy sector in Bangladesh: current status and future potentials, Renew. Sustain. Energy Rev. 73 (2017) 1184–1197.

[67] M.D. Jacobson, C. Draxl, A. Jimenez, B.L. O'Neill, T. Capozzola, S. Haupt, Assessing the Wind Energy Potential in Bangladesh: Enabling Wind Energy Development with Data Products (No. NREL/TP-5000-71077, National Renewable Energy Lab.(NREL), Golden, CO, 2018.

[68] M. Mosaddek Hossen, A.H.M. Sazedur Rahman, A.S. Kabir, M.M. Faruque Hasan, S. Ahmed, Systematic assessment of the availability and utilization potential of biomass in Bangladesh, Renew. Sustain. Energy Rev. 67 (2017) 94–105.

[69] J. Farfan, C. Breyer, Structural Changes of the global power generation capacity towards sustainability and the risk of stranded investments, J. Clean. Prod. 141 (2016) 370–384.

[70] M. Alam Hossain Mondal, L.M. Kamp, N.I. Pachova, Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh-An innovation system analysis, Energy Pol. 38 (8) (2010) 4626–4634.

[71] A.A. Solomon, D. Faiman, G. Meron, An energy-based evaluation of the matching possibilities of very large photovoltaic plants to the electricity grid: Israel as a case study, Energy Pol. 38 (10) (2010) 5457–5468.

[72] A.A. Solomon, D. Faiman, G. Meron, The effects on grid matching and ramping requirements, of single and distributed PV systems employing various fixed and sun-tracking technologies, Energy Pol. 38 (10) (2010) 5469–5481.

[73] P.K. Halder, N. Paul, M.U.H. Joardder, M. Sarker, Energy scarcity and potential of renewable energy in Bangladesh, Renew. Sustain. Energy Rev. 51 (2015) 1636–1649.

[74] M.A. Shaikh, K.M.A. Chowdhury, S. Sen, M.M. Islam, Potentiality of wind power generation along the Bangladesh coast, in: AIP Conference Proceedings 1919, 2017.

[75] K. Bunzel, V. Zeller, M. Buchhorn, F. Griem, D. Thrän, Regionale und globale räumliche Verteilung von Biomassepotenzialen, 2009. Leipzig.

[76] [IEA] - International Energy Agency, "Technology Roadmap – Bioenergy for Heat and Power, 2012. Paris, http://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf.

[77] [IPCC] - Intergovernmental Panel on Climate Change, Special Report on Reneable Energy Sources and Climate Change Mitigation, UNEP, Geneva, 2011. https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf.

[78] [ETIP-PV] -, European Technology and Innovation Platform Photovoltaics, "The True Competitiveness of Solar PV, ETIP-PV, Munich, 2017.

[79] W. Harry, Aktuelle Fakten zur Photovoltaik in Deutschland, Fraunhofer ISE, Freiburg, 2017.

[80] G. Parkinson, Solar Heads to 1c/KWh before 2020 after Mexico Sets Record Low, RenewEconomy, Sydney, 2017. http://reneweconomy.com.au/%0Asolar-heads-to-1ckwh-before-2020-after-mexico-sets-record-low-62163/?%0Autm_source¼REþDailyþNewsletter&utm_campaign¼7ebf9419b8-EMAIL_%0ACAMPAIGN_2017_11_20&utm_medium¼email&utm_term¼0_46a1943223-%0A7ebf9419b8-40387973.

[81] [IEA -PVPS] – International Renewable Energy Agency – Phtotovoltaic Power Systems Programme, Trends 2017 in Photovoltaic Applications: Survey Report of Selected IEA Countries between 1992 - 2016, IEA – PVPS, St. Ursen, 2017. http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_Trends_2017_in_Photovoltaic_Applications.pdf.

[82] B. Nykvist, M. Nilsson, Rapidly falling costs of battery packs for electric vehicles, Nat. Clim. Change 5 (4) (2015) 329–332.

[83] F. Lambert, Electric vehicle battery cost dropped 80% in 6 years down to $227/kWh e tesla claims to be below $190/kWh, Electrek, 2017. https://electrek.co/2017/01/30/electric-vehicle-battery-cost-dropped-%0A80-6-years-227kwh-tesla-190kwh/.

[84] C. Kemfert, T. Burandt, K. Hainsch, K. Löffler, P.Y. Oei, von Hirschhausen, Nuclear power unnecessary for climate protection: there are more cost-efficient alternatives, DIW Econ. Bull. 7 (48) (2017) 498–506.

[85] D.E.H.J. Gernaat, D.P. Van Vuuren, J. Van Vliet, P. Sullivan, D.J. Arent, Global long-term cost dynamics of offshore wind electricity generation, Energy 76 (2014) 663–672.

[86] [DESCO], Dhaka Electricity Supply Company Limited, "Dhaka Electricity Supply Company Limited, Governement of Bangaldesh, Dhaka, 2017. https://desco.org.bd/bangla/.

[87] C. Breyer, A. Gerlach, Global overview on grid-parity, Prog. Photovoltaics Res. Appl. 21 (1) (2013) 121–136.

[88] [PD] - Power Division, Power System Master Plan, Government of Bangladesh, Dhaka, 2011. https://policy.asiapacificenergy.org/sites/default/

files/PSMP2010_reduced.pdf.

[89] A. Toktarova, L. Gruber, M. Hlusiak, D. Bogdanov, C. Breyer, Long-term load forecasting in high resolution for all countries globally, Int. J. Electr. Power Energy Syst. 111 (2019) 160−181.

[90] S. Islam, Climate-threatened Bangladesh to Impose Carbon Tax in June, Thomson Reuters Foundation, Dhaka, 2017. https://www.reuters.com/article/us-bangladesh-climatechange-carbontax/climate-threatened-bangladesh-to-impose-carbon-tax-in-june-idUSKBN18J00V.

[91] A. Siddique, Bangladesh Backtracks on Carbon Tax Proposal Ahead of Election Year, Climate Home News, Dhaka, 2017. http://www.climatechangenews.com/2017/06/02/bangladesh-backtracks-carbon-tax-proposal-ahead-election/.

[92] [IREDe], Integrated Research and Action for Development, "Economic Benefits of Bangladesh−India Electricity Trade, USAID and SARI/EI, New Delhi, 2017. https://irade.org/Executive Summary -India Bangladesh.pdf.

[93] M. Götz, J. Lefebvre, F. Mörs, A. McDaniel Koch, F. Graf, S. Bajohr, et al., Renewable Power-to-Gas: a technological and economic review, Renew. Energy 85 (2016) 1371−1390.

[94] M. Fasihi, D. Bogdanov, C. Breyer, Long-term hydrocarbon trade options for the Maghreb region and Europe-renewable energy based synthetic fuels for a net zero emissions world, Sustainability 9 (2017) 306.

[95] A.A. Solomon, D. Bogdanov, C. Breyer, Curtailment-storage-penetration nexus in energy transition, Appl. Energy 235 (2019) 1351−1368.

[96] BD News, Gas Reserves in Bangladesh to Last till 2031 at Current Extraction Rate: State Minister Nasrul Hamid, bdnews24.com, Dhaka, 2015.

[97] M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, A. Lohrmann, C. Breyer, A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030, J. Clean. Prod. 199 (2018) 687−704.

[98] M. Child, O. Koskinen, L. Linnanen, C. Breyer, Sustainability guardrails for energy scenarios of the global energy transition, Renew. Sustain. Energy Rev. 91 (2018) 321−334.

[99] E. Vartiainen, G. Masson, C. Breyer, D. Moser, E. Román Medina, Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity, Prog. Photovoltaics Res. Appl. (2019) 1−15, https://doi.org/10.1002/pip.3189.

[100] S. Hebbalkar, O. Kutepatil, Floating solar panel industry makes a splash, Power 162 (7) (2018).

[101] M.W. Rahman, M.S. Mahmud, R. Ahmed, M.S. Rahman, M.Z. Arif, Solar lanes and floating solar PV: new possibilities for source of energy generation in Bangladesh, in: *2017 Innovations in Power and Advanced Computing Technologies*, i-PACT 2017 2017−January, 2018, pp. 1−6.

[102] M.R.U. Dastagir, Prospects of Floating Solar Power Plant in Bangladesh, Ministry of Power, Energy and Mineral Resources, Gov. of Bangladesh, Dhaka, 2018. https://d2oc0ihd6a5bt.cloudfront.net/wp-content/uploads/sites/837/2018/06/Mohd.-Dastagir-Prospect-of-Floating-Solar-Power-Plant-in-Bangladesh.pdf.

[103] J. Farfan, C. Breyer, Combining floating solar photovoltaic power plants and hydropower reservoirs: a virtual battery of great global potential, Energy Procedia 155 (2018) 403−411.

[104] D. Majumdar, M.J. Pasqualetti, Dual use of agricultural land: introducing 'agrivoltaics' in phoenix metropolitan statistical area, USA, Landsc. Urban Plann. 170 (2018) 150−168.

[105] J. Xue, Photovoltaic agriculture - new opportunity for photovoltaic applications in China, Renew. Sustain. Energy Rev. 73 (2017) 1−9.

[106] W. Liu, L. Liu, C. Guan, F. Zhang, M. Li, H. Lv, et al., A novel agricultural photovoltaic system based on solar spectrum separation, Sol. Energy 162 (2018) 84−94.

[107] [CERC], Central Electricity Regulatory Comission, "Determination of Benchmark Capital Cost Norm for Solar PV Power Projects and Solar Thermal Power Projects Applicable during FY 2016-17, 2016. New Delhi, http://www.cercind.gov.in/2016/orders/SO17.pdf.

[108] A. Gulagi, M. Ram, C. Breyer, The role of transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India, IET Renew. Power Gener. 14 (2) (2020) 254−262.

[109] A. Oyewo, J. Farfan, P. Peltoniemi, C. Breyer, Repercussion of large scale hydro dam deployment: the case of Congo Grand Inga hydro project, Energies 11 (4) (2018) 972.

[110] C. Breyer, D. Bogdanov, A. Aghahosseini, A. Gulagi, M. Fasihi, On the techno-economic benefits of a global energy interconnection, Econ. Energy Environ. Policy 9 (2020), https://doi.org/10.5547/2160-5890.9.1.cbre [not yet available], in press.

[111] A. Newcombe, E.K. Ackom, Sustainable solar home systems model: applying lessons from Bangladesh to Myanmar's rural poor, Energy Sustain. Dev. 38 (2017) 21−33.

[112] M. Ram, A. Aghahosseini, C. Breyer, Job creation during the global energy transition towards 100% renewable power system by 2050, Technol. Forecast. Soc. Change 151 (119682) (2020).

[113] G. Pleßmann, M. Erdmann, M. Hlusiak, C. Breyer, Global energy storage demand for a 100% renewable electricity supply, Energy Procedia 46 (2014) 22−31.

[114] [EC] - European Commission, ETRI 2014 - Energy Technology Reference Indicator Projections for 2010-2050, EC Joint Research Centre Institute for Energy and Transport, Petten, 2014.

[115] M. Bolinger, J. Seel, Utility-scale Solar 2015: an Empirical Analysis of Project Cost, Performance and Pricing Trends in the United States, Lawrence Berkeley National Laboratory, Berkley, 2016. https://emp.lbl.gov/publications/utilityscale-%0Asolar-2015-empirical.

[116] L. Neij, Cost development of future technologies for power generation-A study based on experience curves and complementary bottom-up assessments, Energy Pol. 36 (6) (2008) 2200−2211.

[117] J.E. Haysom, O. Jafarieh, H. Anis, K. Hinzer, D. Wright, Learning curve analysis of concentrated photovoltaic systems, Prog. Photovoltaics Res. Appl. 23 (11) (2015) 1678−1686.

[118] C. Kutscher, M. Mehos, C. Turchi, G. Glatzmaier, T. Moss, Line-focus Solar Power Plant Cost Reduction Plant, National Renewable Energy Laboratory, Colorado, 2010. http://www.nrel.gov/docs/fy11osti/48175.pdf.

[119] B. Sigfusson, A. Uihelein, Joint Research Center Geothermal Energy Status Report, European Commission Joint Research Center Institute for Energy and Transport, Petten, 2015. https://setis.ec.europa.eu/sites/default/%0Afiles/reports/2015_jrc_geothermal_energy_status_report.pdf.

[120] Agora Energiewende, Stromspeicher in der energiewende, Agora Energiewende, Berlin, 2014. www.agora-energiewende.de/fileadmin/Projekte/2013/%0Aspeicher-in-der-energiewende/Agora_Speicherstudie_Web.pdf.

[121] C. Breyer, E. Tsupari, V. Tikka, P. Vainikka, Power-to-gas as an emerging profitable business through creating an integrated value chain, Energy Procedia 73 (2015) 182−189.

[122] A. McDonald, L. Schrattenholzer, Learning rates for energy technologies, Energy Pol. 29 (4) (2001) 255−261.

[123] [IEA]- International Energy Agency, World Energy Investment Outlook, 2003. Paris.

[124] J. Koomey, N.E. Hultman, A reactor-level analysis of busbar costs for US nuclear plants, 1970−2005, Energy Pol. 35 (11) (2007) 5630−5642.

[125] [IEA] − International Energy Agency, World Energy Outlook 2015, IEA, " Paris, 2015a.

[126] [IEA] − International Energy Agency, Projected Costs of Generating Electricity, 2015th ed, IEA, " Paris, 2015b. https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf.

[127] W. Urban, H. Lohmann, K. Girod, Abschlussbericht für das BMBFVerbundprojekt Biogaseinspeisung, Fraunhofer-Institut Umsicht, Oberhausen, 2009.

[128] W. Hoffmann, Importance and evidence for cost effective electricity storage, in: 29th European PV Solar Energy Conference Exhibition, 2014, pp. 3981−3988.

Publication V

Sadiqa, A., Gulagi, A., and Breyer, C.
Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050

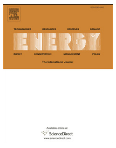
Reprinted with permission from
Energy
Vol. 147, pp. 518-533, 2018

Energy 147 (2018) 518–533

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050

Ayesha Sadiqa [a, b], Ashish Gulagi [a, *], Christian Breyer [a]

[a] Lappeenranta University of Technology, Skinnarilankatu 34, 53850, Lappeenranta, Finland
[b] University of the Punjab, Quied i Azam Campus, 54590, Lahore, Pakistan

ARTICLE INFO

Article history:
Received 20 July 2017
Received in revised form
7 December 2017
Accepted 4 January 2018
Available online 6 January 2018

Keywords:
Pakistan
Energy transition
100% renewable energy
Desalination demand
Storage technologies
Power-to-gas

ABSTRACT

The main aim of this study is to present an energy transition roadmap for Pakistan in which the total energy demand by 2050 is met by electricity generated via renewable sources, in particular, solar photovoltaic. Efforts have been made to assess the energy and cost required for the transition towards a sustainable energy supply covering the demand for power, desalination and industrial gas sectors. Hourly resolved model was used and optimization was carried out for each time period (transition is modeled in 5-year steps) on the basis of assumed costs and technological status till 2050 for all energy technologies involved. Solar PV dominates the installed technologies and contributes 92.7% and 96.6% in power and integrated scenarios. Seawater desalination sector dominates the integrated scenario and clean water demand is found to be $2.8 \cdot 10^{11}$ m^3 by 2050. The levelised cost of electricity declines from 106.6 €/MWh in 2015 to 46.2 €/MWh in 2050 in power scenario. In country-wide scenario, gas storage rules from 2040 to 2050 in terms of total storage capacities while battery storage is prominent in terms of storage output. The results indicates that, 100% renewable system is cost competitive and least cost option for Pakistan's future energy transition.

1. Introduction

Industrialization, intensive use of fossil fuels and nitrogenous fertilizers has pumped more greenhouse gas (GHG) into atmosphere than any natural processes could possibly have done. It is urgently crucial to reduce the carbon dioxide emissions by a significant amount [1]. The level has been estimated at 450 ppm, which would mean a global increase of 2° Celsius in mean ground temperature [2].

Pakistan with more than 188 million inhabitants stands as the sixth most populous country in the world (2013). Traditionally, Pakistan was an agrarian economy, but over the time, industry and services sector have become main contributors to the GDP [3]. Presently energy production and consumption in Pakistan basically depend on conventional fuels. Pakistan's total installed capacity breakdown for the year 2014 has been shown in Fig. 1. Oil and gas contribute 63% (gas 33.0% and oil 30.0%) to the total energy supplies [3,4]. However, the increased dependence on natural gas cannot continue owing to the rapid depletion of country's gas reserves. It has been assessed that only 25–30% of the total assets will be left by the year 2027–28 [5]. The commercial sector is the biggest consumer of energy by consuming 37.6% of total energy, while the transport, residential and commercial sectors consumed 31.4%, 23.4% and 4.0% respectively in 2013 [6,7]. Pakistan's electricity consumption has grown at a compound annual growth rate (CAGR) of 4.6% from 2000 to 2015 [8]. The growth in electricity consumption has been mainly attributed to the increase in population, economic growth, increase in income per capita and urbanisation [9,10]. Additionally, increase in rural electrification has contributed to the rise in electricity consumption [11]. However, in the future the same factors would contribute to the growth in electricity consumption as Pakistan would aim to transit itself in the league of developed countries [12]. Efforts have been made to explore and exploit the indigenous energy resources. Despite the struggles, the imports of energy are about 30% of the total consumption [13]. In the imports, the major part (i.e., ~88%) is of oil (i.e., crude oil and petroleum products), in which, a major share is used for power generation [14]. Any oil price change in the global market extremely influences Pakistan's energy generation rendering existing circular debt issue even more seriously [15].

Pakistan's current installed electricity capacity is 25,000 MW and it is not sufficient to meet the existing electricity demand

---

[*] Corresponding author.
E-mail address: Ashish.Gulagi@lut.fi (A. Gulagi).

https://doi.org/10.1016/j.energy.2018.01.027
0360-5442/

Nomenclature

A-CAES	Adiabatic compressed air energy storage
Capex	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CSP	Concentrating solar thermal power
FLH	Full load hours
GHG	Greenhouse gases
HVDC	High-voltage direct current
IEA	International Energy Agency
LCOC	Levelized cost of curtailment
LCOE	Levelized cost of electricity
LCOG	Levelized cost of gas
LCOS	Levelized cost of storage
LCOT	Levelized cost of transmission
OCGT	Open cycle gas turbine
Opex	Operational expenditure
PHS	Pumped hydro storage
PtG	Power-to-gas
RE	Renewable energy
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
WACC	Weighted average cost of capital

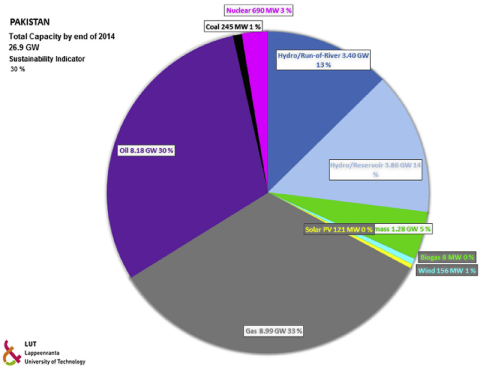


Fig. 1. Pakistan's total installed capacity breakdown till 2014 [4].

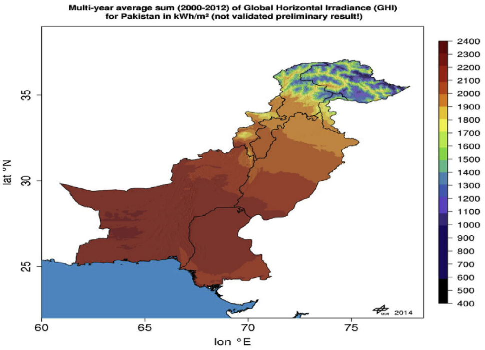


Fig. 2. Pakistan's annual global horizontal irradiation map [28].

resulting into extended load-shedding to the extent of virtual suspension of the social life. The estimated difference in supply-demand is about 5000 MW and projected to be 13,000 MW by 2020 [14]. According to assessments, the energy crisis cost the country 6 bUSD in 2008 [16] while causing losses upwards of 2% of GDP in 2009–2010 [11,17] and resulting into loss of 40,000 jobs annually. The recent findings of a World Bank survey reveal the effects of the electricity shortage on society and the economy in Pakistan and it was found that 66% of business activities are affected by load shedding meaning it has a more significant effect than terrorism [18,19]. Due to dearth in fossil fuel reserves, Pakistan is highly dependent on imports, which severely questions the energy security of the country. Additionally climate change is severely affecting the agricultural sector due to change in the monsoon cycle. Also, investing in fossil fuel power plants would lead to stranded assets [4,20] and high cost of electricity [21]. Investing in renewables could be the answer to the list of problems mentioned as Pakistan does not have to depend on its neighbours for fossil fuels and the cost of power produced from renewables is declining at a rapid pace all over the world.

Apparently, a large potential of power generation from renewable sources such as wind, solar, biomass, geothermal, and tidal is available in the country. Pakistan's solar resources are extremely good and have relatively low seasonal variation. An annual global horizontal irradiance map has been shown in Fig. 2. The economic constraints, poor energy planning, governance issues, underdeveloped technological sector and the capacity building have been recognized as major constraints in harnessing the renewable energy sources [18]. There are some ongoing projects like one of the solar project added a 100 MW of energy in the national grid in 2015 and is being upgraded to add 900 MW [19]. According to the Alternative Energy Development Board, 3 bUSD have been invested in renewable sources in the year 2016 which indicates the investment potential [22]. Numerous studies have demonstrated that Pakistan possesses a huge overall renewable energy potential [23–25]. The wind potential is mainly concentrated in the coastal areas of Sindh and Baluchistan with 2000–3000 full load hours (FLH) and 1000–1500 FLH, respectively. The total potential for wind energy in these areas is around 123 GW [23]. Pakistan is located in the Sun Belt region and therefore has 1500–3000 sun shine hours across the country [24]. The average yearly global horizontal insolation in the province of Baluchistan is 1930–2030 $kWh/(m^2 \cdot a)$ [25] which can be observed from Fig. 2. Studies also reveal that growth rates of markets for wind and PV power are 4.7% higher in late adopters than the early adopters of the technologies due to global knowledge build-up [26].

With all the abundant potential available, it is the right policies and commitment of the government towards the renewables that would enable faster uptake of these technologies. There have been some policies of the Pakistani government for the faster uptake of renewables. The 2006 policy for renewable energy had main features of feed-in tariffs, reduced transmission and distribution costs, net metering and carbon credit transactions [27]. In addition competitive bidding for the renewable energy projects which is the normal all around the world has helped to reduce the price of the projects and create competition among the developers. Also, the State Bank of Pakistan offers loans to RE project developers [27]. A clear strategy and commitment from the government is needed to achieve a high share of renewables in the future.

Due to the novelty of the topic in Pakistan, there are no comprehensive studies among the technical literature which integrate all the aspects of a 100% RE system for Pakistan. The majority of the technical writings on the renewable energy sources mostly deal with the technological aspect of the subject.

Several reports [29–31] indicate that Pakistan is on the verge of disastrous water shortage and turning into a water scarce country. Pakistan's water demand is projected to reach $3.4 \cdot 10^{11}$ m^3 by 2025, while the supply expected to remain stagnate at $2.4 \cdot 10^{11}$ m^3 resulting in a demand supply gap of $1.0 \cdot 10^{11}$ m^3 [31]. According to WWF-Pakistan [32], with per capita water availability reducing down to 1090 m^3, Pakistan is approaching towards threshold level of water scarcity (1000 m^3). Low irrigation efficiency, low water use efficiency, population growth and inadequate water allocation are the key factors in present water scarce condition. The decline in the river inflows, increased variability and location changes of monsoon and shift in the temporal patterns of glacial melt is in line with the data on climate change, resulting in increased vulnerability of the agriculture sector [33,34]. Given this water crisis, policies that would improve irrigation, water use, allocation and distributive efficiencies need to be undertaken.

There have been some energy transition studies with high renewable energy shares (Table 1) for Pakistan. The brief analysis of the results is presented in Table 1.

Table 1
Future energy transition scenarios for Pakistan.

Study	Key findings
Jamal N. [14]	A model for hourly demand-supply balance of Pakistan's power system was developed. The electricity demand was projected 430.1 and 566 TWh in two different scenarios till 2050. Different supply cases were discussed varying the capacities of wind and PV. PV contributes 97–386 TWh, wind 116–132 TWh and biomass 39–111 TWh in different supply system scenarios. Contribution from hydro remains constant at 213 TWh in total electricity supply by 2050. The role of hydro as seasonal storage was also discussed. The discounted system cost was calculated using MESSAGE framework. In all supply cases, system discounted cost was in the range of 170–240 bUSD by 2012.
Jamal N. [35]	In the study, it was found that Pakistan's total electricity demand (587 TWh) is achievable by renewables by 2050. Wind, hydro, solar and biomass will contribute 107.9 TWh, 33.7 TWh, 47.3 TWh and 21.0 TWh respectively.
Perwez U. [36]	"The Long Range Energy Alternative Planning" (LEAP) software is employed to assess different scenarios in the study over the period of 20 years (2011–2030). Increasing the coal composition to 14.1% and that of renewable energy sources to nearly 46% was suggested by 2030. Remaining demand will be fulfilled by conventional energy sources.
Valasai D. G. [37]	Three different electricity generating scenarios were developed using TIMES modelling framework for the period 2013–2033 following BASE, REN50 and REN60 scenarios. Renewable energy share was increased to 50% in REN50 and 60% in REN60 scenarios. The study suggests REN50 and REN60 as more feasible and sustainable scenarios.

This study presents the Pakistan's transition towards a 100% renewable based energy system. Hourly resolved model was used to simulate 100% RE scenario in Pakistan from 2015 to 2050, covering demands of the power, desalination and non-energy industrial gas sectors. The optimization is done on the basis of assumed costs and technological status for every 5-years from 2015 to 2050 for all energy technologies involved.

2. Methodology

The LUT Energy System Transition model was used for the transition research of the Pakistan power system from 2015 to 2050 in 5-year time steps. This model optimizes linearly the energy system parameters under previously defined constraints and the assumption for future RE power generation and demand in the particular region. Bogdanov and Breyer [38] define the model in detail, explaining equations and constraints used in the modelling. The most important parameter, which differentiates the LUT model, is its hourly resolution for an entire year. An hourly resolution for an entire year guarantees an energy system which is much closer to reality and enables a more accurate description which includes the synergy between the different system components utilised. The hourly resolution is similar to EnergyPlan [39], however the LUT Energy System Transition model has an added advantage of modelling a transition pathway of an electricity system using an optimal dispatch of generation and storage technologies and transmission between the two regions of Pakistan. Also utilization of different types of storage technologies, which are often lacking in many of the transition models provides an edge over other modelling tools. The multi-node approach which is utilised in the model, enables a country or a region to be divided into different sub-regions and each sub-region can act as different node and the nodes can be interconnected to form a transmission network. The model is mainly compiled using Matlab. The optimisation is currently carried out in a third party solver, MOSEK ver. 8, however other solvers (Gurobi, CPLEX, etc.) can be used. The post processing of the simulation results is carried out using Matlab.

Fig. 3 gives the main input and output parameters of the model. To achieve a least cost energy system is the main target of system optimization. The cost related to the system are calculated as sum of the annual cost of all power generation capacities, energy generation and generation ramping of the different technologies.

Additionally, included in the energy system are the PV prosumers for residential, commercial and industrial sectors. The term prosumer is used to refer to energy consumers, producing their own power from solar PV systems. Minimizing cost of consumed electricity is the target function for prosumers. The cost related to self-consumed electricity is calculated as a sum of generation, annual cost and cost of electricity consumed from the grid. The prosumers can benefit from the excess electricity generated by feeding into the national grid at an assumed price of 0.02 €/kWh, however prosumers have to fulfil their own demand before selling.

The main constraint of the system optimization is given as Eq. (1).

$$\forall \mathrm{h} \in [1,8760] \left(\sum_{t}^{tech} E_{gen,t}\right), h + \left(\sum_{r}^{reg} E_{imp,r}\right), h + \left(\sum_{t}^{stor} E_{stor,disch}\right), h = (E_{demand}), h + \left(\sum_{r}^{reg} E_{exp,r}\right), h + \left(\sum_{t}^{stor} E_{stor,ch}\right), h + (E_{curt}), h \tag{1}$$

It is defined for every hour of a year in a particular region, electricity generation from all the technologies ($E_{gen,t}$), imported

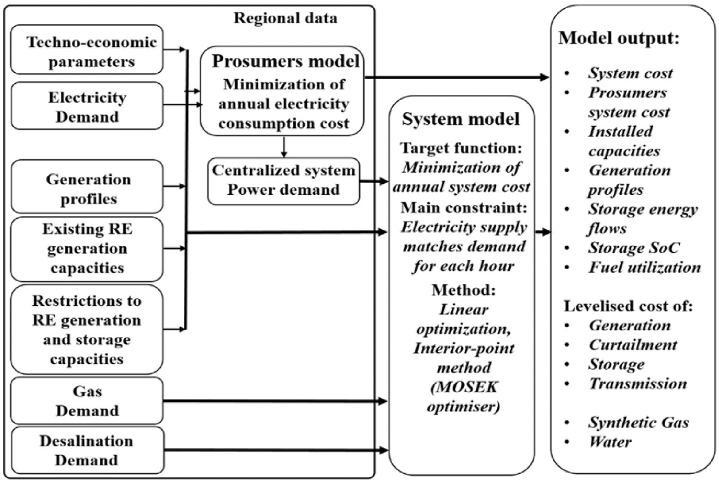


Fig. 3. The LUT Energy System Transition model from inputs to outputs [40].

electricity from the regions ($E_{imp,r}$) and electricity from storage discharge ($E_{stor,disch}$) should be equal to the total demand for an hour (E_{demand}), electricity exported to other regions ($E_{exp,r}$), electricity for charging storage technologies ($E_{stor,ch}$) and curtailed electricity (E_{curt}). The other abbreviations used in this equation are: hours (h), technology (t), all technologies used in modelling ($tech$), sub-region (r) and all sub-regions (reg).

The target function for the optimization is given in Eq. (2).

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}(CAPEX_t\cdot crf_t + OPEXfix_t)\cdot instCap_{t,r} + OPEXvar_t\cdot E_{gen,t,r} + rampCost_t\cdot totRamp_{t,r}\right) \tag{2}$$

The abbreviations used here are: ($CAPEX_t$) - capital cost of each technology, (crf_t) − capital recovery factor for each technology, ($OPEXfix_t$) − fixed operational cost for each technology, ($OPEXvar_t$) - variable operational cost each technology, installed capacity in a region ($instCap_{t,r}$), electricity generation by each technology ($E_{gen,t,r}$), ramping cost of each technology ($rampCost_t$) and annual total power ramping values for each technology ($totRamp_{t,r}$). The target function was applied in time steps of 5-year from 2015 to 2050.

The other important constraints applied were:

- No more than 20% growth in RE installed capacities share compared to total power generation capacities could be achieved for each 5-year time step so as to avoid disruption to the power system.
- No new nuclear or fossil-based power plants could be installed after 2015. However, installation of gas turbines were allowed as they are a highly efficient technology that can accommodate RE-based synthetic natural gas or bio-methane into system [41].

The energy model with all the technologies utilized is provided in Fig. 4.

2.1. Technologies utilized in the transition

Different technologies are utilised for the energy system transition of Pakistan and are divided into four main categories:

- Technologies for electricity generation
- Technologies for electricity storage to provide flexibility to the system
- Transmission technologies for the generated electricity
- Bridging technologies such as Power-to-Gas (PtG) process and Seawater Reverse Osmosis (SWRO) desalination

3. Assumptions for the energy system analysis of Pakistan

3.1. Subdivision and grid structure for Pakistan

The subdivision of Pakistan into two regions was based on population distribution, consumption of electricity and the grid structure. Fig. 5 shows the two sub-regions of Pakistan and interconnection between these regions.

3.2. Scenarios

Two scenarios were studied for the energy system analysis of Pakistan:

- Power scenario, only electricity demand is covered and the energy systems of the regions are interconnected, so trading of electricity between the two regions is possible.
- Integrated scenario, power scenario with SWRO desalination and non-energetic industrial gas demand, where PtG technology is also used to cover the non-energetic industrial gas demand in addition to the storage option

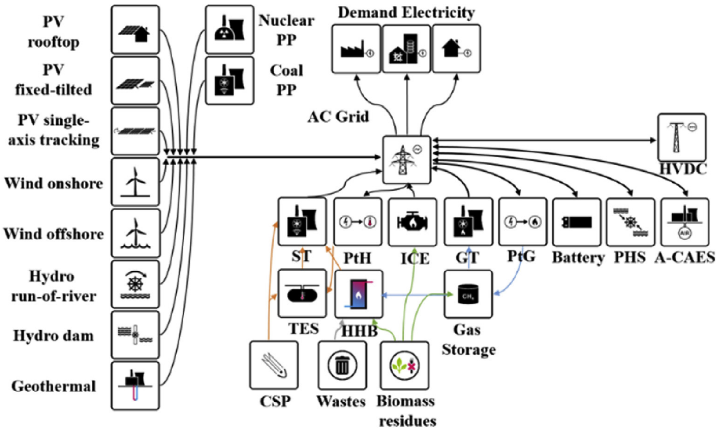


Fig. 4. The LUT Energy System Transition model [21], made up of major renewable energy sources (PV rooftop for prosumers, PV fixed-tilted, PV single-axis tracking, wind onshore and offshore, hydro, geothermal, biomass and waste-to-energy), various storage technologies (batteries, PHS, A-CAES, TES), transmission options (HVDC lines) and different demand sectors (electricity, desalination, non-energetic industrial gas).

Fig. 5. The two sub-regions in Pakistan and the grid connection.

3.3. *Financial and technical assumptions*

The economic and technical assumptions for the technologies utilised for the transition of Pakistan from 2015 to 2050 are tabulated in Table A.1. In Table A.1, individual references are given for each of the technologies utilised in the transition. The decrease in Capex and Opex from 2015 to 2050 are based on the current trends and international literature. For example: The PV rooftop (residential, commercial and industrial) assumptions are based on the data given in Ref. [42] for every 5-year interval. The rationale behind the financial assumptions of the important renewable technologies has been the steady cost decline around the world and the costs assumptions which are expected to fall further in the future. This is based on the number of established studies and international literature [43,44]. For example the cost of power produced from solar PV has gone down to 14.9 €/MWh [45], with many such low cost all around the world. It is assumed that, with the ongoing improvements in technology and production processes the cost of materials and installations will fall considerably from their current values till 2050. Also, in addition cost of batteries have decreased by 77% in the last 7 years [46,47]. The conditions for solar in Pakistan are one of the best in the world and with a surge in investor interest in the solar sector the cost of producing electricity from solar will go down [48].

The cost of onshore and offshore wind power plants, particularly the offshore wind plants are expected to decline sharply in the future [49]. The sharp decline in cost is possible due to the expected learning curves and technological advancements in construction and wind power systems will play a vital role [50].

The weighted average cost of capital (WACC) is set to 7% (in real terms) for all investments, except residential PV prosumers, for which a real WACC of 4% is applied, due to lower financial return requirements. The assumed WACC maybe be lower and do not reflect the financing situation however an increase in WACC does not alter the cost of energy system considerably [51]. The authors assume that a 7% real WACC is possible by the year 2050 in Pakistan. The electricity prices for 2015 for the three prosumer categories are assumed from Gerlach et al. [52] and future prices till 2050 were calculated according to the methodology described in Breyer and Gerlach [53]. The electricity prices for Pakistan are provided in the Supplementary Material (Table 1).

3.4. *Potential for renewable technologies*

The potential for biomass and waste for the two regions in Pakistan are taken from Ref. [54] and divided into: solid wastes, solid residues and biogas. The associated cost calculations for all the biomass categories described above were done according to data from International Energy Agency [55] and Intergovernmental Panel on Climate Change [56]. For solid fuels a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for waste incineration plants and this is reflected in the negative cost for solid waste.

The geothermal energy potential is calculated for the two regions according to the method described in Gulagi et al. [57].

The current installed capacities for solar PV, wind, hydro power and PHS are taken from Farfan and Breyer [4]. The upper limit of these renewable technologies is based on land use limitations and density of capacity [38]. The lower and upper limits of renewables and fossil fuels are given in the Supplementary Material (Tables 4 and 5, respectively).

3.5. Input profiles for solar and wind

The generation profiles for single-axis tracking and optimally tilted PV, solar CSP and wind energy were calculated according to Bogdanov and Breyer [38]. For hydro power, feed-in profiles for the two regions were calculated using the daily resolved water flow data for the year 2005 [58] as a normalized sum of precipitation in the regions.

3.6. Demand

The hourly load profile for electricity for each region is calculated as a fraction of the total demand in Pakistan based on synthetic load data weighted by the region's population. The electricity demand is taken from the National Transmission and Despatch Company Pakistan [8] and extrapolated till 2040 by a policy research working paper from World Bank [59] and till 2050 by South Asian Regional Initiative for Energy Integration [60]. The calculations related to seawater desalination demand and technical and financial assumptions for seawater reverse osmosis (SWRO) are given in Caldera et al. [61]. The electricity demand till 2050 is given in the Supplementary Material (Table 1). The data for non-energetic industrial gas demand is taken from IEA [62] and extrapolated till the year 2050 from the IEA assumptions of non-energetic industrial gas demand growth rate for India [63].

4. Results

4.1. Cost structure of an energy system from 2015 to 2050

The results related to the cost structure of an optimized energy system are presented in Tables 2 and 3 for the power and integrated scenario respectively. The results of these scenarios were evaluated with a set of parameters and formula described in Bogdanov and Breyer [38].

The levelized cost of electricity for both of the scenarios (Tables 2 and 3) is highest for the current setup of power generation technologies which is primarily composed of fossil fuels. The high fuel cost of the fossil fuels and the associated cost of emissions contribute to the increase in LCOE. The fuel costs for all the fossil fuel technologies and the emission cost assumed are shown in the Supplementary Material (Fig. 5 and Table 7 respectively).

The reduction of LCOE from 2015 which is a fossil fuel based system to 2050 which is a fully renewable system is 56–57% depending on the scenario. The cost of power produced will depend on solar PV and batteries as these two technologies contribute majorly to the LCOE.

At first a slight increase in LCOE is observed in both of the scenarios for the year 2025 and then it starts decreasing again from the year 2030 onwards. The current energy system is mainly based on fossil fuels contributing to high total primary LCOE due to high fuel costs and a smaller share of GHG emission costs (Figs. 6 and 7). In 2020, total primary LCOE decreases considerably in the scenario due to decrease in expensive fossil share in the electricity generation which is being replaced by renewables particularly solar PV. The slight increase observed for the year 2025 for both of the scenarios is due to new investments in the renewables sector and need to install storage capacities due to the intermittency created by the renewables. However, fossil gas is still utilized to overcome intermittency as it is a cheaper source for power generation. This creates an additional fuel cost and associated GHG emission costs as observed from Figs. 6 and 7. After 2025, a constant trend of decrease

Table 2
Financial results from 2015 to 2050 – power scenario for Pakistan.

	LCOE total [€/MWh]	LCOE primary [€/MWh]	LCOC [€/MWh]	LCOS [€/MWh]	LCOT [€/MWh]	Total annualized cost [b€]	Total capex [b€]	Capex needed in 5-years period [b€]
2015	106.6	105.5	0.5	0.0	0.5	12.0	25.9	–
2020	54.1	52.9	0.3	0.6	0.3	8.0	40.3	14.4
2025	56.6	51.3	0.5	3.3	1.5	10.9	69.3	29.0
2030	55.0	40.2	1.3	12.3	1.2	13.7	113.1	43.8
2035	52.7	34.6	1.6	15.6	0.9	17.3	150.3	37.2
2040	50.7	30.8	1.7	17.5	0.7	21.9	191.9	41.6
2045	48.4	25.2	1.6	20.8	0.7	25.0	225.0	33.2
2050	46.2	23.7	1.8	20.1	0.6	28.8	259.1	34.1

Table 3
Financial results from 2015 to 2050 – integrated scenario for Pakistan.

	LCOE [€/MWh]	LCOE primary [€/MWh]	LCOC [€/MWh]	LCOS [€/MWh]	LCOT [€/MWh]	Total annualized cost [b€]	Total capex [b€]	Capex needed in 5-years periods [b€]
2015	106.3	105.2	0.5	0.0	0.5	12.94	25.9	–
2020	54.2	53.6	0.3	0.0	0.3	10.76	53.4	27.5
2025	62.0	56.4	1.0	3.3	1.3	27.35	197.6	144.2
2030	61.3	42.5	1.9	15.9	1.0	46.28	475.8	278.2
2035	57.5	32.9	2.4	21.1	1.2	76.42	881.5	405.7
2040	52.5	26.5	1.8	23.2	0.9	90.27	1113.8	232.3
2045	49.0	22.0	1.7	24.6	0.7	109.04	1376.7	262.9
2050	46.8	20.9	1.8	23.5	0.6	122.20	1534.5	157.8

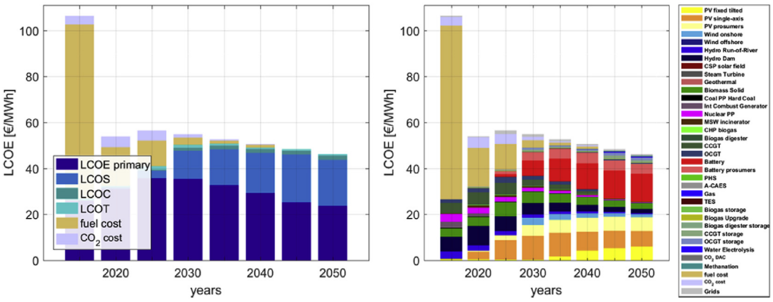


Fig. 6. Contribution of levelized cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost and carbon emission cost to total LCOE (left) and contribution of all technologies to LCOE (right) from 2015 to 2050 for the power scenario.

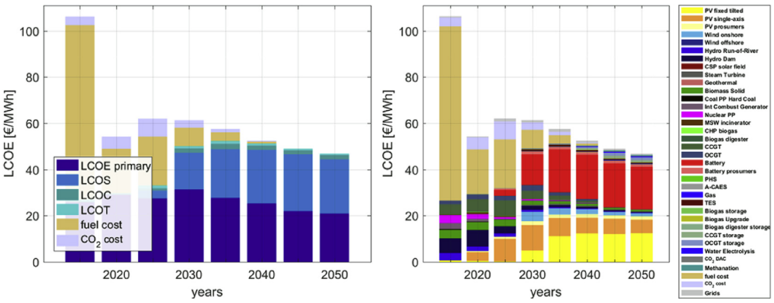


Fig. 7. Contribution of levelized cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost and carbon emission cost to total LCOE (left) and contribution of all technologies to LCOE (right) from 2015 to 2050 for the integrated scenario.

in LCOE is observed till 2050, due to decrease in the share of fossil fuels, and also associated costs of GHG emissions and fuel costs.

Sector integration of desalination and non-energetic industrial gas demand does not provide the expected benefit in terms of reduction of LCOE in comparison to the power scenario. This is due to the huge demand created by the desalination sector. However, even a huge electricity demand for desalination does not increase the price of electricity considerably in comparison to the country-wide scenario for the year 2050.

4.2. Installed capacities of generation technologies in the energy transition

The installed capacities for a fully renewable energy system in 2050 are dominated by solar PV and batteries (Table 4) due to its low cost and the excellent solar resource conditions. The gradual increase in installed capacities for the energy transition period is shown in Fig. 8 and absolute numbers can be found in the Supplementary Material (Table 2). The total power plant capacity is dominated by fossil gas and oil for the year 2015. However, after 2015, renewables, particularly solar PV, start to dominate the installed capacities to overcome the current and future supply deficit created by phasing out of the fossil fuel power plants. The electricity generation is mainly based on PV technologies, complimented by wind, hydro and biomass in periods of low solar

Table 4
Key power plant capacities required to achieve a fully renewable energy system for Pakistan in 2050 for the two scenarios.

		Power	Integrated
PV prosumers	[GW]	87	87
PV single-axis tracking	[GW]	102	382
PV optimally tilted	[GW]	133	1047
Wind energy	[GW]	8	34
Geothermal power	[GW]	0	0
CSP	[GW]	0	0
Hydropower	[GW]	10	11
Biomass PP	[GW]	6	6
Biogas Digester	[GW]	1	1
Biogas Upgrade	[GW]	0	0
Battery self-consumption	[GW]	207	207
Battery system	[GW]	567	3430
Gas storage	[GW]	15051	87549
PHS	[GW]	0	0
TES storage	[GW]	9	346
PtG electrolyser input	[GW_{el}]	8	112
A-CAES storage	[GW]	0	0
CCGT PP	[GW]	7	27
OCGT PP	[GW]	15	59
Oil PP	[GW]	0	0
Nuclear PP	[GW]	0	0
Coal PP	[GW]	0	0

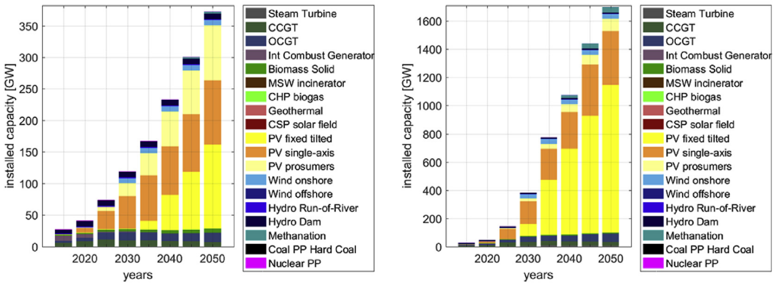


Fig. 8. Cumulative installed capacity for all generation technologies from 2015 to 2050 for the power (left) and integrated (right) scenarios.

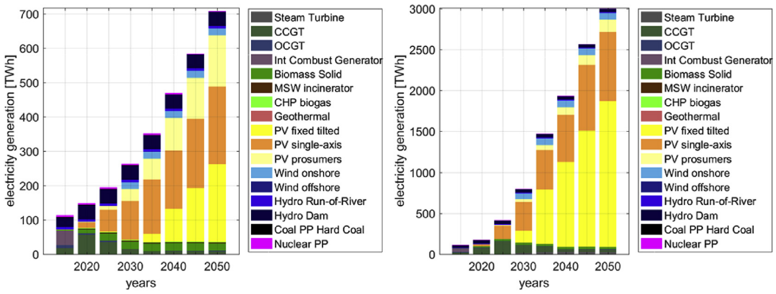


Fig. 9. Total annual electricity generation from all technologies from 2015 to 2050 for the power (left) and integrated (right) scenarios.

irradiation for both of the scenarios which can be seen from Fig. 9. Due to a low availability of wind in the areas of high population density, wind does not play a vital role as the cost of transmission is higher for importing wind from western Baluchistan to Karachi. In comparison, solar PV which is available all over the country and it can provide in combination with low cost batteries a least cost solution to satisfy the increasing electricity demand.

The higher installed capacities for the integrated scenario is due to additional demand created by non-energetic industrial gas and seawater desalination. The additional demand is satisfied mainly by installation of additional PV power plants. For the year 2050, 371% more solar PV and 370% of additional battery capacities are installed in the integrated scenario in comparison to power scenario. Solar PV plants develop quickly after 2020 and wind power develops after 2025 and remains almost constant till 2050. The renewables especially solar PV grow at a constant rate for all the years.

For the year 2050, PV optimally tilted contributes 63% and PV single-axis contributes 23% to the total RE generation capacity in the integrated scenario. In 2050, PV optimally tilted contributes to 227 TWh and 1785 TWh of electricity and PV single-axis contribute to 226 TWh and 845 TWh to the total electricity generation in the power and integrated scenarios, respectively. The PtG technology creates an additional demand of 15 TWh_{el} for the power and 194 TWh_{el} for the integrated scenario in the year 2050, which is observed in increased generation capacity. The full load hours for all the technologies in the power scenario can be found in the Supplementary Material (Table 3). As the share of renewables increases, curtailment increases due to the intermittency of the renewables (Supplementary Material Fig. 6). However, the curtailment remains less than 8% of the total electricity generated.

4.3. Desalination sector

Fig. 10 explains the growth of Pakistan's seawater reverse osmosis (SWRO) desalination sector from 2015 to 2050 and the red

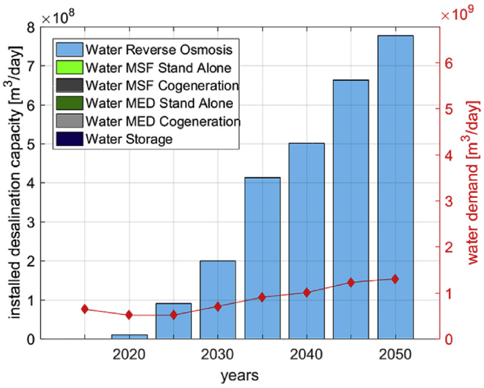


Fig. 10. Water desalination installed capacities to meet Pakistan's total water demand.

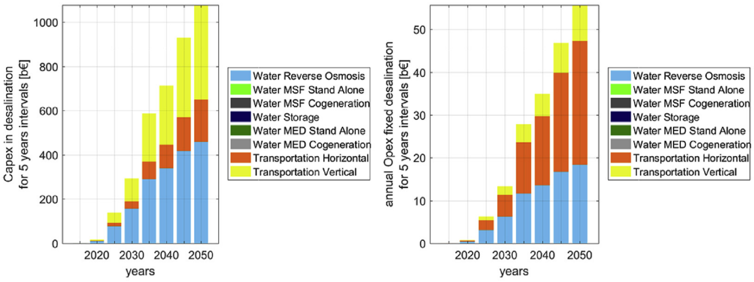
line shows water demand in m^3/day. The installed desalination capacity in 2050 is $7.8 \cdot 10^8$ m^3/day while the water requirement is $1.3 \cdot 10^9$ m^3/day. The difference between the total water demand and installed desalination capacity is met by the renewable water sources and non-renewable groundwater sources. Installed water desalination capacity is becoming noticeable after 2025. The statistics also indicate the existing desalination water demand [m^3/day] for Pakistan is extremely high [31,34].

Fig. 11(a) shows the capital expenditure of different components of the desalination sector in 5-year intervals. The share of water transportation (vertical and horizontal) is gradually increasing and is the biggest expenditure in 2050. The fixed operating cost increases as the installed desalination capacities increases in 2050 dominated by the expense on water transportation. The share of the transportation factor is going to increase to 67% in 2050 from 5% in 2020 in total annual operational expenditures. The annual variable operating cost explains the cost of gas and electricity consumption of the desalination plants. The increase in consumption of electricity is due to the installation of more desalination plants over the years to meet the country's increasing water demand. In Fig. 11(c) LCOW is decreasing continuously for the desalination from 2015 to 2050 especially in the initial years when the system will gradually get accustomed with new technology. The gradual decrease in desalination cost is attributed to the expected increase in the efficiency of desalination plants in the coming years.

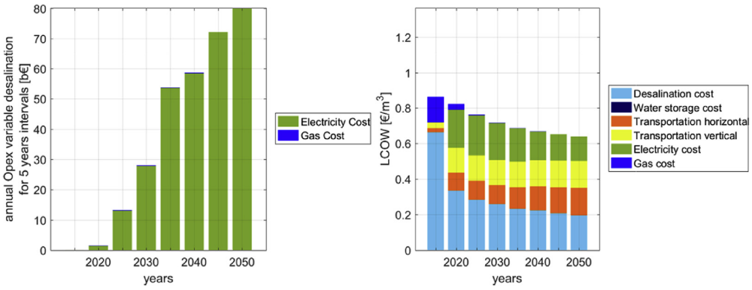
4.4. The role of storage technologies in the energy transition

Comparing Figs. 8, 9, 12 and 13, it is observed that the role of storage technologies increase with the rising share of renewable energy in the system. As, there is no PHS storage available in Pakistan, batteries provide electricity on daily basis and gas storage is used as an option for long-term storage. By 2025, prosumer and system batteries come into effect due to the increasing influence of solar PV on the system. The batteries provide the system with the required flexibility and they emerge as a more cost effective option than utilising the fossil fuel power plants for electricity generation. The batteries provide 39% and 47% of electricity of the total electricity demand in the year 2050 for the power and integrated scenario, respectively. The increasing share of solar PV (Figs. 8 and 9) corresponds to the increasing share of batteries output (Figs. 12 and 13), as hybrid solar PV-battery systems evolve as the least cost combination to provide electricity till 2050. Batteries help electricity generated by solar PV to be used in the evening and night time.

The gas storage is utilised from the year 2030 when the share of renewables crosses 80%, however huge installed capacities of gas storage are observed in the year 2045 and 2050. The storage output of gas storage is very low in comparison to batteries as seen from Figs. 12 and 13. The gas storage provides around 3% of electricity of the total electricity demand in the year 2050 for the power and integrated scenario. Gas storage is required as a seasonal storage



(a) Capex of desalination sector components. (b) Annual fixed opex of the desalination sector.



(c) Annual variable opex of desalination sector components. (d) LCOW of all components of the desalination sector.

Fig. 11. (a) Capex of desalination sector components. (b) Annual fixed opex of the desalination sector. (c) Annual variable opex of desalination sector components. (d) LCOW of all components of the desalination sector.

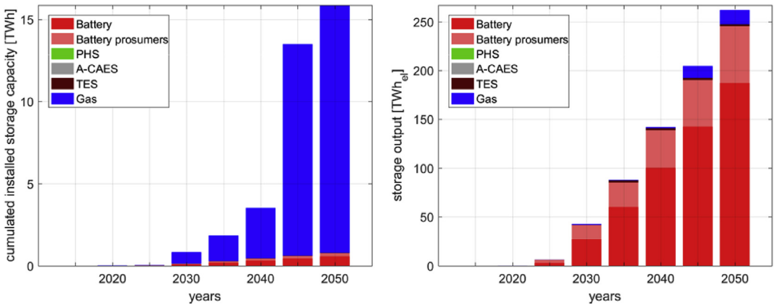


Fig. 12. Cumulative installed capacities of storage technologies (left) and storage output (right) required from 2015 to 2050 for the power scenario.

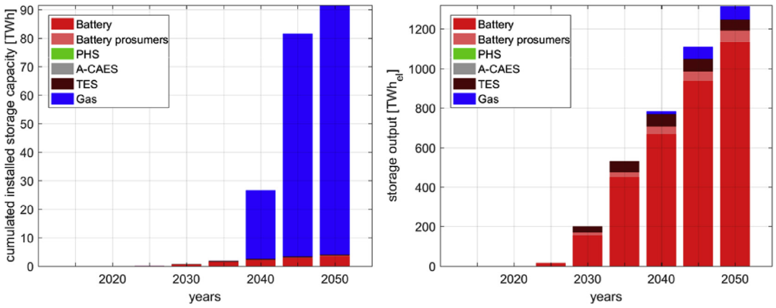


Fig. 13. Cumulative installed capacities of storage technologies (left) and storage output (right) required from 2015 to 2050 for the integrated scenario.

from 2040 and the reason for the huge installed capacities in 2045 and 2050.

4.5. Sub-regional analysis of an optimized fully renewable energy system

The installed capacities for a fully renewable energy system in 2050 for the two sub-regions: Pakistan North and South for the two scenarios is shown in Fig. 14. The installed solar PV capacities exceed 70% of the total RE installed capacities in each of the regions, despite FLH of wind exceeding full load of solar PV. It is observed that for the year 2050, solar PV is the cheapest option to power the electricity demand. However, in Pakistan South the available wind resources are utilized due to good wind conditions on the Southern coast which helps balancing the system in periods of low solar radiation. The diagram for electricity generation from the installed

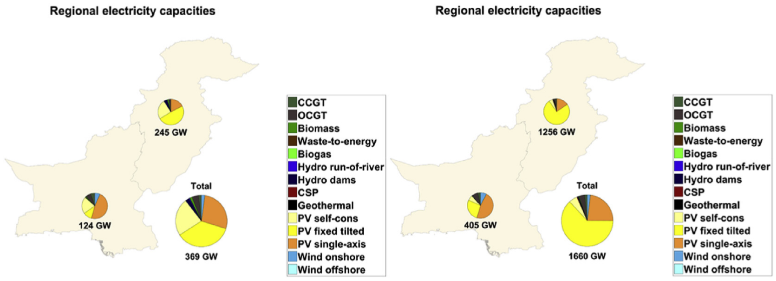


Fig. 14. Installed RE capacities for power (left) and integrated (right) scenarios for the two sub-regions of Pakistan for 2050.

renewable sources can be found in the Supplementary Material (Figs. 17 and 18).

The sub-region of Pakistan North is a region with high demand and a region with best RE resources which helps to balance out the sub-region of Pakistan South where the availability of RE resources is limited. From Fig. 15 it can be observed the demand (solid circle) and generation (line circle) with Pakistan North as a net exporter of electricity. The import and export of electricity and loss due to storage creates a difference observed between the demand and generation.

4.6. Annual CO_2 emissions in the transition period

Annual net zero CO_2 emissions are achieved for the year 2050 which is illustrated in Fig. 9 for the power and integrated scenario. In the integrated scenario, an increase in annual GHG emissions is observed for the year 2030 due to a high electricity demand by the additional desalination and gas sectors and solar PV and other renewables are not yet cost competitive. The additional demand is satisfied by increased electricity generation from gas power plants. However, the ratio of GHG emitted per MWh of electricity produced decreases in the transition period to ultimately zero in the year 2050 as observed from Fig. 16. As the renewables become cost competitive and its share increases in the energy system there is a substantial decrease in the GHG emissions. The power system of Pakistan is completely decarbonized by 2050.

5. Discussion

The main aim of this study was to show a least cost electricity transition pathway for Pakistan, which is compatible to the Paris Agreement [64]. This can be realised with the abundant renewable energy potential available in the country and with some political will and change in policies regarding renewables. This study describes a pathway, which avoids the risk of climate change, in addition to stranded assets caused by investing in fossil fuel technologies and the high cost of electricity generation from nuclear.

A 100% renewable based electricity system for Pakistan by 2050 is found to be least cost and most efficient electricity option. This study incorporates all aspects of a fully sustainable energy system including RE technologies and energy storage solutions. The LCOE are 46.2 €/MWh and 46.8 €/MWh for the year 2050 for the power and integrated scenario respectively. There is a considerable decrease in LCOE from 2015 to 2050 because of the transition from the fossil fuel to a RE-based electricity system.

By the year 2050, PV single-axis tracking and PV optimally tilted power generation dominates the energy transition towards a sustainable energy system by contributing 453 TWh and 2630 TWh in total electricity supply in the power scenario and integrated scenario respectively. In another study [35] contribution is 160 TWh only one-fourth of the energy supply and wind contribute an even higher proportion to total supply mix. The solar resource available in the country are excellent with a very low seasonal variation in most parts of the country except in Northern areas. The main load

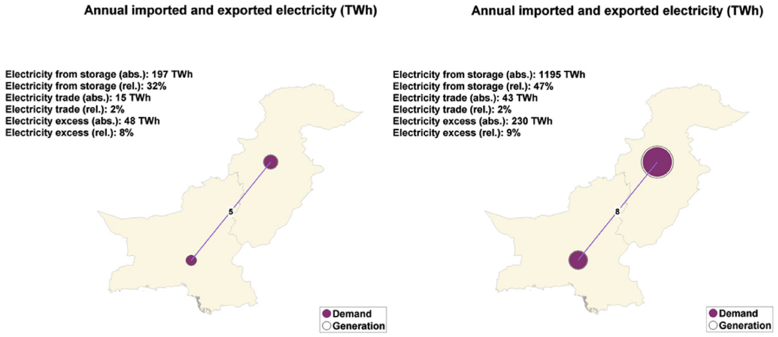


Fig. 15. The annual import and export of electricity between the two sub-regions for power (left) and integrated scenario (right) scenarios for year 2050.

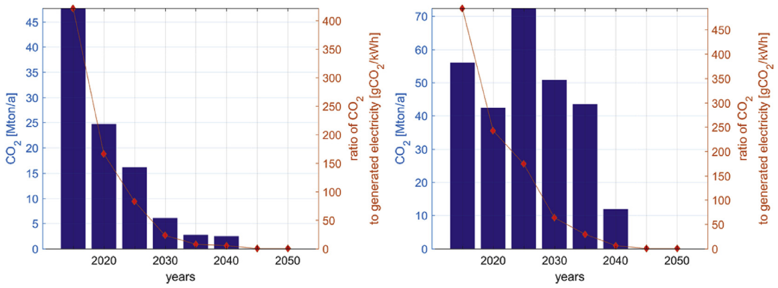


Fig. 16. Total annual GHG emissions and ratio of GHG emissions to electricity generation during the transition period for the power (left) and integrated (right) scenario.

centers of the country are located in very high solar insolation areas. Therefore, a photovoltaic based power generation system is ideal for this demand-supply scenario. Another study [14] proposed the hydro power share of 213 TWh and a maximum PV share of 386 TWh in the total energy supply mix. The hydro power would increase the vulnerability of the water sector in the country which is already in stress and facing problems like mismanagement and shortage. Solar PV and wind energy can also be used to reduce the risk in the hydropower system [65]. The discounted cost of the system is estimated to be 162 to 240 bUSD in two different supply cases by 2012. Perwez and Sohail [36] and Valasai et al. [37] report that an optimal mix of solar and wind energy will increase the energy sustainability in the country. These studies report a higher share of wind than PV in the total energy mix. But according to Muneer and Asif [66] wind energy is a less economical option as compared to solar energy. The average wind speed does not cross the economical threshold in most parts of the year except the four monsoon months. It was also found [35] that integration of wind resources also poses serious challenges to system stability. However, wind energy can be utilized by the energy system in periods of low solar irradiation as observed from this study. Of the total available wind energy potential of 123 GW [23], 6–28% is developed in the year 2050 depending on the scenarios. All the installed capacities of wind are situated in the Pakistan-South region which has the best wind sites. The contribution of PV prosumers to the total electricity generated is low due to the low cost of electricity from the grid. The PV prosumers contribute about 5% to the total electricity generation in 2050. Wind power generation starts after 2025 and remains constant throughout the period contributing about 8 GW. Storage technologies play a vital role in the 100% renewables based sustainable electric system providing flexibility and maintaining a balance between demand and supply. By 2050, gas storage dominates the total installed capacities of storage technologies as PtG is used as seasonal storage after 2040 when the installed renewable capacity exceeds 80%. But the results show that batteries come into effect after 2030. In terms of storage output, battery storage represents the largest share of 69% and 88% of the total storage output in power and integrated scenarios respectively. The installation of PV results into the system reliance on battery storage especially to use the power in evening and night generated in daytime. The role of the batteries in the PV based power system intensifies due to the favorable economics of system batteries. As fossil-based electricity generation is replaced by RE generation, the relevance of storage increases significantly from 2030, particularly, due to the dominance of solar PV in the energy system.

The results obtained are comparable to Gulagi et al. [57] for the SAARC region, which apply an overnight approach for the year 2030 with slightly different cost assumptions for some of the technologies. However, the LCOE obtained for both the studies is lower than the cost of the current system. The energy system of Pakistan will be powered by solar PV and supported by batteries according to both the study results. However in this research we do not consider HVDC connections with neighbouring countries, i.e India and Afghanistan which would further impact on the cost of electricity by reducing the need to store electricity and reducing the curtailment. According to Gulagi et al. [57], HVDC grid connection between neighbouring countries has a positive impact on reducing cost of electricity, which is attributed to less installed capacities of generation technologies.

The integrated scenario is dominated by an extremely high desalination water demand. Water desalination can make a real difference solving the looming water crises in the country. By 2050, seawater desalination demand is expected to rise to $2.8 \cdot 10^{11}$ m^3/a which is in line with other studies [29,30]. The only installed desalination plants are seawater reverse osmosis (SWRO) plants because they are more efficient and cost competitive as compared to other desalination technologies and would be powered by RE energy [67]. SWRO plants and renewables could be combined to solve water and power problems [68]. The estimated installed desalination capacity to meet the demand in 2050 is $7.8 \cdot 10^8$ m^3 and energy required for the SWRO plants is 1721 TWh. The levelized cost of water (LCOW), which includes water production, electricity, water transportation and water storage costs is found to be 0.84 €/m^3 and 0.62 €/m^3 in 2015 and 2050 respectively. The capex to meet Pakistan's water demand by 2050 is estimated to 1100 b€. The total annual opex fixed and variable are found in study to be 60 b€ and 80 b€ by 2050. Thus, our work presents that the water crisis in Pakistan could be averted in a productive and sustainable manner. Water desalination is a new technology to the country but recently some SWRO plants had started working [69] in Gwadar City, which is on the southwestern coast of Pakistan.

Despite being a low emitter of GHG emissions (0.8% of the total global GHG emission), Pakistan is highly vulnerable to climate change owing to its geographic location, elevation as well as demographics. Moreover, the electricity sector in Pakistan is currently facing formidable challenges of an insufficient installed capacity, a suboptimal infrastructure, circular debt and revenue shortage. The government's plan to depend on imports of fossil fuels and invest in fossil fuels would backfire in terms of highly unstable fossil fuel prices in the global market, energy security, huge part of GDP going to the imports, climate change and electricity shortages. On the other hand, renewables can reduce the reliance on depleting natural gas resources and substantial oil imports and would result into an independent and secure energy supply. In order to continue the pace of economic growth, electrification of villages and to cope with the rising gap between energy supply and demand, renewable energy is the optimal option for Pakistan [70].

The renewable energy sector in Pakistan is in its nascent stage. However, successful installation of 400 MW of solar PV and 256 MW of wind power plants has encouraged further investment in this sector [71]. There are 35 projects with 1.1 GW capacity, which are under development within the framework of the policies of Alternative Energy Development Board (AEDB) [48]. The government expects to add 1556 MW of solar PV to the national grid in 2018 [72]. The formation of AEDB has given a boost to the renewable energy sector with increased investments in recent years with AEDB issuing letters of intent (LOI) to 24 projects with a combined capacity of 556.8 MW [72]. With a clear government strategy, support, commitment towards renewable, stability and long-term targets will attract huge investments. There has been a good beginning, however Pakistan has a long way to go.

Huge potential for solar PV and wind is available in the country to materialise the required solar and wind capacity by 2050. However, some barriers do exits for the renewable energy sector like the policy barriers, institutional barriers, financial barriers and information and social barriers [73]. With the formation of AEDB, some of the policy and regulatory barriers have been addressed in the last years. It can be seen from the installation of renewables and number of projects in the pipeline. However, some of the other barriers need to be addressed to fully realise the renewable energy potential of the country and join the league of countries leading in renewable energy.

The cost of electricity obtained from this study can be compared with the LCOE of the alternative technologies of ‘clean’ energy which has been a discussion in Pakistan and around the world such as a new nuclear power plant (assumed for 2023 in the UK and Czech Republic) and gas CCS (assumed for 2019 in the UK) with LCOE of 112 €/MWh, and 126 €/MWh for coal CCS (assumed for 2019 in the UK) [74]. According to a report [75], CCS technology will not be available until 2030, and lot of questions are being asked whether it will be profitable at all [76]. The results obtained for a 100% RE-based system would help achieve the goal of net zero GHG emissions set at COP 21 [77].

6. Conclusion

Pakistan needs to concentrate on renewables for achieving a secure, cost effective and reliable electricity supply system. A 100% RE based power system is possible for Pakistan by 2050. Exploitation of indigenous energy resources should be the real policy option to enhance energy security of the country through lessening reliance on energy imports. RE technologies can produce enough electricity to cover the total demand by 2050 on significantly lower cost compared to the current non-renewable based electricity system. The LCOE obtained for a fully sustainable energy system for Pakistan by 2050 is 46.2 €/MWh for the power and 46.8 €/MWh for integrated scenario, while covering the huge water desalination demand of country. Solar PV and batteries dominate the installed RE technologies due to their low cost and excellent solar resource conditions in Pakistan. Solar PV provides almost 86% of the total electricity demand and is complimented by wind and biogas in low solar irradiation areas. The huge share of solar PV in electricity generation corresponds to the huge share of batteries as storage technology as the least cost and sustainable option. The gas storage becomes prominent in 2030 when the RE share crosses 80%, however the storage output of gas storage is very low in comparison to batteries. Water desalination demands appear as the dominating factor in the integrated scenario and this problem needs to be solved on urgent basis. This study shows that RE can not only solve the energy but also the looming water crises in the country. However, there exits several barriers for renewable energy development in the country which needs to be addressed. Adequate planning among the stakeholders and implementation by the government is needed to harness the available renewable resources to overcome the present energy crisis. Examples of innovative financing programs can be taken from elsewhere in the world and adopted to local conditions. Local manufacturing of renewable energy systems could reduce investment costs and create employment for the local people. The key to renewable energy future is the political will.

In the present research, the methodology is focusing on two regions of Pakistan and demand sectors of power, desalination and non-industrial gas demand. Future research will be based on higher spatial resolution which will better describe the regional variation and in detail analysis of the transmission lines plus addition of all energy sectors.

Acknowledgements

The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14 which enabled the LUT Energy System Transition model and second author would like to thank Fortum Foundation for the valuable scholarship. The authors would like to thank Michael Child for proofreading.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2018.01.027.

Appendix A

Table A.1

Technical and financial assumptions of all energy system components used in the energy transition from 2015 to 2050 for Pakistan. Assumptions are taken from Pleβmann et al. [78] and European Commission [79] and further references are individually mentioned.

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
PV rooftop - residential	Capex	€/kWp	1360	1169	966	826	725	650	589	537	[42]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kWp	1360	907	737	623	542	484	437	397	[42]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kWp	1360	682	548	459	397	353	318	289	[42]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally fixed-tilted	Capex	€/kWp	1000	580	466	390	337	300	270	246	[42]
	Opex fix	€/(kWp a)	15	13,2	11,8	10,6	9,6	8,8	8,0	7,4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kWp	1150	638	513	429	371	330	297	271	[42] [80]
	Opex fix	€/(kWp a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW	1250	1150	1060	1000	965	940	915	900	[81]
	Opex fix	€/(kW a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/m^2	270	240	220	200	180	170	150	140	[82] [83]
	Opex fix	%	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	
	Opex var	–	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal power	Capex	€/kW	5250	4970	4720	4470	4245	4020	3815	3610	[79] [84]
	Opex fix	€/(kW a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	

Table A.1 (*continued*)

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW	800	685	500	380	340	310	280	260	[85] [86]
	Opex fix	€/(kW a)	32	27	20	15	14	12	11	10	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW	492	421	310	234	208	190	172	160	[85] [86]
	Opex fix	€/(kW a)	10	8	6	5	4	4	3	3	
	Opex var	€/(kWh)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	
CO$_2$ direct air capture	Capex	€/kW	749	641	470	356	314	286	258	240	
	Opex fix	€/(kW a)	29.9	25.6	18.8	14.2	12.6	11.4	10.3	9.6	
	Opex var	€/(kWh)	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
	Lifetime	years	30	30	30	30	30	30	30	30	
CCGT	Capex	€/(kW$_{el}$)	775	775	775	775	775	775	775	775	[87]
	Opex fix	€/(kW$_{el}$ a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	58	58	58	58	59	60	60	60	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT	Capex	€/(kW$_{el}$)	475	475	475	475	475	475	475	475	[87]
	Opex fix	€/(kW$_{el}$ a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	43	43	43	43	43	43	43	43	
	Lifetime	years	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	Capex	€/(kW$_{el}$)	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW$_{el}$ a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	42	42	42	43	44	44	45	45	
	Lifetime	years	25	25	25	25	30	30	30	30	
Steam turbine (coal-fired PP)	Capex	€/(kW$_{el}$)	1500	1500	1500	1500	1500	1500	1500	1500	[87] [88]
	Opex fix	€/(kW$_{el}$ a)	20	20	20	20	20	20	20	20	
	Opex var		0	0	0	0	0	0	0	0	
	Efficiency	%	45	45	45	45	46	46	47	47	
	Lifetime	years	40	40	40	40	40	40	40	40	
Biomass CHP	Capex	€/kW	3400	2900	2700	2500	2300	2200	2100	2000	
	Opex fix	€/(kW a)	238	203	189	175	161	154	147	140	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	36	37	40	43	45	47	47.5	48	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas CHP	Capex	€/kW	503	429	400	370	340	326	311	296	
	Opex fix	€/(kW a)	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	35	36	39	42	44	46	46	47	
	Lifetime	years	30	30	30	30	30	30	30	30	
Waste incinerator	Capex	€/kW	5940	5630	5440	5240	5030	4870	4690	4540	
	Opex fix	€/(kW a)	267.3	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
	Opex var	€/(kWh)	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Efficiency	%	27	31	32.5	34	35.5	37	29.5	42	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW	771	731	706	680	653	632	609	589	
	Opex fix	€/(kW a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW	340	290	270	250	230	220	210	200	[89]
	Opex fix	€/(kW a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	98	98	98	98	98	98	98	98	
	Lifetime	years	20	20	20	20	25	25	25	25	
Battery, Li-ion	Capex	€/(kWh$_{el}$)	600	300	200	150	120	100	85	75	[90]
	Opex fix	€/(kWh$_{el}$ a)	24	12	8	6	4.8	4	3.4	3	
	Opex var	€/(kWh$_{throughput}$)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
Adiabatic compressed air energy storage (A-CAES)	Capex	€/kWh	35.0	35.0	33.0	31.1	30.4	29.8	28.0	26.3	
	Opex fix	€/(kWh a)	0.46	0.46	0.43	0.40	0.40	0.39	0.36	0.34	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh$_{th}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Table A.2
Energy to power ratio and self-discharge rates of the storage technologies

Technology	Energy/Power Ratio (hrs)	Self-Discharge	References
Battery	6	0	[78]
PHS	8	0	[78] [79]
A-CAES	100	0.001	[79]
TES	8	0.002	[78]
Gas storage	80*24	0	[78]

References

[1] Behringer W. A cultural history of climate. Cambridge: Polity Press; 2010 [Available Online]: http://www.suarasitaronews.com/a-cultural-history-of-climate.pdf.

[2] Graßl H, Kokott J, Kulessa M, Luther J, Nuscheler F, Sauerborn R, et al. World in transition: towards sustainable energy systems. Germany: German Advisory Council on Global Change (WBGU); 2004 [Available Online]: http://www.wbgu.de/fileadmin/user_upload/wbgu.de/templates/dateien/veroeffentlichungen/hauptgutachten/jg2003/wbgu_jg2003_engl.pdf.

[3] [UNDP] - United Nations Development Programme. Sustainable energy for all (SE4ALL), Pakistan: rapid assessment and gap analysis. Islamabad. 2014 [Available Online]:, http://www.se4all.org/sites/default/files/Pakistan_RAGA_EN_Released.pdf.

[4] Farfan J, Breyer C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. J Clean Prod 2017;141:370–84.

[5] Abbasi AH. Rethinking Pakistan's energy equation: Iran-Pakistan gas pipeline, ministry of petroleum and natural resources. Islamabad. 2014 [Available Online]:, http://www.mpnr.gov.pk/mpnr/userfiles1/file/3rdMEReport%20Revised.pdf.

[6] Sheikh MA. Energy and renewable energy scenario of Pakistan. Renew Sustain Energy Rev 2010;14(1):354–63.

[7] Shaikh F, Ji Q, Fan Y. The diagnosis of an electricity crisis and alternative energy development in Pakistan. Renew Sustain Energy Rev 2015;52: 1172–85.

[8] [NTDC] - National Transmission and Despatch Authority. Electricity demand forecast based on multiple regression analysis, planning power. Islamabad. 2015 [Available Online]:, http://www.ntdc.com.pk/LoadForecast.pdf.

[9] Komal R, Abbas F. Linking financial development, economic growth and energy consumption in Pakistan. Renew Sustain Energy Rev 2015;44:211–20.

[10] Zaman K, Khan MM, Ahmad M, Rustam R. Determinants of electricity consumption function in Pakistan: old wine in a new bottle. Energy Pol 2012;50: 623–34.

[11] Kessides IN. Chaos in power: Pakistan's electricity crisis. Energy Pol 2013;55: 271–85.

[12] Perwez U, Sohail A. Forecasting of Pakistan's net electricity energy consumption on the basis of energy pathway scenarios. Energy Procedia 2014;61: 2403–11.

[13] Pakistan economic survey 2014-15. Ministry of finance. Islamabad: Finance Division, Government of Pakistan; 2015 [Available Online]: http://www.finance.gov.pk/survey/chapters_15/Highlights.pdf.

[14] Jamal N. A renewable electricity supply system in Pakistan by 2050: assessment of generation capacity and transmission system requirements. Dissertation. Flensburg: Europa-Universität Flensburg; 2016.

[15] Mirza I, Khalil M. Renewable energy in Pakistan: opportunities and challenges. Sci Vis 2011;16:13–20.

[16] Alauddin A. Energy efficiency & renewable energy: the key to sustainable development. Islamabad: AEDB; 2009 [Available Online]: http://www.sciencevision.org.pk/BackIssues/Vol16_Vol17/02_Vol16_and_17_Renewable%20Energy%20in%20Pakistan_IrfanAfzalMirza.pdf.

[17] Lodhi RN, Malik R. Impact of electricity shortage on daily routines: a case study of Pakistan. Energy Environ 2013;24(5):701–9.

[18] Uqaili MA, Harijan K, Mirani M, Memon MD. Renewable energy technologies for rural electrification in Pakistan: status and prospects. In: Proceedings of electric supply industry in transition: issues and prospects for Asia, an international conference, vol. 14. Khlong Nung, Thailand: AIT; 2004. p. 16. 2004 Jan.

[19] Khaliq A, Ikram A, Salman M. Quaid-e-Azam Solar Power park: prospects and challenges. Islamabad: 2015 Power Generation System and Renewable Energy Technologies (PGSRET); 2015. p. 1–6 [Available Online]: http://ieeexplore.ieee.org/abstract/document/7312186/.

[20] Farfan J, Breyer C. Aging of European power plant infrastructure as an opportunity to evolve towards sustainability. Int J Hydrogen Energy 2017;42: 18081–91.

[21] Ram M, Child M, Aghahosseini A, Bogdanov D, Poleva A, Breyer C. Comparing electricity production costs of renewables to fossil and nuclear power plants in G20 countries. Greenpeace report, Hamburg. 2017 [Available Online]:, https://goo.gl/MyJFs2.

[22] $3bn invested in renewable energy sector in one year: official, in Dawn News. [APP] - Associated Press of Pakistan; Dec 07, 2015 [Available Online]: https://www.dawn.com/news/1224736.

[23] Harijan K, Uqaili MA, Memon M, Mirza UK. Forecasting the diffusion of wind power in Pakistan. Energy 2011;36(10):6068–73.

[24] Jabeen M, Umar M, Zahid M, Rehaman MU, Batool R, Zaman K. Socio-economic prospects of solar technology utilization in Abbottabad, Pakistan. Renew Sustain Energy Rev 2014;39:1164–72.

[25] Mirza UK, Maroto-Valer MM, Ahmad N. Status and outlook of solar energy use in Pakistan. Renew Sustain Energy Rev 2003;7(6):501–14.

[26] Gosens J, Hedenus F, Sandén BA. Faster market growth of wind and PV in late adopters due to global experience build-up. Energy 2017;131:267–78.

[27] Khan MA. Policy review and recommendations on the promotion of renewable energy and energy efficiency, draft policy. Pakistan: UNIDO; 2016 [Available Online]: http://www.solarthermalworld.org/sites/gstec/files/news/file/2017-01-25/pakistan_reee_policy_reviewadvisory_first_draft_2.pdf.

[28] [WB] - The World Bank. Solar resources mapping in Pakistan: solar modelling report. Washington D.C: Energy Sector Management Associate Programme (ESMAP); March 2015 [Available Online]: http://documents.worldbank.org/curated/en/200771468096863184/pdf/95710-REVISED-ESM.pdf.

[29] Briscoe J, Qamar U. Pakistan's water economy: running dry. World Bank document. Washington, D.C: Oxford University Press; 2006 [Available Online]:, http://johnbriscoe.seas.harvard.edu/files/johnbriscoe/files/7._briscoe_-.

[30] Kochhar K. Is the glass half empty or half full? Issues in managing water challenges and policy instruments, IMF Staff discussion note. Washington D.C.: International Monetary Fund; June 2015. p. 7 [Available Online]: https://www.imf.org/external/pubs/ft/sdn/2015/sdn1511.pdf.

[31] Mustafa D, Akhter M, Nasrallah N. Understanding Pakistan's water-security nexus. Washington, D.C.: United States Institute of Peace; June 2013 [Available Online]: http://futuredirections.org.au/wpcontent/uploads/2015/04/PW88_Understanding-Pakistan's-Water-Security-Nexus.pdf.

[32] [WWF] - World wildlife fund Pakistan, annual report. 2016 [Available Online]: http://hdl.handle.net/123456789/15144.

[33] Altaf S, Kugelman M, Hathaway RM. Running on empty: Pakistan's water crisis. Washington, D.C.: Woodrow Wilson International Center for Scholars; 2009 [Available Online]: https://www.wilsoncenter.org/sites/default/files/ASIA_090422_Running%20on%20Empty_web.pdf.

[34] Siddiqi TA, Tahir-Kheli S. Water needs in South Asia: closing the demand-supply gap. GEE-21. New York: John Hopkins University; 2004 [Available Online]: http://www.eastwestcenter.org/publications/water-needs-south-asia-closing-demand-supply-gap.

[35] Jamal N, Hohmeyer O. Solar resources' potential role in the development of renewable based electric power system by 2050: the case of Pakistan prospects of solar in Pakistan, energy systems and policies (ICESP). In: International conference on energy system and policies, Nov 24-26, Islamabad; 2014 [Available Online]:https://www.zhbflensburg.de/fileadmin/content/spezial-einrichtungen/zhb/dokumente/dissertationen/jamal/phd-thesis.pdf.

[36] Perwez U, Sohail A. Forecasting of Pakistan's net electricity energy consumption on the basis of energy pathway scenarios. Energy Procedia 2014;61: 2403–11.

[37] Valasai G, Uqailli M, Memon H, Samoo S, Mirjat N, Harijan K. Assessment of renewable energy for electricity generation: using Pakistan TIMES energy model. Sindh Univ Res J SURJ (Sci Series) Dec 21, 2016;48(4).

[38] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag 2016;112:176–90.

[39] EnergyPlan, Advanced energy system analysis computer model, Department of Development and Planning, Aalborg University, Denmark. [Available Online]: http://www.energyplan.eu/.

[40] Barbosa LSNS, Bogdanov D, Vainikka P, Breyer C. Hydro, wind and solar power as a base for a 100% Renewable Energy supply for South and Central America. PLoS One 2017;12, e0173820.

[41] Fasihi M, Bogdanov D, Breyer C. Economics of global LNG trading based on hybrid PV-wind power plants. In: 31st European photovoltaic solar energy conference; 2015. Hamburg, September 14 – 18, 2015. [Available at]: https://goo.gl/3kCcPQ.

[42] [ETIP-PV] - European Technology and Innovation Platform Photovoltaics. The true competitiveness of solar PV. Munich: A ETIP-PV; 2017 [Available Online]: https://goo.gl/GrSBAS.

[43] World Energy Council. World energy resources. London: World Energy Council; 2016.

[44] Wirth H. Aktuelle Fakten zur Photovoltaik in Deutschland. Freiburg: Fraunhofer Institute for Solar Energy Systems; 2017.

[45] Parkinson G. Solar heads to 1c/KWh before 2020 after Mexico sets record low. In: RenewEconomy; 2017 [Available Online]: http://reneweconomy.com.au/solar-heads-to-1ckwh-before-2020-after-mexico-sets-record-low-62163/?utm_source=RE+Daily+Newsletter&utm_campaign=7ebf9419b8-EMAIL_CAMPAIGN_2017_11_20&utm_medium=email&utm_term=0_46a1943223-7ebf9419b8-40387973.

[46] Nykvist B, Nilsson M. Rapidly falling costs of battery packs for electric vehicles. Nat Clim Change 2015;5(4):329–32.

[47] Lambert F. Electric vehicle battery cost dropped 80% in 6 years down to $227/kWh – tesla claims to be below $190/kWh, in Electrek. 2017 [Available Online]: https://electrek.co/2017/01/30/electric-vehicle-battery-cost-dropped-80-6-years-227kwh-tesla-190kwh/.

[48] [IFC] – International Finance Corporation. A solar developer's guide to Pakistan, a report, Washington D.C. 2016 [Available Online]: http://www.ifc.org/wps/wcm/connect/b46619004b5e398cb8b5fd08bc54e20b/IFC+-

+Solar+Developer%27s+Guide+-+Web.pdf?MOD=AJPERES.

[49] Kemfert C, Burandt T, Hainsch K, Löffler K, Oei PY, von Hirschhausen C. Nuclear power unnecessary for climate protection — there are more cost-efficient alternatives. Econ Bull 2017;7(48):498–506.

[50] Gernaat DEHJ, Van Vuuren DP, Van Vliet J, Sullivan P, Arent DJ. Global long-term cost dynamics of offshore wind electricity generation. Energy 2014;76: 663–72.

[51] Breyer C, Bogdanov D, Gulagi A, Aghahosseini A, Barbosa LSNS, Koskinen O, et al. On the role of solar photovoltaics in global energy transition scenarios. Prog Photovoltaics Res Appl 2017;25:727–45.

[52] Gerlach A, Breyer C, Werner C. Impact of financing cost on global grid-parity dynamics till 2030. In: 29th European photovoltaic solar energy conference; 2014. Amsterdam, [Available online]: https://goo.gl/dv75Py.

[53] Breyer C, Gerlach A. Global overview on grid-parity. Prog Photovoltaics Res Appl 2013;21:121–36.

[54] Bunzel K, Zeller V, Buchhorn M, Griem F, Thrän D. Regionale und globale räumliche Verteilung von Biomassepotenzialen. Leipzig: German Biomass Research Center; 2009.

[55] [IEA] - International Energy Agency. Technology roadmap – bioenergy for heat and power. Paris: IEA Publishing; 2012 [Available online]: http://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf.

[56] [IPCC] - Intergovernmental Panel on Climate Change. Special report on renewable energy sources and climate change mitigation. Geneva: Intergovernmental Panel on Climate Change; 2011 [Available online]: http://www.ipcc.ch/pdf/special-reports/srren/SRREN_Full_Report.pdf.

[57] Gulagi A, Choudhary P, Bogdanov D, Breyer C. Electricity system based on 100% renewable energy for India and SAARC. PLoS One 2017;12(7), e0180611.

[58] Verzano K. Reports on Earth System Science. Climate change impacts on flood related hydrological processes: further development and application of a global scale hydrological model, vol. 71. Hamburg: Max-Planck-Institut für Meteorologie; 2009. Dissertation, Faculty of Electrical Engineering and Computer Science, University of Kassel.

[59] Timilsina GR, Toman M, Karacsonyi J, de Tena Diego L. How much could South Asia benefit from regional electricity cooperation and trade?. Policy Research Working Paper. Washington, D.C.: World Bank; June. 2015 [Available Online]:, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2623783.

[60] [SARI/EI] - South Asian Regional Initiative for Energy Integration. Presentation on the draft interim findings of the study on assessment of the electricity trading potential in the South Asia region. New Delhi. August 2015 [Available Online]:, https://sari-energy.org/presentations/page/7/.

[61] Caldera U, Bogdanov D, Breyer C. Local cost of seawater RO desalination based on solar PV and wind energy: a global estimate. Desalination 2016;385: 207–16.

[62] [IEA] - International Energy Agency. Energy balances of OECD and non-OECD countries. Paris. 2014.

[63] [IEA] - International Energy Agency. India energy outlook. Paris: IEA publications; 2015.

[64] [UNFCCC] - United Nations Framework Covention on Climate Change. In: Conference of the parties (COP) Paris climate change conference, COP 21. Adopt Paris agreement propos by pres; November 2015. https://doi.org/10.FCCC/CP/2015/L.9/Rev.1. 2015;21932 (December):32.

[65] Schmidt J, Cancella R, Pereira AO. The role of wind power and solar PV in reducing risks in the Brazilian hydro-thermal power system. Energy 2016;115:1748–57.

[66] Muneer T, Asif M. Prospects for secure and sustainable electricity supply for Pakistan. Renew Sustain Energy Rev 2007;11(4):654–71.

[67] Desalination technologies and economics: CAPEX, OPEX and technological game changers to come, mediterranean regional technical meeting. Marseille: Almar water solutions; 2016 [Available Online]: http://www.cmimarseille.org/sites/default/files/newsite/library/files/en/1.6.%20C.%20Cosin_%20Desalination%20technologies%20and%20economics_%20capex%2C%20opex%20and%20technological%20game%20changers%20to%20come%20-ilovepdf-compressed.pdf.

[68] Tsai YC, Chiu CP, Ko FK, Chen TC, Yang JT. Desalination plants and renewables combined to solve power and water issues. Energy 2016;113:1018–30.

[69] Andreas F, Basel S. Water segment industry report desalination. San Diego: World trade center; July 2012 [Available Online]: http://www.wtcsd.org.

[70] Aslam A, Ahmad PAV, Munawar Z. National economic & environmental development study (NEEDS). Pakistan: Ministry of Environment; 2011 [Available Online]: https://unfccc.int/files/adaptation/application/pdf/pakistanneeds.pdf.

[71] Ishaque H. Is it wise to compromise renewable energy future for the sake of expediency? An analysis of Pakistan's long-term electricity generation pathways. Energy Stud Rev 2017;17:6–18.

[72] [AEDB] – Alternative Energy Development Board. Progress so far made in solar power sector in Pakistan. Islamabad: Ministry of Energy, Government of Pakistan; 2017 [Available Online]: http://www.aedb.org/index.php/ae-technologies/solar-power/solar-current-status.

[73] Farooqui SZ. Prospects of renewables penetration in the energy mix of Pakistan. Renew Sustain Energy Rev 2014;29:693–700.

[74] Energiewende Agora. Comparing the cost of low-carbon technologies: what is the cheapest option? report by Prognos AG on behalf of Agora Energiewende. Berlin. 2014. p. 10–3 [Available online]:, www.prognos.com/fileadmin/pdf/publikationsdatenbank/140417_Prognos_Agora_Analysis_Decarbonisationtechnologies_EN.pdf.

[75] European Commission. Integration of renewable energy in Europe, study prepared by KEMA Consulting, DNV GL – Energy. Brussels: Imperial College and NERA Economic Consulting on behalf of DG Energy; 2014. pp. 7–8 and 54.

[76] Citi Research Equities. Paris climate change Agreement [Sydney]. 2015.

[77] [UNFCCC] – United Nations Framework Convention on Climate Change. Adoption of the Paris Agreement – proposal by the president. Paris: UNFCCC; 2015 [Available online]: http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf.

[78] Pleßmann G, Erdmann M, Hlusiak M, Breyer C. Global energy storage demand for a 100% renewable electricity supply. Energy Proc 2014;46:22–31.

[79] European Commission. ETRI 2014-Energy technology reference indicator projections for 2010-2050. Petten, Netherlands: EC Joint Research Centre Institute for Energy and Transport; 2014 [Available online]: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC92496/ldna26950enn.pdf.

[80] Bolinger M, Seel J. Utility-scale solar 2015: an empirical analysis of project cost, performance and pricing trends in the United States. Berkley: Lawrence Berkeley National Laboratory; 2016. https://emp.lbl.gov/publications/utility-scale-solar-2015-empirical.

[81] Neij L. Cost development of future technologies for power generation – a study based on experience curves and complementary and bottom-up assessments. Energy Pol 2008;36:2200–11.

[82] Haysom JE, Jafarieh O, Anis H, Hinzer K, Wright D. Learning curve analysis of concentrated photovoltaic systems. Prog Photo 2014;23:1678–86.

[83] Kutscher C, Mehos M, Turchi C, Glatzmaier G, Moss T. Line-focus solar power plant cost reduction plant. Colorado: National Renewable Energy Laboratory; 2010 [Available Online]: http://www.nrel.gov/docs/fy11osti/48175.pdf.

[84] Sigfusson B, Uihelein A. Joint research center geothermal energy status report. Petten: European Commission Joint Research Center Institute for Energy and Transport; 2015 [Available Online]: https://setis.ec.europa.eu/sites/default/files/reports/2015_jrc_geothermal_energy_status_report.pdf.

[85] Energiewende Agora. Stromspeicher in der Energiewende. Berlin. Sep., 2014 [Available Online]:, www.agora-energiewende.de/fileadmin/Projekte/2013/speicher-in-der-energiewende/Agora_Speicherstudie_Web.pdf.

[86] Breyer C, Tsupari E, Tikka V, Vainikka P. Power-to-Gas as an emerging profitable business through creating an integrated value chain. Energy Procedia 2015;73:182–9.

[87] [IEA] - International Energy Agency. World energy investment outlook. Paris: IEA; 2003.

[88] McDonald A, Schrattenholzer L. Learning rates for energy technologies. Energy Pol 2001;29:255–61.

[89] Urban W, Lohmann H, Girod K. Abschlussbericht für das BMBF-Verbundprojekt Biogaseinspeisung. Fraunhofer UMSICHT; 2009.

[90] Hoffmann W. Importance and evidence for cost effective electricity storage. In: 29th EU PVSEC; Sep 22-26, 2014. Amsterdam.

Publication VI

Gulagi, A., Pathak, S., Bogdanov, D., and Breyer, C.

Renewable energy transition for the Himalayan countries Nepal and Bhutan: Pathways towards reliable, affordable and sustainable energy for all

Reprinted with permission from
IEEE Access
Vol. 9, pp. 84520-84544, 2021

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 31, 2021, accepted June 3, 2021, date of publication June 7, 2021, date of current version June 17, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3087204

Renewable Energy Transition for the Himalayan Countries Nepal and Bhutan: Pathways Towards Reliable, Affordable and Sustainable Energy for All

ASHISH GULAGI, SANJEEV PATHAK, DMITRII BOGDANOV, AND CHRISTIAN BREYER
School of Energy Systems, LUT University, 53850 Lappeenranta, Finland
Corresponding author: Ashish Gulagi (ashish.gulagi@lut.fi)

ABSTRACT The Himalayan countries Nepal and Bhutan have been confronted with similar climate change and energy emergencies for quite a long time. Its influence is felt as a barrier in financial, social, infrastructural, and political development. Despite having an enormous amount of renewable energy sources, these countries are unable to fulfil their current energy demand. While the power sector is entirely dependent on hydropower, other sectors depend on fossil fuel imports from India. This study offers a pathway for energy independency, energy for all and transition towards a 100% renewables based energy system. The modelling of the energy sector is done using the LUT Energy System Transition model for a period from 2015 to 2050 in a 5-year time step. This study covers the main energy sectors: power, heat, and transport. Two scenarios are visualised, one considering greenhouse gases (GHG) emissions and the associated mitigation cost and another without these costs, though both scenarios aim at achieving a high share of renewable energy by 2050. A substantial drop in levelised cost of energy is observed for the scenario without GHG emission cost, however, taxing GHG emissions will accelerate the energy transition with the levelised cost of energy on a similar level. It is well possible to transition from 90 €/MWh in 2015 to 49 €/MWh by 2050 for the entire energy system by utilizing indigenous low-cost renewable energy. Solar photovoltaics and hydropower will play a dominant role in 2050, having a share of 67% and 31% respectively. Consequently, this leads to zero GHG emissions. An energy transition towards a sustainable and secure energy system for all by 2050 is well possible in Nepal and Bhutan only through 100% renewable sources and it is both technically and economically feasible despite having substantial limitations in infrastructure and economic development currently.

INDEX TERMS 100% renewable energy, Nepal, Bhutan, energy transition, Himalayan countries, hydropower, solar photovoltaics.

I. INTRODUCTION

The sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) on impacts of global warming finds that, warming in the South Asian region is expected to be higher than the global average [1]. Consequently, resulting in changing monsoon patterns [2], rising sea levels [3] and melting glaciers [4], [5], drastically impacting the South Asian society. Nepal and Bhutan, two small countries situated on the Himalayan slopes, will be severely impacted by flooding due to glacier melt and irregular rainfalls; threatening the livelihood, food security, health and general well-being across these nations [6]. Therefore, dependence on fossil fuels; a major contributor to greenhouse gases (GHG) emissions will not only accelerate these consequences, but also contribute to energy insecurity and unaffordability to the common people.

During the last few decades, Nepal and Bhutan have experienced tremendous growth in energy consumption, not only due to growing population and rising 'materialistic' standard of living, but also due to increase in industrialization and economic activities. However, this growth has resulted in

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

increased dependence on fossil fuel imports, wrecking the economic balance and increase in traditional and unsustainable use of biomass (fuelwood) resources, resulting in additional GHG emissions.

Hydropower is and has been the main renewable electricity generation source in Nepal and Bhutan. While it is the main source of income for Bhutan due to hydropower export to India, Nepal has been not able to replicate this model due to various issues and utilises all its hydropower domestically [7]. In 2016, Bhutan's hydropower export provided a contribution of about 8% to its gross domestic product (GDP) [8]. Majority of the hydropower is run-of-river, depending on the monsoon and glacier melt, thus reducing the power output during the dry seasons. Even though with large hydropower potential, these countries are not able to provide uninterrupted power, with unplanned power blackouts on daily basis lasting several hours to some lasting for several days [7]. These conditions are hampering economic growth and not to forget the daily hardship faced by the common people [9].

For many years, hydropower has been promoted as the main source of electricity to provide uninterrupted power and economic development [10]. However, large hydropower projects not only face many social and environmental hinderances, but also technical and financial concerns, particularly in Nepal and Bhutan [11], due to their overdependence on one energy resource. In addition, rural electrification and extension of grid lines have been problematic due to various factors and large hydropower will amplify the problem.

Therefore, Nepal and Bhutan need to diversify their energy resource mix to accommodate remote unelectrified areas by providing electricity to 6.6 million people, uninterrupted electricity to those having access to electricity and boosting the economic growth [10]. Distributed and utility-scale solar photovoltaics (PV), wind energy, bioenergy and hydropower will not only overcome this challenge, but also broaden the portfolio of the energy generation mix making Nepal and Bhutan energy independent. Falling cost of renewables especially solar PV will make this transition faster and at an affordable cost for end-users.

This research aims to fulfill the gap in energy transition pathways towards the future for the Himalayan countries: Nepal and Bhutan. This is done by integrating solar PV, wind energy, bioenergy, and hydropower towards a high share of renewable energy in the power, heating, and transport sectors. The scenarios are optimised based on a least cost solution using the LUT Energy System Transition Model [12].

A. CURRENT ENERGY SITUATION IN NEPAL AND BHUTAN

1) ENERGY SUPPLY AND CONSUMPTION

The energy sector in Nepal is small, inefficient and unreliable, aptly reflected in its energy consumption and dominated by traditional energy sources [13], [14]. Nepal's per capita annual primary energy consumption was 5 MWh in 2016, which is one of the lowest in the world [15], [16], in contrast to its growing energy demand in industry and transport [8]. Bhutan had a per capita annual primary energy consumption of 23 MWh [15].

Due to no significant local deposits of fossil fuels, Nepal and Bhutan rely heavily on traditional energy resources such as firewood, agriculture residues and animal dung. In 2014, about 80% of Nepal's primary energy supply was based on biomass, whereas commercial fuels made up the remaining share (Figure 1). On the other hand, Bhutan had a comparatively, smaller share of traditional biomass in its total primary energy supply, due to its developed energy sector and higher share of electricity in final energy consumption (Figure 1). The commercial fuels, coal, diesel, and petroleum products, play an important role to satisfy the demand of industry and transport, while achieving an overall development of the country.

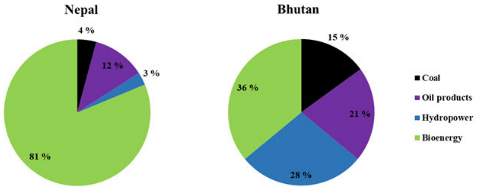


FIGURE 1. **Primary energy supply mix for Nepal (2014) and Bhutan (2015) [8], [17].**

In 2014, the residential sector had the largest share in final energy consumption (84%) in Nepal [17]. As majority of the population lives in rural areas, traditional biomass sources are used to meet the residential demand [18]. The share of industry and transport is small, however considerable growth has been observed. Between 2005 to 2014 the energy consumption in industry sector grew by a compound annual growth rate of 7.8%, while the transport sector saw the largest growth of 13.5% [17]. The rise in population, economic growth and standard of living has mainly attributed to the growing energy demand in the industry and transport sectors. Similarly, in Bhutan, the largest energy consuming sector was the residential sector with 41.6%, followed by the industry (33%) and transport sector (19%), while the remaining share was from the agriculture [8].

2) DEPENDENCE ON BIOENERGY AND FUEL IMPORTS

Large percentage of the population in developing countries relies on traditional biomass for cooking and heating [10]. In Nepal and Bhutan, the situation is no different. Due to lack of access to other clean forms of energy, majority of people rely on ineffective, hazardous, time intensive energy resources such as fuelwood, agricultural residues, charcoal and animal dung [19]. More than 85% of the residential energy demand comes from biomass, used in traditional open fire cooking stoves, space heating and other purposes [8], [20]. Thus, high dependence on biomass use has given rise to excessive deforestation beyond their sustainable limits and forests are becoming scarce [21]. The use of traditional biomass as a direct fuel has severe health impacts, due to hazardous emissions. Indoor air pollution causes direct physical health risks and continuous exposure increases the risk of acute respiratory problems, lung issues, increases child mortality and other ailments [22], [23]. In Nepal alone, 15,000 women and children died due to indoor air pollution in 2013 [24]. According to [25], on average 7500 women and children die each year due to using transitional biomass for cooking and heating. On top of the hazardous consequences due to indoor air pollution, women and children spend majority of their daily time collecting fuelwood, depriving them of education and other income generating activities [22]. Hence, the governments in these countries are encouraging use of electric cooking in view of reducing biomass consumption.

According to the International Energy Agency (IEA), energy security is defined as 'uninterrupted availability of energy sources at an affordable price' [26]. Due to rising energy demand in Nepal and Bhutan, there is often a mismatch between 'local energy availability' and 'energy affordability'. This effect is compounded as these countries do not have any significant deposits of petroleum reserves nor any oil refinery for processing crude oil [10], [27]. Bhutan has some reserves of low grade coal; however, this is not used as higher grade coal and coke are imported [27]. They rely completely on India for their energy needs (petroleum products) and this creates a situation of uncertainty in supply and trade balance deficit.

This uncertainty is amplified due to extremely short storage capacity of petroleum products in Nepal of only 15 days [10]. The economic blockade of 2015 from India on goods and energy products created a severe deficit of petroleum products, slowing economic activity considerably as well as impacting daily lives of 5 million households [28]. On a national level, these kind of events raise questions on the vulnerability of countries in the turbulent times of geopolitical crises.

3) HYDROPOWER – A CHALLENGING RESOURCE

Hydropower is the main source of electricity generation in Nepal and Bhutan and is often promoted as the most viable option for economic development [27]. The economically exploitable potentials are estimated at 26.7 GW for Bhutan and 43 GW for Nepal [11]. Despite having a huge potential, the growth in installed hydropower capacities has been limited, especially in Nepal. Considering the first hydropower plant constructed in 1911, total installed capacity reached a meagre 856 MW in 2016 [29]. On the other hand, Bhutan has been able to tap into its hydropower potential with an installed capacity of 1614 MW at the end of 2016 [30]. An interesting fact to note here is, Nepal has 36 times the population of Bhutan, but with an installed capacity of nearly half that of Bhutan [31]. The growth in hydropower in Bhutan has been attributed to attractive policies, stable governments and its diplomatic relationship with India. On the contrary, unstable political situations in Nepal have created delays in hydropower development which have resulted in its power crises [11].

The growth in large-scale hydropower is often marred with questions on its social, economic, technical and financial impacts [32]. These impacts are often unevenly distributed, with prospects of high rewards vs high risks [33]. Most of the times the risks outweigh the rewards gained. Storage of water in reservoirs often cause biomass decomposition, producing significant amounts of greenhouse gases emissions [34]. On top of that, excessive flooding of reservoirs can cause destruction of arable land, wildlife, scenic land and residential area [34]. Most of the large hydropower projects in Nepal experience large cost and time overruns adding to the already huge initial capital investment [35]. Most of the time the overruns are due to the entire project management of Nepal Electricity Authority and the political instability in the country [36]. These factors need to be considered before starting large hydropower projects. Small-scale hydropower plants are becoming popular due to their ability to supply off-grid power to challenging remote locations.

4) RELIABILITY AND ACCESS TO MODERN ENERGY SERVICES

''Ensure access to affordable, reliable, sustainable and modern energy for all'' is the seventh of the 17 Sustainable Development Goals of the United Nations [37]. By providing access to modern energy services it not only fulfils the basic human requirement but also secures reasonable standard of living with opportunities of human development.

This idea is farfetched in some of the developing countries like Nepal where, still, millions of people spend the majority of their time and household expenditure procuring energy for their daily livelihood and activities [38]. Despite the large hydropower potential, the share of electricity in final energy demand is low. The supply side has not been able to keep pace with the recent growth in electricity demand, as it is unable to attract large foreign investment due to the socio-political situation and long political transition after the end of the Maoist regime [28].

Nepal has one of the lowest per capita electricity consumption of 139 kWh per year compared to the world average of 3104 kWh [39]. On top of this, households having access to electricity face long hours of load shedding of about 8-16 hours on a daily basis. According to Acharya and Adhikari [28], households in Nepal are 'accustomed' to load shedding since the beginning of 2005 due to inadequate supply of electricity, amplified further by the declaration of National Energy Crisis in 2008. To overcome this situation, many households, commercial establishments and industries depend on expensive diesel generators, which creates indoor and outdoor pollution [35]. These diesel generators are expensive due to fuel import which adds to final cost of the products and reduces competitiveness of the Nepalese industry [40].

On the other hand, Bhutan has achieved universal electrification as of today, however, reliability remains an issue [8].

Like Nepal, load shedding is practiced when the peak load cannot be met by the current capacity and power imports. About 58% of households had faced one or more load shedding for at least one hour during the last seven days, with rural population facing more frequent power cuts than the urban areas [8]. These power outages have severe impact on the entire country, especially the industry sector which is the backbone of any economy.

B. BRIEF OVERVIEW ON THE POWER, HEAT AND TRANSPORT SECTORS

The power generation mix in Bhutan and Nepal is dominated by hydropower, with some capacities from diesel-based generators. Due to load shedding on daily basis and remote locations; households and businesses must depend on diesel generators.

Bhutan's power generation capacity till end of 2017 was 1.6 GW, while total electricity generation was estimated at 7.7 TWh. Bhutan's domestic electricity requirement was only 2.2 TWh in 2017 [41]. The rest of the electricity is exported to India, which accounted for 74% of the total generation in 2017 [42]. Due to higher electricity demand and lower generation in winter, Bhutan imports some smaller amounts of electricity from India. The electricity imports from India were around 92 GWh in 2017 [43]. On the other hand, in 2016, Nepal had an installed capacity of about 856 MW, with majority of hydropower and some capacities from diesel-based generators [44]. The electricity generation was about 5.1 TWh. Due to run-of-river hydropower plants, electricity generation fluctuates and is seasonal, as a result, Nepal imported 1.6 TWh of electricity from India [17]. Still, the supply is inadequate to meet the ever-increasing demand, especially in the dry season resulting in daily load shedding.

Most of the heating requirement is based in the residential and industrial sectors. Fuelwood is the dominant fuel in the residential sector, while the industrial sector uses coal as a major fuel. There has been decrease in use of fuelwood and kerosene in Bhutan, especially in the industrial sector. Electricity has been the dominant fuel, with about 57% share in the total industrial energy demand. However, the remaining share is based on diesel and coal, which is imported [8].

In Nepal and Bhutan, the transport sector has seen tremendous growth in energy consumption due to increase in GDP per capita and rapid urbanization, with demand for petroleum fuels more than doubling from 2000s until end of 2010s [8]. The predominant mode of transport is road, due to the terrain of these countries. This has led to more motor vehicles in Bhutan, and this accounted 18.6% of total energy consumption in 2014 [45], which is about 1.2 TWh. Increasing vehicle numbers, lack of proper laws on vehicle emissions and fossil fuels has led to continuous increase in Bhutan's GHG emissions [46]. Bhutan has acknowledged the transport sector importance and increasing energy demand in the future. Thus, Bhutan introduced the 'Transport Vision 2040' [47], which constitutes nine transport strategies which are road network, civil aviation, intercity passenger transport, freight transport, regional connectivity, urban transport, road safety, road transport regulation and transport sector management. Moreover, future plans include ways for transport-based GHG emission reduction and vehicles switching to renewable fuels and electric vehicles [48]. Similarly, Nepal's road passenger and freight has a share of about 90% in the transport sector [17]. To address the aggressive increase in transportation demand, Nepal's Government set up a national sustainable transport strategy (2015-2040) to lower GHG emissions in the transport sector. Hydrogen as a potential fuel is also studied in the country [49]. Currently, due to a lack of domestic fossil fuel reserves, Nepal and Bhutan rely heavily on expensive petroleum product imports from India [50].

C. 'OTHER' RENEWABLE ENERGY SOURCES

Nepal and Bhutan depend on imports of energy resources, as they do not have significant reserves of petroleum and coal. The mountainous topography, price fluctuation of crude oil, unsustainable use of firewood; causing indoor air pollution and deforestation, high infrastructure cost and long delays associated with hydropower generation has prompted the governments of these countries to consider alternative energy sources, which are sustainable and affordable [21].

Nepal and Bhutan are blessed with abundant water resources and hydropower is often promoted as the most viable option [10]. Currently, hydropower dominates electricity generation, though other means of renewable energy (RE) based electricity generation are also abundantly available. Commercially exploitable hydropower potential of 26,760 MW and 42,000 MW is available in Bhutan and Nepal respectively [8], [17]. However, large hydropower projects have often been associated with environmental, social, cultural, technical, financial and economic impacts [10].

The solar resources in the mountainous terrain of Nepal and Bhutan are very promising. Nepal receives on average 300 sunshine days per year with global horizontal irradiation ranging between 1080-1860 kWh/(m^2·a) [51]. Satellite maps show the global horizontal solar radiation vary in Bhutan from 1460-2007 kWh/(m^2·a) [52]. Solar PV technology is extremely modular and low cost, can be installed in decentralised locations, which is a major advantage in Nepal and Bhutan. On the other hand, wind resources are quite limited and often areas with good wind speeds are in high altitude mountains tops [8]. Therefore, these areas are inaccessible for the logistic requirements of larger modern wind turbines [53]. The wind potential in Nepal and Bhutan is 3000 MW and 760 MW respectively [8], [10].

Since, agriculture and forestry form a major part of the economy in the Himalayan countries, large agricultural residues are produced. These residues together with sustainable biomass resources are potential sources of electricity production. Currently, traditional use of biomass creates indoor air pollution and associated health hazards [22], [23]. Unfortunately, these two countries have not been able to harness green energy with respect to its resource availability, except for hydropower.

TABLE 1. List of studies conducted on renewable energy transition scenarios for Nepal and Bhutan.

Study	Scope	Key findings
Gulagi et al. [54]	SAARC	The LUT Energy System Model was used to model an overnight scenario for a 100% RE based system for the SAARC (South Asian Association for Regional Corporation) region, with Nepal and Bhutan as one of the sub-regions. The total installed capacities in 2030 for an integrated scenario is 10 GW, while the storage capacity is 1 GW. Solar PV dominates the installed capacity with about 50% share, while batteries dominate the storage capacity with 90% share. The levelised cost of electricity in 2030 will be around 63 €/MWh.
Shakya [55]	Kathmandu, Nepal	A study on GHG mitigation specifically for Kathmandu city using the LEAP framework over a period of 19 years (2012-2030). Six different scenarios are considered in the study. The study concludes that, relative to the base case scenario in 2030, the impact of adopting different low carbon development strategy options will eliminate 35.2% of overall GHG emissions from energy usage. On top of GHG emissions reduction, results also focus on energy security and the economic cost of GHG mitigation. During the year 2030, the final energy consumption is mostly through electricity, diesel, biomass which accounts to 16%, 15% and 14% respectively. The remaining shares is fulfilled by petroleum products, coal and solar.
Yangka and Diesendorf [27]	Bhutan	A MARKAL model framework study on the benefits of electric cooking over traditional kerosene and firewood cooking from the year 2005 to 2040. The fuel share in total primary energy supply in 2005 is mostly from biomass (58%), followed by hydropower (16%), diesel and petrol (14%), coal (7%), kerosene & LPG (4%) and other (1%). The study highlights the socio-economic impacts on the livelihood and emissions reductions of CO_2, SO_2 and NO_x by 17%, 12% and 8% respectively by the year 2040.
Jacobson et al. [56]	Nepal	The study finds that a 100% renewables based energy system is possible by 2050 utilising wind, hydropower and solar energy. The share of solar PV plants (rooftop and utility-scale) will be 64.6%, concentrating solar thermal power will be 4.8%, onshore wind will have a share of 26% and hydropower will have a share of 4.6%. Further benefits of the transition include a 62% reduction in energy demand in comparison to the current, while creating a total of 90,670 jobs. The average energy cost will be 64.6 USD/MWh (58.7 €/MWh).

With abundant availability of solar resources across the regions of Nepal and Bhutan, these countries could tap into the enormous solar PV potential for renewable energy. A major 7.8 Richter scale magnitude earthquake in 2015 disrupted the entire energy system due to landslides and floods which destroyed poorly built hydropower plants. This example shows the vulnerability of Nepal's dependence on hydropower. Therefore, development of other RE technologies together with hydropower is the utmost way for Nepal and Bhutan to be energy independent.

For Nepal and Bhutan, there have been almost no studies capturing an energy transition of the integrated power, heat and transport sector towards a 100% renewable based energy system. Table 1 outlines the energy system studies with high RE share and their key findings. However, none of these studies consider the spatial and temporal resolution as used in this research for Nepal and Bhutan. Also, this study considers analyses on a sub-regional level, with regional interconnections via a power transmission grid.

II. METHODS

The objective of this research is to analyse all sector energy transition pathways towards a 100% RE-based system for the Himalayan countries, Nepal and Bhutan. The LUT Energy System Transition model is applied on an hourly temporal resolution from 2015 to 2050 at an interval of every 5 years. An exogenous model for self-generation and consumption of power and heat for residential, commercial, and industrial consumers is also simulated on the above-mentioned temporal resolution. A detailed description of the model, input data, technical and financial assumptions and various constraints are described in the following sections.

A. LUT ENERGY SYSTEM TRANSITION MODEL OVERVIEW

The LUT Energy System Transition Model [12] is a linear optimisation tool, which models a transition of the integrated power, heat and transport sectors on an hourly time scale for every 5-year time step from 2015 to 2050, under given specific constraints. For a given integrated energy system, the model defines an optimal cost structure and operation modes for each of the energy system's elements to give a least optimal cost. The hourly time scale increases the reliability of the results, as it takes into consideration that for every hour of a year, demand and supply matches. However, this increases the computation time for every time step. The target function of the optimisation is minimisation of the total cost of the system calculated as sum of the annual capital and operational expenditures, including ramping costs, for all the considered technologies in the modelling as given in (1). The reference year for this study was chosen as 2015, due to unavailability of the all the input data for the year 2020. The main energy balance constraint for the power sector optimisation is matching the power generation and demand for every hour of the applied transition years as shown in (2). For every hour of the year the total generation within a sub-region and electricity import cover the local electricity demand.

$$\min\left(\sum_{r=1}^{\text{reg}}\sum_{t=1}^{\text{tech}}(\text{CAPEX}_t\cdot\text{crf}_t+\text{OPEXfix}_t)\cdot\text{instCap}_{t,r}\right.$$
$$\left.+\ \text{OPEXvar}_t\cdot\text{E}_{\text{gen},t,r}+\text{rampCost}_t\cdot\text{totRamp}_{t,r}\right)\qquad(1)$$

Abbreviations: capital cost of each technology (CAPEX_t), capital recovery factor for each technology (crf_t), fixed operational cost for each technology ($\text{OPEXfix}_{,t}$), variable operational cost each technology ($\text{OPEX}var_{,t}$), installed capacity in a region ($\text{instCap}_{t,r}$), electricity generation by each technology ($\text{Egen}_{t,r}$), ramping cost of each technology (rampCost_t), annual total power ramping values for each technology ($\text{totRamp}_{t,r}$), region (reg), and technology (tech).

$$\forall h\in[1,8760]\sum_{t}^{\text{tech}}\text{E}_{\text{gen},t}+\sum_{r}^{\text{reg}}\text{E}_{\text{imp},r}+\sum_{t}^{\text{stor}}\text{E}_{\text{stor,disch}}$$
$$=\text{E}_{\text{demand}}+\sum_{r}^{\text{reg}}\text{E}_{\text{exp},r}+\sum_{\text{t}}^{\text{stor}}\text{E}_{\text{stor,ch}}+\text{E}_{\text{curt}}+\text{E}_{\text{other}}\qquad(2)$$

Abbreviations: hours (h), technology (t), all modelled power generation technologies (tech), sub-region (r), all sub-regions (reg), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies (stor), electricity from discharging storage ($\text{E}_{\text{stor,disch}}$), electricity demand ($\text{E}_{\text{demand}}$), electricity exported (E_{exp}), electricity for charging storage ($\text{E}_{\text{stor,ch}}$), electricity consumed by other sectors (heat, transport, industry) (E_{other}), and curtailed excess energy (E_{curt}).

The heat sector energy balance is defined by three equations: for industrial high temperature heat demand, for industrial high and medium temperature heat demand, and all centralised heat demand. High temperature heat can only be generated by fuel-based boilers as given in (3). Medium temperature heat can also be generated by electrical heating and can be stored in high temperature heat storage and used to produce electricity with steam turbines as given in (4). Low temperature heat can also be provided by heat pumps, electric heating rods and waste heat from other technologies as given in (5).

$$\forall h\in[1,8760]\sum_{t}^{\text{techHH}}\text{E}_{\text{gen},t}$$
$$\geq\text{E}_{\text{demandHH}}\qquad(3)$$

$$\forall h\in[1,8760]\sum_{t}^{\text{techHH}}\text{E}_{\text{gen},t}+\sum_{t}^{\text{techMH}}\text{E}_{\text{gen},t}+\text{E}_{\text{stor,disch}}$$
$$\geq\text{E}_{\text{demandHH}}+\text{E}_{\text{demandMH}}+\text{E}_{\text{stor,ch}}\qquad(4)$$

$$\forall h\in[1,8760]\sum_{t}^{\text{tech}}\text{E}_{\text{gen},t}+\sum_{t}^{\text{stor}}\text{E}_{\text{stor,disch}}$$
$$=\text{E}_{\text{demand}}+\sum_{t}^{\text{stor}}\text{E}_{\text{stor,ch}}+\text{E}_{\text{curt}}+\text{E}_{\text{other}}\qquad(5)$$

Abbreviations: hours (h), technology (t), high temperature heat generation technologies (techHH), medium temperature heat generation technologies (techMH), all heat generation technologies (tech), industrial high temperature heat demand ($\text{E}_{\text{demandHH}}$), industrial medium temperature heat demand ($\text{E}_{\text{demandMH}}$), total centralised heat demand, including industrial, and space heating and water heating demand (E_{demand}).

The individual residential, commercial and industrial prosumers can install their own rooftop PV systems and heating technologies as part of self-generation of electricity and heat. These heating technologies based on electricity or fuels satisfy demand of hot water and space heating. The electricity storage for these prosumers is based on lithium ion batteries. These prosumers can purchase in times of low generation or sell surplus electricity to the distribution grid in order to fulfil their power demand. Minimisation of the cost of consumed electricity and heat is the target function of the prosumers. This cost is calculated as a sum of power, heat and storage capacities' annual cost, cost of consumed fuels for heating, cost of purchased electricity from the grid minus profit earned on selling excess electricity to the grid.

Some of the additional important constraints used in the modelling of the energy system and prosumers: First, a restriction on installation of new coal, oil and nuclear based power plants after the starting period. Therefore, power plants which are planned or in the construction phase after the starting period are not considered in this study. However, gas turbines can be installed as they can be operated by fuel switching from fossil gas to synthetic gas. Second, no more than 20% of the total installed capacity share can be changed in any 5-year time step to avoid excessive RE capacities installation in a single time step which would lead to disruption of the power system. Third, if profitable, share of prosumers can progressively increase from 3% in 2015 to 20% in 2050.

The general flow of the LUT model from data preparation to the results and evaluation is shown in Figure 2 detailed description of the model can be found in Bogdanov *et al.* [12].

B. ASSUMPTIONS USED IN THE MODELLING

The parameters and baseline assumptions for the core analysis of the energy system are briefly explored in this section. The financial and technical assumptions used in the study are given in Section B.2 and Section B.3 respectively. The final section provides the demand growth in all sectors and the applied technologies.

1) SUB-REGIONS AND GRID TRANSMISSION

The sub-division of Nepal is done based on the provincial states, which are seven regions. The districts which lies under

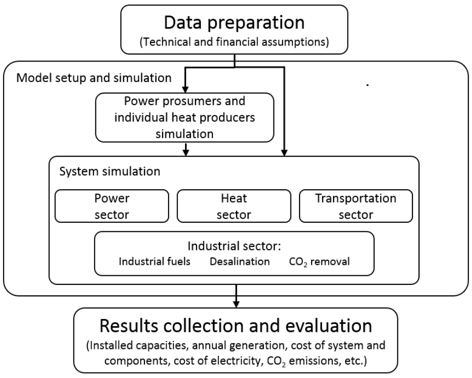


FIGURE 2. Process flow representation of the model input data, optimisation, and results [57].

TABLE 2. Distribution of districts by provincial states in Nepal.

States	Districts
Province 1	Taplejung, Panchthar, Illam, Jhapa, Morang, Sunsari, Dhankuta, Tehrathum, Sankhuwasabha, Bhojpur, Solukhumbu, Okhaldhunga, Khotang, Udaypur.
Province 2	Saptari, Siraha, Dhanusha, Mahottari, Sarlahi, Rautahat, Bara, Parsa.
Province 3	Sindhuli, Ramechhap, Dolakha, Sindhupalchowk, Kavrepalanchowk, Lalitpur, Bhaktapur, Kathmandu, Nuwakot, Rasuwa, Dhading, Makawanpur, Chitwan.
Province 4	Gorkha, Lamjung, Tanahun, Syangja, Kaski, Manang, Mustang, Myagdi, Parbat, Baglung, Nawalparasi (East of Bardghat)
Province 5	Nawalparasi (West of Bardghar), Rupandehi, Kapilbastu, Palpa, Argakhanchi, Gulmi, Pyuthan, Rolpa, Dang, Banke, Bardiya, Rukum (East).
Province 6	Rukum (West), Salyan, Surkhet, Dailekh, Jajarkot, Dolpa, Jumla, Kalikot, Mugu, Humla.
Province 7	Bajura, Bajhang, Aachham, Doti, Kailali, Kanchanpur, Dadeldhura, Baitadi, Darchula

each province are mentioned in Table 2. Bhutan is taken as an individual region, due to its comparatively smaller area. The sub-division to the level of provinces enables high spatial resolution of the individual state's RE generation potential, consumption pattern and transmission. On top of that, it also facilitates in analysing the energy storage needs for the future use. The grid transmission network is assumed to be connected to each of the provincial headquarter, with Kathmandu as the main consumption center in Nepal as shown in Figure 3. In Bhutan, Thimphu is the main consumption center. The connections between the provinces is assumed to be HVAC and within the provinces it is assumed that the existing and future grid expansions will supply electricity to all end-users. The population of Nepal and Bhutan in 2015 and projected population at every 5-year interval till 2050 is tabulated in the Supplementary Material (Table S1). Individual population projection growth rates of 1.4% for Nepal [77] and 0.61% for Bhutan [58] are applied.

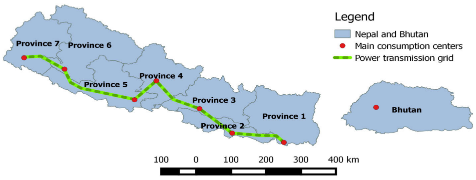


FIGURE 3. The seven provincial states of Nepal and Bhutan with the main power transmission grid.

2) FINANCIAL ASSUMPTIONS

The various financial assumptions related to capital expenditures (CAPEX) and operating expenditures (OPEX fixed and variable) for all technologies, applied during the energy transition for Nepal and Bhutan are shown in the Supplementary Material (Table S8). The weighted average cost of the capital (WACC) is set to 7% for all RE technologies whereas a WACC of 4% is considered for the residential PV rooftop prosumers due to lower risk and hence lower financial return expectations. Due to the unavailability of country specific cost projection data, financial projections were assumed to be based on a global average for all the technologies. The cost reduction in most of the RE-based technologies is following a downward curve globally and it will result in a continued capacity installation in the future [59], [60]. The price of raw materials and new installations are anticipated to decrease until 2050 due to technology developments and production upgrades. In addition to the electricity generation technologies, the capacity boom and decreasing cost of battery storage has set off a quick ascent in capacity installations in many nations [59], [61].

The price of electricity for three prosumer categories i.e. residential, commercial, and industrial, in the year 2015 were assumed from [7], [29], [62]. Based on a method developed by Breyer and Gerlach [63], the future electricity prices until 2050 was projected. The cost assumptions of the applied energy system technologies for Nepal and Bhutan are tabulated in the Supplementary Material (Table S8).

3) TECHNICAL ASSUMPTIONS

The technical lifetime and efficiencies of all applied technologies can be found in the Supplementary Material (Table S8 and S9). The installed capacities till end of 2014 for hydropower and fossil fuels are taken from [64]. and assumed that they will be utilised till their technical lifetime and then decommissioned. The calculation of upper limits for solar and wind is described in the next sub-section, while the economically exploitable hydropower potential is assumed from [11], [29], [62], [65].

4) RESOURCE POTENTIAL AND INPUT PROFILES

For the modelling, as an input, hourly capacity factor profiles for an entire year of solar PV, wind energy and hydropower were used. Solar PV was divided into optimally tilted PV, single axis tracking PV and solar CSP. As for wind energy wind onshore is considered. The raw data is for the year 2005 from NASA databases [66], [67] by German Aerospace Center [67] and having a resolution of 0.45°×0.45°. These data are further processed to calculate hourly capacity factor profiles as described in Bogdanov and Breyer [69] and Afanasyeva *et al.* [70]. This study does not consider increasing efficiency of solar PV systems on the land area requirements during the transition. A monthly resolved river flow data for 2005 is used to prepare hydropower capacity factor profiles as a normalised sum of the river flow throughout the country.

The biomass potential was divided into three categories: solid wastes (municipal waste and waste wood), solid residues (waste from agriculture and forestry), and biogas (biowastes, manure and sludge). The raw data on the biomass and waste resources were obtained from Food and Agricultural Organisation of the United Nations. The potentials were calculated according to the methods described in Mensah *et al.* [71]. The cost calculation for the three biomass categories were done according to the data from International Energy Agency [72] and Intergovernmental Panel on Climate Change [73]. For solid fuels, a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for waste incineration plants and this is reflected as negative costs for solid waste [74]. The geothermal energy potential in Nepal and Bhutan, is calculated according to the method described in Aghahosseini *et al.* [75].

The installed capacities of generation technologies in 2015 were taken from Farfan and Breyer [64] and Department of Electricity Development [76] for Nepal. The potential (upper limits on installed capacities) for solar PV and wind were calculated based on a criterion that the total land area availability should not exceed 6% and 4%, respectively.

5) DEMAND PROJECTION

The 2015 electricity demand of the 7 provinces in Nepal and Bhutan were calculated based on the electricity demand per capita and population [77]–[80]. The demand for each of the future time steps was calculated based on different growth rates during the transition period. The electricity demand for Nepal was extrapolated using annual growth rates of 15.1%, 12.2%, 10.2%, 9.6% and 9.5% for 2015-2020, 2020-2025, 2025-2030, 2030-2035, 2035-2040 and 2040-2050, respectively, while for Bhutan a growth rate of 11.9% was assumed till 2030 and after that growth rate similar to Nepal was assumed [41]. For Bhutan, as electricity export forms a large part of its GDP, future growth in exported electricity is also considered. This study does not differentiate between flexible and inflexible demand. However, indirect flexibility to the system could be provided by electrolysers and to some extent by heat pumps. Implementation of demand response would bring in some financial savings and cost reduction to the entire energy system.

The heat demand from 2015 to 2050 was taken from Bogdanov *et al.* [57]. The final electricity and heat demand during the transition for Nepal and Bhutan are given in the Supplementary Material (Table S2). The final power sector excludes direct electricity used in heat and transport sectors.

The hourly load profile of electricity and heat for the provinces in Nepal was calculated as a fraction of the total demand in the country, while for Bhutan the country profile was used. The synthetic load profiles are taken from Toktarova *et al.* [81], while the space heating, domestic hot water, biomass for cooking, and industrial heat profiles are taken from Bogdanov *et al.* [57]. Currently, there are no district heating networks in Nepal and Bhutan, and it is assumed that this status will not change until the end of the transition period.

The main transport modes in Nepal and Bhutan are road and aviation. There is one railway line in Nepal, which was assumed in this study and further projected that the demand for rail will increase in the future, due to growth in population and demand for a faster mode of transport. The total transport demand for Nepal was divided on a sub-region level based on relative population for road, rail and aviation transport modes. These individual transport modes were further sub-divided into passenger (p-km) and freight (t-km) demands. The road passenger transport segregated into light duty vehicles (LDV), buses (BUS) and 2-3 wheelers (2/3W), while freight transport was divided into medium-duty vehicles (MDV) and heavy-duty vehicles (HDV). The different fuel demand from these transport modes and several vehicle types were assumed according to Khalili *et al.* [82] and is shown in Supplementary Material (Table S25-S26).

6) APPLIED TECHNOLOGIES

An overview on the energy system presenting the relevant technologies for the power, heat and transport is provided in Figure 4. The technologies can be classified according

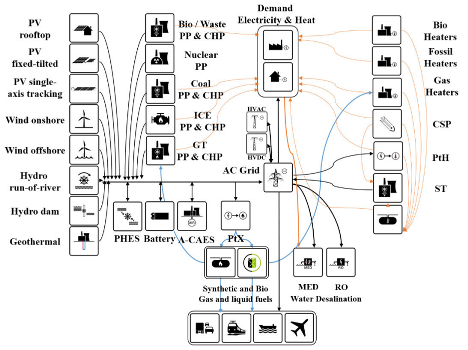


FIGURE 4. LUT Energy System Transition model's schematic diagram for power, heat and transportation. The diagram is adapted from [12]. Abbreviations: CHP – Combined Heat and Power; CSP – Concentrating Solar Power; GT – Gas Turbines; ICE – Internal Combustion engine; PtH – Power-to-Heat; PHES – Pumped Hydro Energy Storage.

TABLE 3. Detailed description of the two applied scenarios.

Scenario	Description
Best Policy Scenario (BPS-1)	Achieving a 100% RE system with a least cost and zero GHG emissions by the end of the transition period is the primary target. To reach this target, certain assumptions were made. First, no new fossil fuel capacities were allowed to be installed after year 2015, with the exception of gas turbines. Meanwhile, phased-out fossil capacities are allowed to be replaced by renewables and storage technologies. This results in no fossil fuel imports from other countries. Second, an assumption was made that there will be a pricing for GHG emissions. The GHG emissions cost would be 9 € per ton of CO_2 in the starting year 2015 which would gradually increase to 28 €, 53 €, 61 €, 68 €,75 € 100 € and finally 150 € per ton of CO_2 in the five-year interval of 2020, 2025, 2030, 2035, 2040, 2045 and 2050, respectively. Third, the total installed RE capacity share cannot grow more than 20% in any 5-year time step to avoid excessive RE capacities installation in a single time step. This scenario includes the potential role of prosumers (electricity and heat self-consumption), with rooftop PV-based electricity generation and possibility to install batteries during the transition period. This is applied for residential, commercial, and industrial customers. Furthermore, prosumers can sell the excess electricity to the grid, after fulfilling their own demand, at a price of 0.02 €/kWh, however no more than 50% of their own generation.
Best Policy Scenario (BPS-2) without GHG emission cost	This scenario is assumed to be the identical to the BPS-1 with an exception that the cost of the GHG emissions is not taken into consideration for the entire transition period. Currently, Nepal and Bhutan do not have any GHG emissions costs and there is no evidence from the government that any costs will be applied soon. The main idea behind this scenario development is to see the cost competitiveness of RE-based solutions compared to fossil fuel options. Moreover, this scenario does not limit fossil fuel usage.

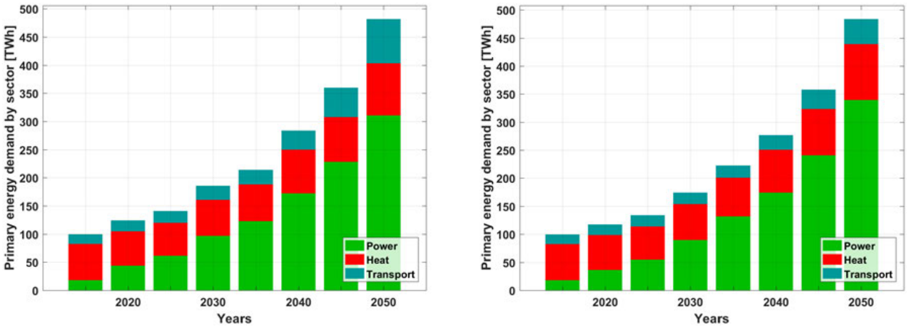


FIGURE 5. Primary energy demand for power, heat and transport sector in the BPS-1 (left) and BPS-2 (right) in the transition years.

to the electricity generation from RE and fossil fuels; heat generation from RE and fossil fuels; road, rail and aviation transport modes; energy storage for electricity, heat and fuels and electricity transmission using High Voltage Alternating Current (HVAC).

7) APPLIED SCENARIOS FOR THE ENERGY TRANSITION

For this study, transition pathways towards high shares of RE for integrated power, heat and transport sectors is showcased for two scenarios. A Best Policy Scenario (BPS-1) with GHG emission cost and a Best Policy Scenario (BPS-2) without GHG emission cost (BPS-2). Based on the overall system cost and GHG emissions reduction, these scenarios focus on two policy options, leading to an energy transition in Nepal and Bhutan. Table 3 provides a detailed description of the scenarios and specific assumptions made in each of the scenarios.

III. RESULTS

The results obtained by applying the LUT model are presented below.

A. PRIMARY ENERGY DEMAND DURING THE TRANSITION

Figure 5 shows the total primary energy demand by sector during the transition years from 2015 to 2050. The share of the primary energy demand varies largely during the years from as low as 100 TWh to as high as 480 TWh in 2015 and 2050, respectively. The largest share is from the heat sector which is almost 61% in 2015 but shrinks to around 20% by the year 2050. The transport share remains quite stable during the period. The main changes happen with the power sector which has a share of under 20% in 2015 but rises to around 65% in the year 2050. The increase in population from 28.70 million in 2015 to 46.45 million in 2050 and the corresponding increase per capita energy use is the reason behind such massive growth.

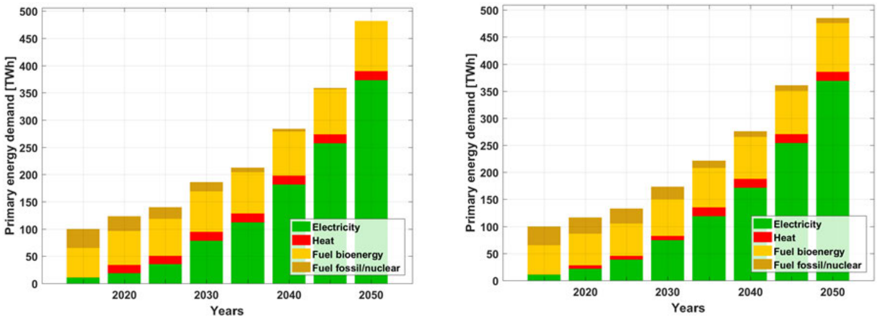


FIGURE 6. **Primary energy demand by energy form for the BPS-1 (left) and BPS-2 (right) throughout the transition period 2015 to 2050.**

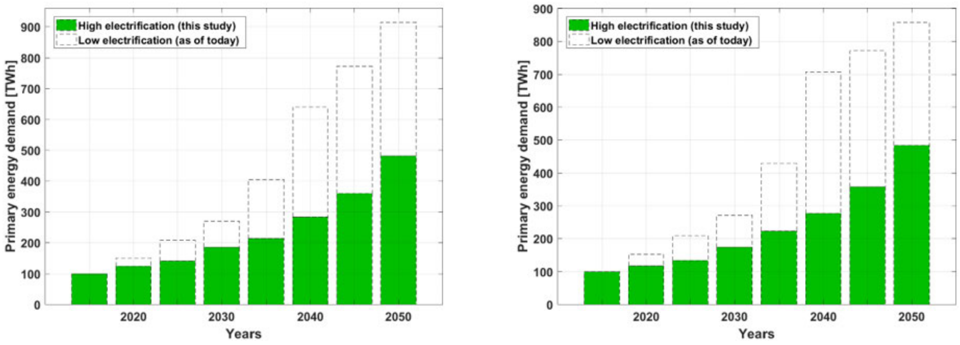


FIGURE 7. **Efficiency gain in primary energy demand with low and high electrification in the BPS-1 (left) and BPS-2 (right) during the transition years.**

Figure 6 shows the total primary energy demand by the primary energy source during the transition period in both scenarios. During the transition, the share of fossil fuels in the primary energy demand decreases to zero in 2050 in the BPS-1. Even though with no GHG emissions cost in the BPS-2, a downward trend in fossil fuel use is observed, however it is not completely eliminated in 2050. The decrease in fossil and bioenergy share is compensated by electricity as a primary energy resource, which increases during the transition as it forms the backbone of the entire energy system. In the BPS-1, the share of electricity grows exponentially from 11% in 2015 to 77% by 2050. Consequently, the share of other sources, especially, bioenergy and fossil fuel shrink from around 89% in 2015 to around 19% in 2050.

Figure 7 shows the role of direct and indirect electricity use, in reducing the total primary energy demand in the two scenarios. In the BPS-1 and BPS-2, continuing with the current energy system having low electricity use in different sectors, the total primary energy demand would increase exponentially to reach 916 TWh and 858 TWh in 2050 respectively, from 100 TWh in 2015. This is around 815% increase in the BPS-1 and about 760% increase in the BPS-2. However, an energy system with high levels of electricity use across the sectors would limit the primary energy demand to only 484 TWh in 2050 for both BPS-1 and BPS-2, which is an increase of 380% from 2015. This increase in total primary demand is in accordance with the corresponding population, GDP and standard of living growth in Nepal and Bhutan. An aggregate of around 61.7% population increment in 2050 is estimated in comparison to the population in 2015. A 100% renewable resource-based energy supply and high direct and indirect electrification in the power, heat and transport sectors ensure the energy system to be highly efficient compared to the current fossil fuel-based energy system by the end of the transition period in 2050.

B. INSTALLED CAPACITIES AND ELECTRICITY GENERATION

Figure 8 shows a steep increase in the installed capacities dominated by RE-based resources in the BPS-1 and BPS-2. The share of PV is prominent in a fully RE system in 2050 due to its cost competitiveness and excellent resource availability.

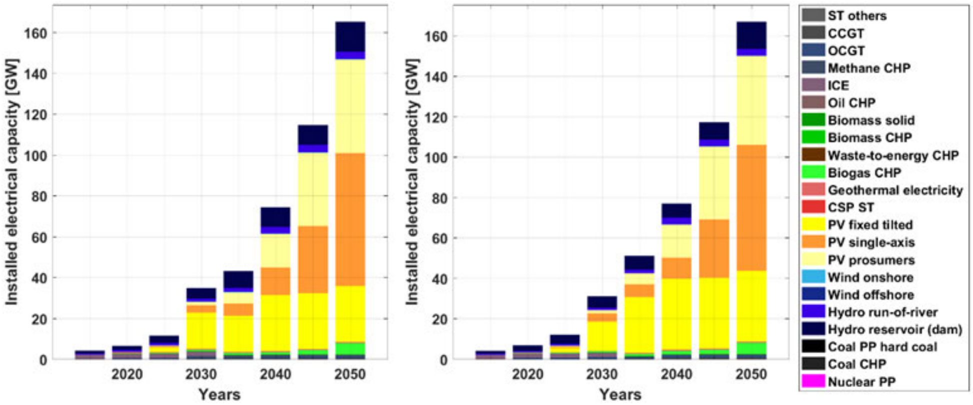


FIGURE 8. Cumulative installed capacities for all power generation technologies from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

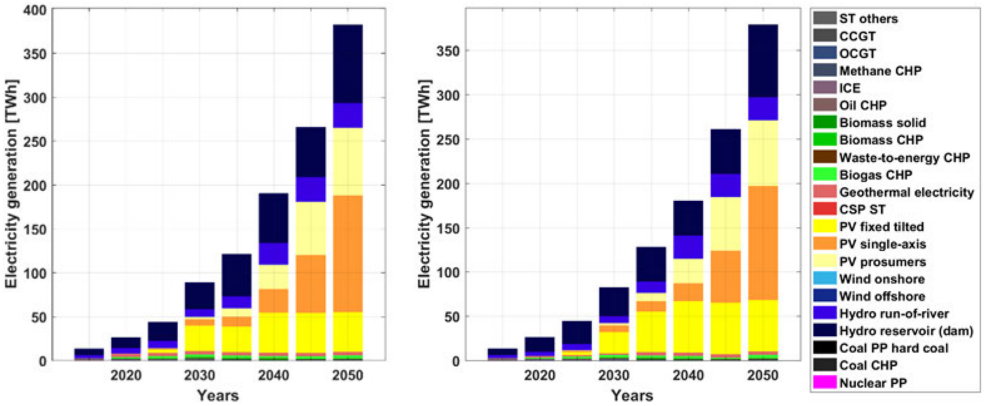


FIGURE 9. Technology-wise electricity generation in the BPS-1 (left) and BPS-2 (right) during the transition period.

Mostly, solar PV dominates the entire energy system starting from the year 2030 to fulfill the future energy demand. Hydropower followed by biogas based electricity compliments the energy deficit during periods of low solar irradiation in both scenarios.

The total electricity generation in the Himalayan countries is 382 TWh in the BPS-1 and 379 TWh in the BPS-2 to cover the demand of power, heat and transport in 2050. Figure 9 shows the total electricity generation in the BPS-1 and BPS-2 based on the different technologies. However, it can be clearly seen that solar PV forms the backbone of electricity supply, complemented by hydropower. With more than 80% dependency on hydropower in 2015 and remaining contributed by imported electricity assumed to be from fossil fuels, there is a transition away from the present hydropower-based supply towards embracing solar PV during the period 2025 to 2050. The shares of other RE sources like wind and geothermal energy play a minor role in the final electricity generation in 2050. Due to the unavailability of fossil fuel and coal reserves, the share is negligible in the electricity generation in 2015. Despite having abundant hydropower as a major electricity generation source since decades, installed capacities of solar PV increases rapidly because of its extremely low cost, high modularity and fast installation time. Therefore, in 2050, electricity generation from solar PV accounts for 67% share in 2050, followed by 31% from hydropower in the BPS-1. The remaining share is contributed by wind energy, geothermal energy, and bioenergy.

As mentioned earlier in Section II, the modelling of the energy system for Nepal was done by further sub-dividing the country into provinces to analyse their detailed

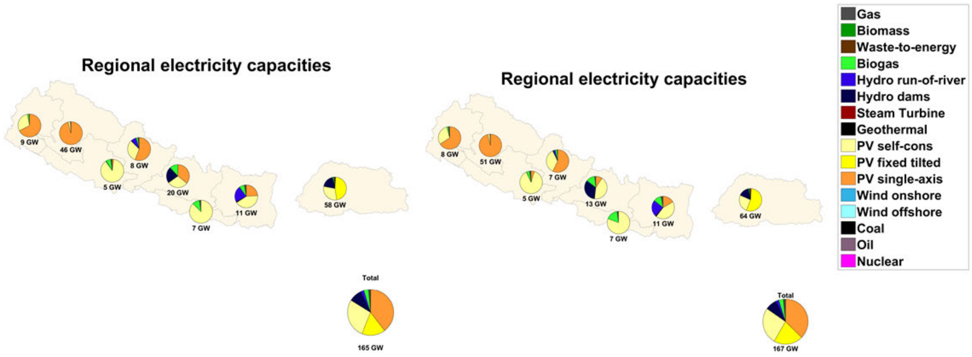


FIGURE 10. Installed RE capacities in the provincial regions of Nepal and Bhutan in the BPS-1 (left) and BPS-2 (right) in 2050.

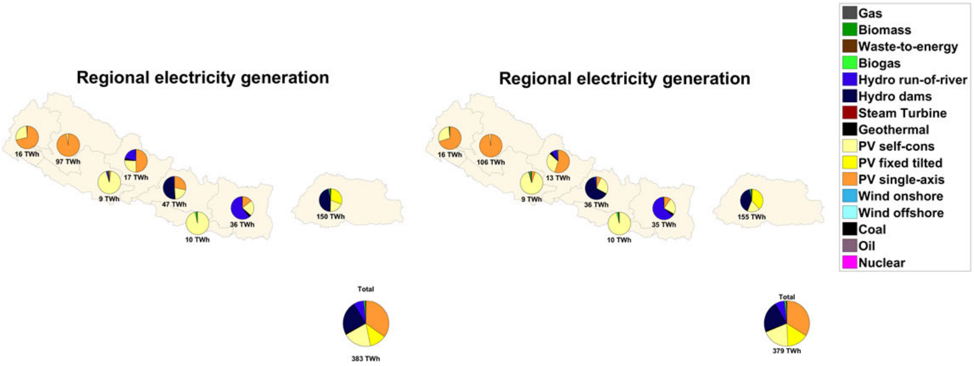


FIGURE 11. Installed electricity generation in provincial regions of Nepal and Bhutan in the BPS-1 (left) and BPS-2 (right) in 2050.

energy structure. Figure 10 and Figure 11 shows detailed installed capacities and electricity generation according to the provinces for the two scenarios.

In the BPS-1, the largest total solar PV installed capacity of 46 GW is observed in Province 6, due to excellent solar resource availability and large solar PV potential. This region exports low cost solar PV electricity to other regions. Province 3 has the second largest installed capacity of solar PV, while additional capacities of hydropower are needed due to a high energy demand in the capital region. Bhutan has installed capacities of 45 GW and 10 GW of solar PV and hydropower, respectively. A similar distribution of solar PV and hydropower shares are observed in the BPS-2.

Solar PV plays a dominant role in total electricity generation in both scenarios in 2050. However, electricity generated from hydropower plays an important role in Provinces 1, 3 and Bhutan in both scenarios due to the hydropower potential available in these regions.

The electricity in far western provinces of Nepal is solely generated by solar PV using single-axis tracking and fixed tilted ground mounted power plant solutions. The highest power generation is in Province 6, which is 97 TWh and 106 TWh in the BPS-1 and BPS-2 respectively as shown in Figure 11. The eastern and central parts of Nepal have big rivers which flow through the snowmelt mountains from north to south and have a steep topography that accounts for an excellent hydro run-off power generation. The lower southern part has a flat topography and it is more expensive due to the need for construction of large dams for hydropower generation. Therefore, cost-effective solar PV electricity generation is most suited in these regions.

Table S14 and S15 in the Supplementary Material provides detailed installed capacities of all technologies for the BPS-1 and BPS-2 respectively, while the electricity generation is given in Table S16 and S17 for the BPS-1 and BPS-2 respectively.

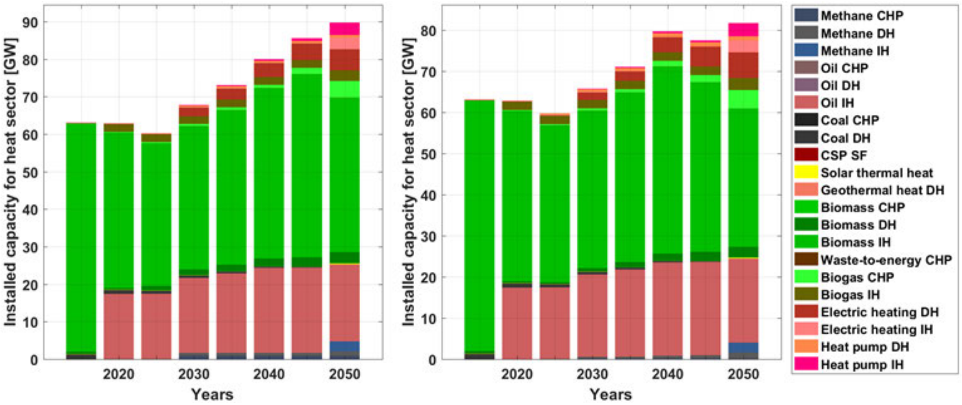


FIGURE 12. Installed capacity in the heat sector in the BPS-1 (left) and BPS-2 (right) in the transition years.

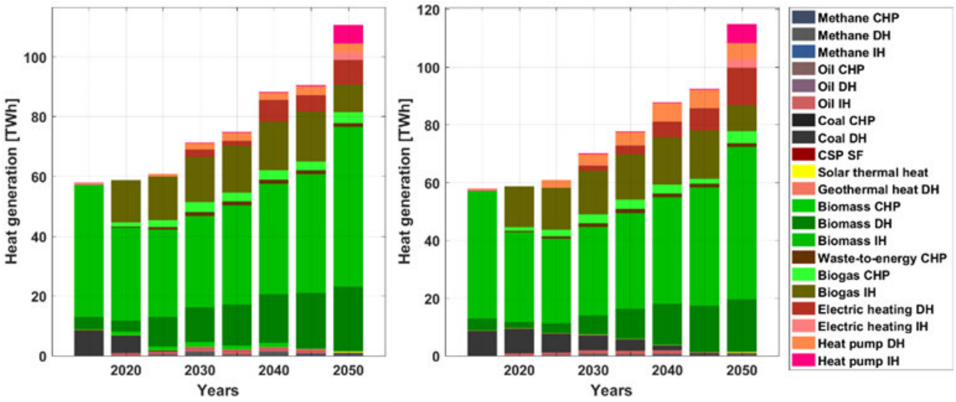


FIGURE 13. Heat generation in the BPS-1 (left) and BPS-2 (right) in the transition years.

C. HEAT GENERATION AND INSTALLED CAPACITIES

Figure 12 and 13 shows the total installed capacities in the heat sector and total heat generation respectively by different heat generation technologies during the transition period in the BPS-1 and BPS-2.

The share of biomass-based heat generation is dominant in the heat sector in both scenarios during the transition. In 2015, majority of biomass was used as a heat source for cooking, which is highly unsustainable and leads to various issues such as indoor air pollution and health hazards. However, during the transition, biomass use in cooking decreases and is replaced by electricity-based cooking. The replacement technologies could be a mix of induction and electric resistance cooking. However, detailed numbers on the mix of different cooking technologies is beyond the scope of this study. The use of agricultural and forest residues and municipal solid waste increases during the transition. In 2020, heat generation technology based on direct electricity use and oil as a transition fuel are used. Oil-based individual heat boilers account for 1.4% of heat generation share in 2020 whilst, biomass accounts for 88% in the BPS-1. While for the BPS-2, there is a small share of heat generation from oil-based boilers mainly in residential and commercial heating, while the majority share is from biomass, which has a share of around 75%. A gradual decrease in fossil-based heating is observed during the transition for both scenarios, replacing with mainly direct electricity-based heating and heat pumps. In 2050 in the BPS-1 scenario, the share of heat pumps and direct electricity-based heating in residential and commercial establishments is 10% and 4%, respectively.

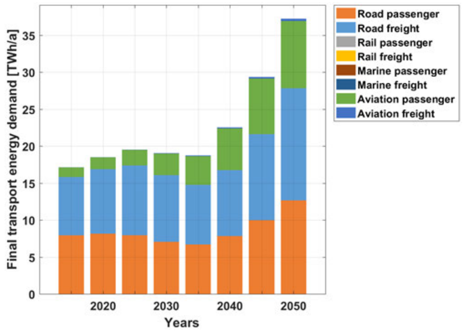


FIGURE 14. **Final energy demand for transportation by transportation modes in the BPS-1 and BPS-2 for the transition period at generation in the BPS-1 (left) and BPS-2 (right) in the transition years.**

D. TRANSPORT SECTOR

The final energy demand for transport according to different modes for the two scenarios is shown in Figure 14 and by fuel types for the BPS-1 and BPS-2 in Figure 15. The final energy demand for transport, increases at a slower rate until 2035. After that, the demand accelerates till 2050 to 37 TWh. An increase of 20 TWh is observed within the start of the transition period until 2050. Due to an increase in standards of living, a rapid increase of energy demand is observed for the aviation sector. The increase in energy demand is directly associated with an increase in transportation of freight and passengers.

The direct use of electricity has the largest share in meeting the final demand in transport by 2050, as shown in Figure 15. On the other hand, electricity plays a minor role in 2015, as less efficient fossil fuels form a major share. However, during the transition, shares of direct and indirect electrification increases as a result of more cost-efficient solutions.

In the BPS-1 and BPS-2, the share of direct electricity from the early 2020s and of hydrogen and synthetic liquid fuel from 2030 onwards increases during the transition period. In the BPS-1, direct electricity has a share of 57%, while hydrogen and synthetic liquid fuels have a share of 17% and 26% respectively, in a fully sustainable transport sector in 2050. On the other hand, the BPS-2 has a fossil fuel share of 25% in 2050, due to no GHG emission pricing, as fossil fuels are cheaper to use. The role of liquid fossil fuels in the BPS-1 decreases during the transition period and does not play any role to meet the transport demand, however, synthetic liquid fuels are utilised for aviation transportation, to achieve full sustainability. The GHG emissions cost is factored in the BPS-1, also leading to a full phase out of polluting fossil fuels. To replace those, technically and commercially viable synthetic liquid fuels are injected to the energy system.

The role of direct electricity is important to a certain share during the transition, however, large scale sustainability in the transport sector is achieved by converting renewable electricity to hydrogen and synthetic fuels. This is clearly observed from the BPS-1 and BPS-2 results. The fuel conversion capacity needed is nearly 3.5 times higher in the BPS-1 compared to the BPS 2 in 2050 as shown in Figure 16. Around 11 GW of fuel conversion technologies are installed in the BPS-1, in which water electrolysis has the largest share, as hydrogen is used as a fuel itself and is used to produce synthetic hydrocarbons. Other conversion processes like Fischer-Tropsch, liquid hydrogen production and methanation have a comparative lower share.

E. ROLE OF STORAGE TECHNOLOGIES

Energy storage technologies play a crucial role during the transition towards large scale renewables utilisation to balance the temporal variability of demand and generation.

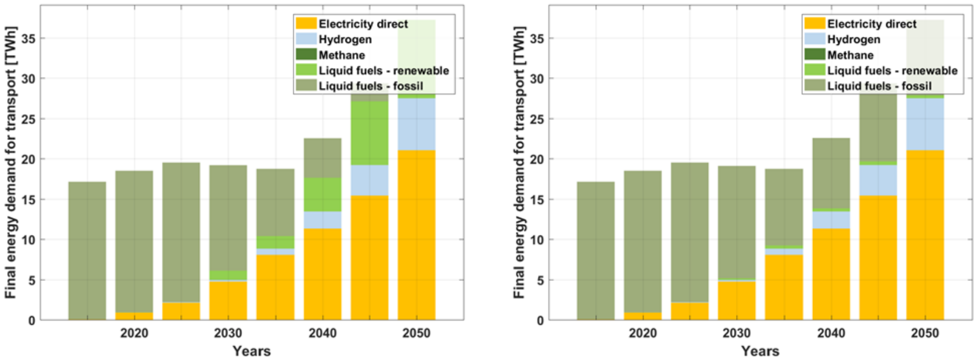


FIGURE 15. **Final energy demand for the transportation sector by fuel in the BPS-1 (left) and BPS-2 (right) for the transition period.**

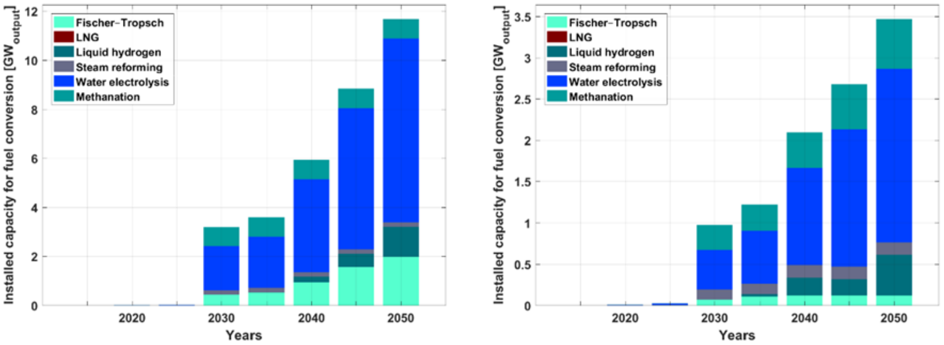


FIGURE 16. Installed capacity needed for transport fuel conversion in the BPS-1 (left) and BPS-2 (right) during the transition years.

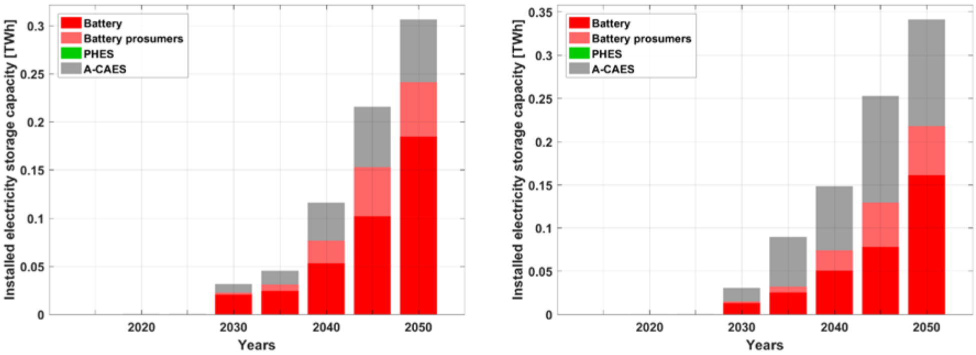


FIGURE 17. Installed electricity storage capacity in the BPS-1 (left) and BPS-2 (right) in the transition years.

The energy storage is reported in energy capacity (TWh), while the power capacity can be calculated from the Energy-to-Power ratio.

As the future energy system is solar PV dominated, batteries are necessary to maintain stability of the energy system. The demand for electricity storage kicks in after 2030, as in the initial years a low electricity generation share from renewables and the availability of dispatchable fossil fuel share, a need for storage technologies does not arise. The total installed electricity storage capacity increases to nearly 320 GWh in 2050 in the BPS-1 as shown in Figure 17.

The impact of PV prosumers battery in storage starts in 2035 due to low cost of solar PV rooftop installations in both scenarios. By 2050, the battery capacity share rises in the total electricity storage. Utility-scale battery and prosumer battery together account for nearly 108 TWh electricity output in the BPS-1 as shown in Figure 18. The adiabatic compressed air energy storage (A-CAES) starts appearing already in 2030 with a small share and increases afterwards. Based on their location, Nepal and Bhutan have specific geologies suitable for the development of A-CAES [83]. The total electricity storage output is projected to reach 120 TWh_{el} and 122 TWh_{el} in the BPS-1 and BPS-2 respectively in 2050. The Energy-to-Power (h) ratio of all storage technologies is given in the Supplementary Material (Tables S10 and S11 for the BPS-1 and BPS-2 respectively).

The need for thermal energy storage (TES) is crucial for the heat sector transition. Figure 19 illustrates the increase of installed heat storage capacity starting from the year 2030, which would scale to 2.7 TWh and 4.4 TWh in the BPS-1 and BPS-2 respectively by 2050. A large amount of gas storage capacity is added in the last 10 years of transition in BPS-1 and BPS-2 to provide the seasonal storage need for heat and electricity. Gas (CH_4) storage accounts for nearly 99% for the total heat storage capacity in the BPS-1 and BPS-2. However, the share of gas (CH_4) storage in thermal heat output is very limited, mostly for high temperature heat in industry and a small share for electricity production A steep

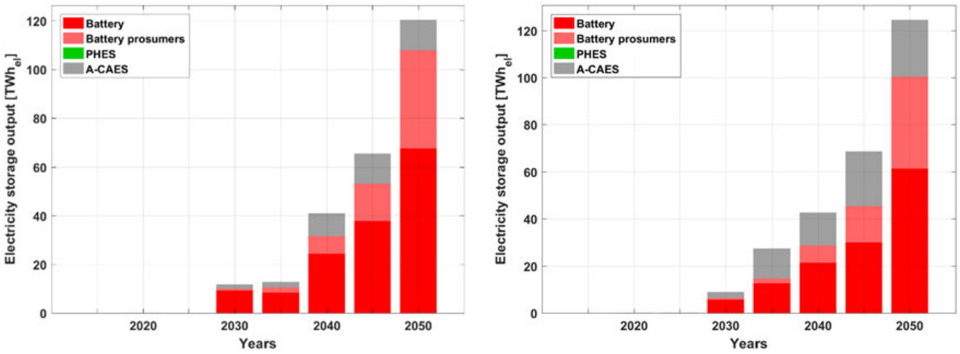


FIGURE 18. Electricity storage output in the BPS-1 (left) and BPS-2 (right) in the transition years.

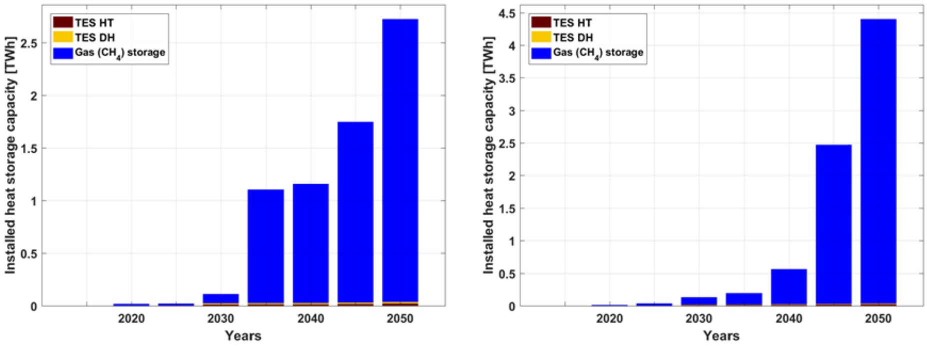


FIGURE 19. Installed heat storage capacity in the BPS-1 (left) and BPS-2 (right) in the transition years.

rise in heat storage output is noticed in early 2030s in which TES DH and TES HT together accounts to 50 TWh_{th} and 37 TWh_{th} in the BPS-1 and BPS-2 respectively. A maximum of 82 TWh_{th} in the BPS-1 and 50 TWh_{th} in the BPS-2 is seen from Figure 20 during the years 2040 and 2035 respectively.

F. ENERGY COSTS DURING THE TRANSITION

The total annual system cost and levelised cost of energy are shown in Figure 21 and 22, respectively.

The total annual system cost during the transition years lies within a range of 7 to 27 b€ and 7 to 18 b€ in the BPS-1 and BPS-2 respectively. The BPS-2 does not take into consideration the GHG emissions cost and there is no constraint on the fossil fuel usage even in 2050. This can be observed from the GHG emissions (Figure 27) in 2050. The heat and the power sectors are completely defossilised, while the transport sector still uses fossil fuels in 2050 in the BPS-2. In the total annual system cost, the heat sector accounts around 5 b€, while the remaining 2 b€ comes from the power and transport sectors in 2015 for the two scenarios. The annual system cost increases for the power and transport sectors during the transition years, especially for the power sector, due to an increasing energy demand and shifting of fuel demand for electricity in transport and heat sectors. The cost of the transport sector slightly increases over the years in the BPS-1, but a large increase happens during the late 2040s due to the change in vehicle stocks, and the associated shift in corresponding fuel types and a constraint of 100% renewable energy in the transport sector. On the other hand, the BPS-2, follows the same trajectory, however the absolute annual investment in the transport sector is lower due to the utilisation of fossil fuels and no additional investments needed for the complete defossilisation of this sector. This can be clearly observed from Figure 16, where installed capacities of fuel conversion technologies are 3.5 times higher in the BPS-1. The additional installed capacities require additional annual investments, which increase the total cost of the system.

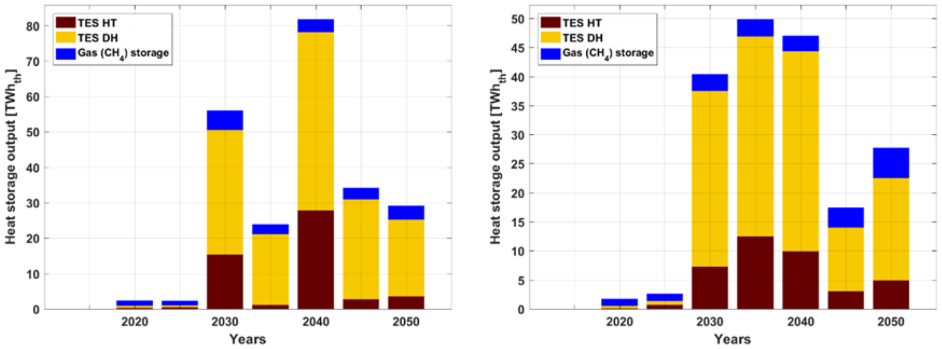


FIGURE 20. Heat storage output in the BPS-1 (left) and BPS-2 (right) in the transition years.

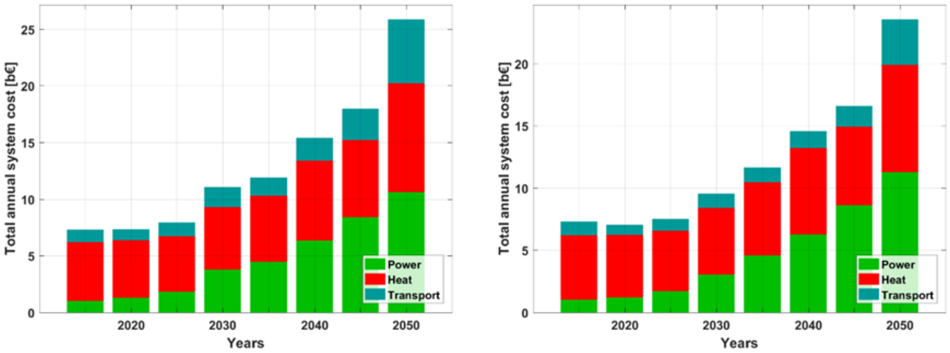


FIGURE 21. Total annual system cost for power, heat and transport sectors in the BPS-1 (left) and BPS-2 (right) in the transition years.

The levelised cost of energy declines to 49 €/MWh in 2050 compared to 90 €/MWh in 2015 in the BPS-1. A fully RE-based system not only offers a cost competitive solution but also an energy system with zero GHG emissions as shown in Figure 22. On the other hand, the BPS-2 follows a similar cost trajectory, however this scenario does not lead to a complete removal of fossil fuel usage from the transport sector. With no penalty on the usage of fossil fuels even in 2050, the transport sector utilises fossil fuels. However, if the emitted GHG emissions are taxed, the levelised cost of energy will increase. The high share of CAPEX implies an increase in the installation of new renewable technologies and energy storage solutions, while decreasing the cost of fuels, imported in the case of Nepal and Bhutan. Operational expenditures are around a quarter of the total cost in 2050. The GHG emission cost is near to zero during early 2035 and remains zero till 2050 in the BPS-1.

The LCOE is slightly higher in the BPS-1 compared to the BPS-2 in all transition years. In both the scenarios during the start of the transition, the total LCOE is 90 €/MWh in which the cost of fuel and LCOE primary has a major share. Mostly fossil fuel costs in the transport sector play a major role in having a higher share of 47% in LCOE costs in 2015. In the BPS-1 scenario in Figure 23 (left), LCOE gets reduced to 52.2 €/MWh from 90 €/MWh, in the early 2020s of the energy transition. Limiting the usage of expensive fossil fuels-based energy and the incorporated GHG emission costs are the key drivers for this reduction. The trend continues to a lower LCOE of 45 €/MWh until 2025. But in the year 2030, the LCOE rises by about 20% to 54.3 €/MWh. The rise in the LCOE is due to the installation of new power generation and storage capacities and the associated CAPEX. The solar PV and battery-based storage technology complemented by hydropower, plays an important role in the energy system which further lowers the LCOE to 49 €/MWh, a 54% reduction by the end of the transition period in 2050. The BPS-2 does not consider GHG emission cost, which is not sustainable, though the LCOE is quite low. Thus, a 100%

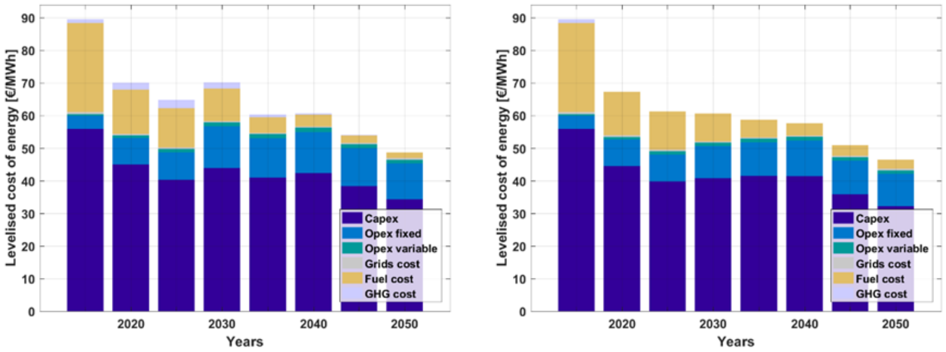


FIGURE 22. Breakdown of the levelised cost of energy in the BPS-1 (left) and BPS-2 (right) in the transition years.

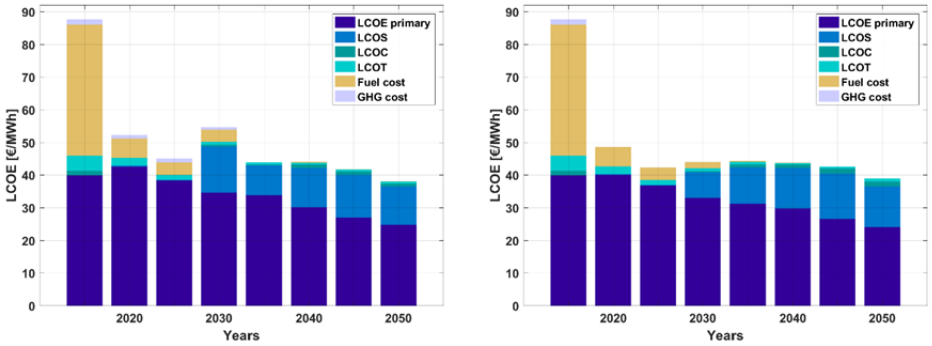


FIGURE 23. LCOE total cost breakdown from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

RE-based sustainable energy system is substantially lower in cost by 2050 than the currently existing energy system.

The LCOH decreases in the early 2020s to around 83 €/MWh from around 100 €/MWh in 2015 in the BPS-1 and BPS-2 as shown in Figure 24. The LCOH remains at 80-85 €/MWh range till 2040. A decrease is observed in 2045 and again an increase in 2050 is seen in both scenarios with a LCOH of 95 €/MWh and 86 €/MWh in BPS-1 and BPS-2 respectively.

Figure 25 and Figure 26 show the final transport passenger and freight costs in the BPS-1 and BPS-2 respectively during the transition years. The final transport passenger cost declines considerably for road whereas aviation and rail transport follow a marginal decrease in the BPS-1 during the transition. In the BPS-2, the final transport passenger cost in aviation decreases from 0.034 €/p-km in 2015 to 0.019 €/p-km in 2050. Similarly, final transport freight cost in the BPS-1 and BPS-2 decrease substantially from 0.12 €/t-km in 2015 to around 0.03 €/t-km in 2050. In 2050, the transport passenger cost in aviation and transport freight cost in road have a major contribution towards the final transportation sector cost.

G. GHG EMISSIONS REDUCTION

The total GHG emissions starting from the year 2015 to the end of transition period 2050 in the BPS-1 and BPS-2 are presented in Figure 27.

Finding a least cost transition pathway for an energy system with zero GHG emissions is one of the main targets of this study. The BPS-1 has achieved the GHG emissions-free target by the end of the transition period, whereas in BPS-2 the GHG emissions is still around 2.8 MtCO2eq in 2050, which solely comes from the transport sector. In the case of Nepal and Bhutan, a high share of GHG emissions comes from the transport sector, followed by heat and power sectors in the BPS-1 and BPS-2. Both scenarios having GHG emissions of 10.2 MtCO2eq in 2015 achieve a steep reduction throughout the transition period. The decrease in GHG emissions is already at a faster rate starting 2020 in the BPS-1, whereas

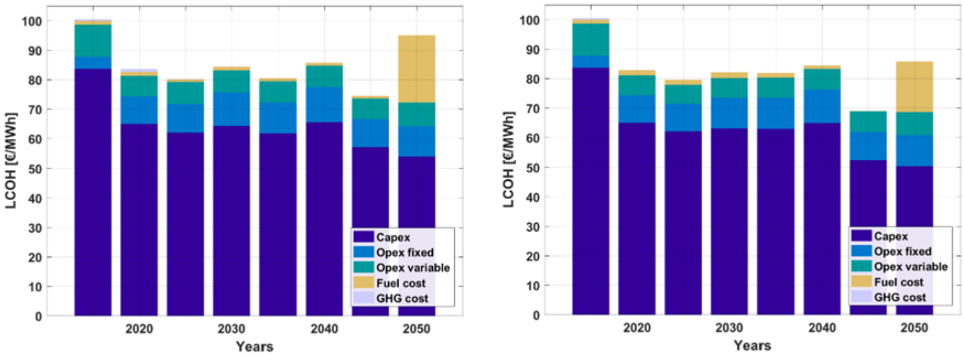


FIGURE 24. LCOH total cost breakdown from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

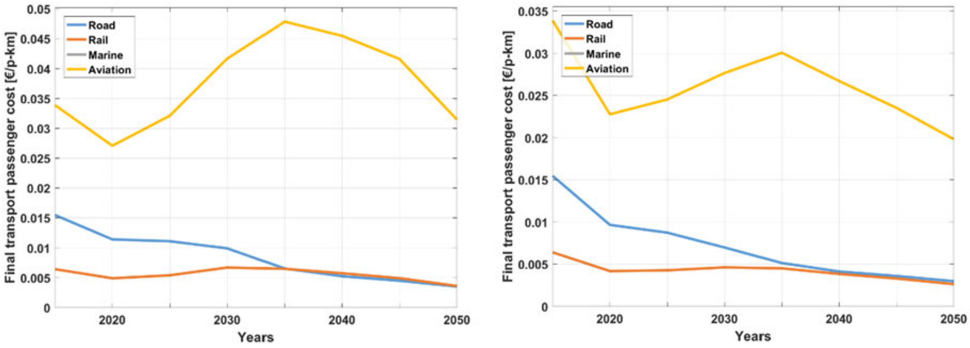


FIGURE 25. Final transport passenger cost per person-kilometer in the BPS-1 (left) and BPS-2 (right).

the reduction rate is slightly slower in the BPS-2 because of no limitation on fossil fuel usage. The heat sector sees a major transition already in the late 2020s in the BPS-1, and its impact on GHG emissions is limited. The most important and less challenging sector to defossilise is the power sector, which is GHG emission free after 2030 in both scenarios. GHG emissions from the transport sector also get considerably reduced due to usage of direct electricity, hydrogen fuel and synthetic liquid fuels.

IV. DISCUSSION

A. OVERALL RESULTS

The primary objective of this research was to demonstrate a least-cost energy system transition pathway by 2050 for Nepal and Bhutan, which is aligned to the Paris Agreement [84]. This can be achieved by using indigenous renewable resources in the country. However, missing piece of the puzzle is strong political will and long-term national policies towards integrating large shares of renewables into the energy system. This study illustrates two energy transition pathways: the BPS-1 shows a pathway towards a self-sufficient, least-cost, zero GHG emission energy system, whilst the BPS-2 shows a pathway with no GHG emission cost implemented. These two scenarios show that RE technologies, especially solar PV, would reduce unsustainable use of fuelwood. This will increase the use of direct electricity, especially in cooking [85]. Therefore, enhancing the quality of life of women and children mostly in rural areas by reducing time spent on collection of fuelwood thus creating additional opportunities for employment, heath improvement and education [86].

During the transition, the energy supply mix changes considerably from fuelwood and hydropower dominated electricity generation to solar PV electricity dominated in 2050. Solar PV dominates the installed capacity in electricity generation with 138 GW in BPS-1 and 141 GW in BPS-2. Due to the available economic potential of hydropower, addi-

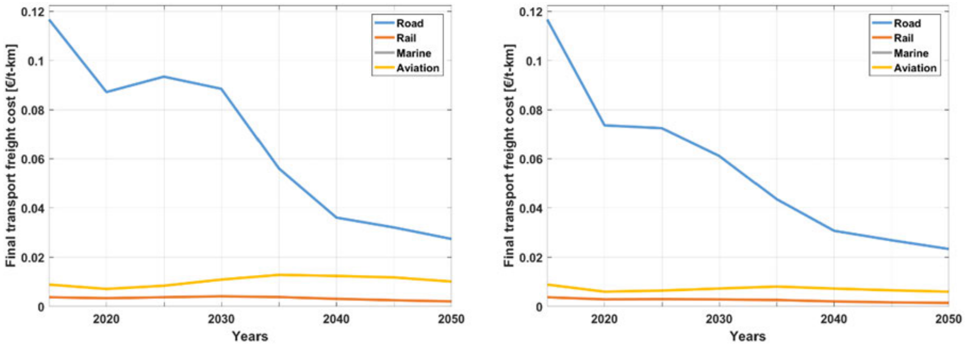


FIGURE 26. Final transport freight cost per ton-kilometer in the BPS-1 (left) and BPS-2 (right) in the transition years.

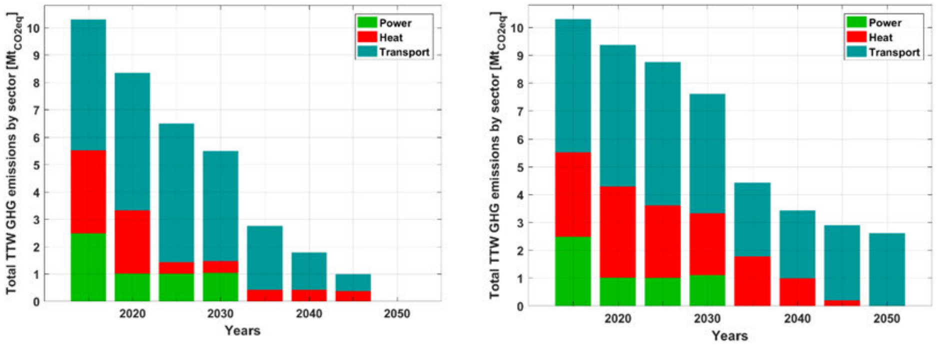


FIGURE 27. Sector-wise GHG emissions during the transition period in the BPS-1 (left) and BPS-2 (right).

tional capacities are installed during the transition years, as hydropower generation compliments in periods of low solar resource availability. Biogas-based CHP plants are installed from 2045 onwards, due to bio-waste availability from the increasing population. Due to flexibility provided by the integration of power, heat and transport sectors, curtailment is reduced to 4.3% in BPS-1 and 6.3% in BPS-2 of the total electricity generation in 2050. For remote locations in mountainous terrain, grid extension is often very expensive, in such cases, solar PV provides affordable electricity access in a decentralised way [87], [88]. However, care must be taken on proper cleaning mechanism of dust and other particles during periods of no rainfall, as it decreases the output considerably [89]. Almost all the provinces in Nepal and Bhutan receive excellent solar irradiation all year around, this is observed in installed capacity, as solar PV dominates installed capacity and electricity generation in each of these regions. The high share of solar PV in the BPS-1 and BPS-2 is made feasible through the current and expected cost decline of solar PV and battery energy storage systems, with manageable lithium resource supply in the future as projected by Greim *et al.* [90]. The combination of solar PV with battery storage enables electrification of remote villages located in mountainous terrain without the need for grid extension, utilising the modularity of these technologies [87]. In addition to solar PV, micro and mini hydropower provides access to electricity in remote areas not connected to the central grid [87]. However, impacts of hydropower projects on local living conditions and sustainability of the projects before and after implementation should be analysed. The biomass potential considered in this study is sustainable which consists of agricultural residues and wastes [71]. The role of biomass in electricity generation is negligible, while most of the biomass is used in the heat sector. A scenario without biomass would be possible, however the total cost of the system will be higher.

The total electricity demand grows considerably during the transition, primarily due to the projected growth in population and GDP. Additionally access to modern services and appliances will increase as these countries will try to adapt to living standards of the OECD countries. The electricity demand in 2050 will be primarily used for the basic power demand and this forms the largest share (81.6%) of the total electricity demand, while in the heat sector, electricity will be used for heat pumps and direct electricity-based heating and some for synthetic fuel production, so the electricity share in heating is 3.6% of the total electricity demand. In the transport sector, electricity is used directly by electric vehicles and indirectly for production of synthetic fuels, so the total share of electricity in transport sector is 14.8% of the total electricity demand.

The storage requirements on a daily cycle are primarily met by utility and prosumer scale lithium-ion batteries in both the scenarios in 2050, due to a low seasonality of solar resources in Nepal and Bhutan. On the other hand, A-CAES provides a buffer when solar resource is not available for some days. Lithium-ion battery recycling after their useful life enhances the sustainability as it reduces the rate of global extraction of resources and dependence on other countries. The heating sector seems to face more challenges than the power sector due to specificity and complexity of the processes. However, transitioning of the heat sector will not only reduce unsustainable fuelwood and fossil fuels consumption, but also increase the overall efficiency, making the industrial sector competitive on the global market. In 2050, in both the scenarios about 61% of the total heat demand is met by modern biomass and waste-based technologies, while the remaining demand is met by heat pumps and direct electricity based heating.

The transport sector faces a major transition due to a complete phase-out of imported fossil fuels used in this sector, according to the scenario projections. These fossil fuels are replaced by direct electricity, hydrogen, and liquid fuels generated from RE during the transition towards 2050. According to Shakya and Shrestha [91], utilising direct electricity brings various co-benefits such as emission reduction, improving energy security and employment generation. Comparing the cost of these new fuels, utilising direct electricity is the cheapest option. However, direct electricity cannot be used in all the transport modes especially in international aviation due to issues with range and weight. Within the road segment, passenger vehicles are shifted to direct electricity and hybrid plug-in solutions. On the other hand, aviation and rail transport modes utilise hydrogen and Fischer-Tropsch fuels, respectively. The cost of synthetic natural gas and especially hydrogen as fuel are quite comparable to fossil fuels. The implementation of GHG emission costs on fossil fuels used in the transport sector will greatly increase their cost, making them more expensive, which better reflects the real societal costs of these fuels. Even without GHG emission costs, the cost of fossil fuels is still higher than direct electricity in 2050, with a strong impact on all transportation options, in particular those with direct electrification. Additionally, implementation of social costs on the air pollution due to the fossil fuels would increase their total cost, while a 100% renewable based energy system would substantially reduce these cost [56].

B. COMPARING RESULTS WITH RELATED STUDIES

The results of this study are in line with the studies presented in Table 1, comparing capacity mix, cost of generation and GHG emissions. According to Gulagi *et al.* [54], in the power sector, solar PV and batteries have the largest share in installed capacity mix in 2030 due to their expected cost decline and related assumption. This trend can also be compared with countries in the South Asian region [74], [92], [93] where solar PV and batteries form a least cost hybrid power system solution to enable the renewable energy transition. According to the results of this study, GHG emissions decrease through the transition, as fossil fuels are phased out in all the sectors and cost-competitive renewables are adopted. This was also observed by Shakya [55] and Yangka and Diesendorf [27], where a decrease in GHG emissions was observed while adopting low carbon emitting sources. According to Jacobson *et al.* [56], solar PV would have a share of 64.6% in 2050, which is line with the share of 66.7% observed in this study. Additionally, transition to a 100% renewables based energy system would create jobs and lower the cost of energy.

C. IMPLICATIONS OF THE RESULTS

A study conducted on the role of renewable energy in Nepal [94] emphasises the need of locally available renewables to be utilised and provide electricity access in all areas and non-dependence on foreign fuel imports. Thus, an investment in locally prevailing resources such as mini hydropower and solar PV will ensure uninterrupted power in every household despite the difficult terrain and sparse household settlements in the rural areas. This also decreases GHG emissions and expensive fossil fuel purchases from India. According to the Nepalese government plan [76], a mix of different RE sources and a blend of centralised and distributed energy supply guarantees affordable energy access to every citizen. To support the government's plan, the Alternative Energy Promotion Centre (AEPC), was set up to mainstream RE capacities in Nepal. In 2016, around 30 MW of mini and micro hydropower plants were installed, and about 15 MW of solar PV systems [95]. The Nepalese government has set up a long-term goal to achieve clean, reliable and affordable RE solutions by 2030. The new policy on Renewable Energy Technologies (RETs) development prioritises on providing long-term loans to investors to meet the UN's objectives of the Sustainable Development Goals and the Sustainable Energy for All programme [95].

A 100% RE-based system for Nepal and Bhutan is not only cost-competitive but also technically feasible. It ensures continuous and uninterrupted energy supply in power, heat and transport sectors. In the BPS-1, the levelised cost of energy decreases considerably to 49 €/MWh in 2050 compared to 90 €/MWh in 2015, while in the BPS-2 it further decreases to about 47 €/MWh. Due to the high shares of least cost renewables and storage technologies in the system, levelised cost of energy decreases from the levels of the current fossil fuel-based system. Specifically, the drastic cost decline of solar PV and batteries, which are projected to play a major role in electricity generation and storage, lowers the energy system cost. Therefore, Nepal and Bhutan should utilise the recent cost reductions in solar PV and tap into the growing market, while creating new jobs in manufacturing and operation and maintenance [96].

Summing up, the two scenarios show that indigenous RE resources in Nepal and Bhutan help in achieving energy independency which ensures affordable energy supply for all of their population. The respective nations should enforce strong policies and guidelines about the need to phase in RE-based solutions. It is recommended to Nepal's RE development governing body, AEPC, and the Royal Government of Bhutan to come up with specific roadmaps, measures and policies. In addition, the collaboration with the neighbouring country India, which is far ahead in new renewable electricity generation, and with a whole South Asian region creates mutual benefits.

D. LIMITATIONS OF THE STUDY

The results and main findings of this study show two of the various pathways to achieve a common goal of zero GHG emissions across the energy sectors. One of the main assumptions here was that the existing power grid available within each of the regions will supply electricity to every household, where there is a demand. A high granular data of solar and wind resources will describe the regional variability in detail. As a next step of research, sensitivity analysis of the assumptions and the input data should be done. This may alter the results, but no structural changes are expected.

V. CONCLUSION

The Himalayan countries Nepal and Bhutan are rich in indigenous renewable resources. This is aptly reflected in the results of this study which show that a 100% RE-based system is technically possible and economically feasible by 2050 for Nepal and Bhutan with zero GHG emissions in the BPS-1 scenario. Moreover, the energy system in 2050 will be substantially more efficient than the current energy system. The renewable energy technologies and storage solutions can adequately supply energy consistently at every hour for all sectors throughout the year by 2050. The levelised cost of energy for Nepal and Bhutan decreases from 90 €/MWh in the present not sustainable energy system to 49 €/MWh and 47 €/MWh by 2050 in BPS-1 and BPS-2 respectively, documenting an increase in levels of sustainability and overall economics. Despite having huge snowmelt high current rivers and sloping terrain, which is excellent for hydropower generation, solar PV emerges as the backbone of the electricity generation supported by batteries. Excellent solar resource availability combined with the decreasing cost of PV systems and Li-ion batteries enable a transition towards a 100% RE system. Achieving a 100% renewables-based energy system enabling zero GHG emissions by 2050 demands bold, strict, and intense ambitious national policies by the two nations.

ACKNOWLEDGMENT

The authors would like to acknowledge Arman Aghahosseini for the core set of diagrams and Theophilus Nii Odai Mensah for providing the biomass potential.

SUPPLEMENTARY MATERIAL

Supplementary Material available under the tab ''Media.''

REFERENCES

[1] [IPCC]—Intergovernmental Panel on Climate Change. (2014). *AR5 Climate Change 2014: Mitigation of Climate Change—IPCC*. Geneva, Switzerland. [Online]. Available: https://www.ipcc.ch/report/ar5/wg3/

[2] M. Suman and R. Maity, ''Southward shift of precipitation extremes over south Asia: Evidences from CORDEX data,'' *Sci. Rep.*, vol. 10, no. 1, p. 6452, Dec. 2020.

[3] S. A. Kulp and B. H. Strauss, ''New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding,'' *Nature Commun.*, vol. 10, no. 1, Dec. 2019, Art. no. 4844.

[4] J. M. Maurer, J. M. Schaefer, S. Rupper, and A. Corley, ''Acceleration of ice loss across the Himalayas over the past 40 years,'' *Sci. Adv.*, vol. 5, no. 6, Jun. 2019, Art. no. eaav7266.

[5] J. Xu, R. E. Grumbine, A. Shrestha, M. Eriksson, X. Yang, Y. Wang, and A. Wilkes, ''The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods,'' *Conservation Biol.*, vol. 23, no. 3, pp. 520–530, Jun. 2009.

[6] U. Bastola and P. Sapkota, ''Relationships among energy consumption, pollution emission, and economic growth in Nepal,'' *Energy*, vol. 80, pp. 254–262, Feb. 2015.

[7] K. Ogino, M. Nakayama, and D. Sasaki, ''Domestic socioeconomic barriers to hydropower trading: Evidence from Bhutan and Nepal,'' *Sustainability*, vol. 11, no. 7, p. 2062, Apr. 2019.

[8] *Renewables Readiness Assessment—Kingdom Of Bhutan*, International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Dec/IRENA_RRA_Bhutan_2019.pdf

[9] G. R. Timilsina, *How Would Cross-Border Electricity Trade Stimulate Hydropower Development in South Asia*. Washington, DC, USA: The World Bank, 2018. [Online]. Available: http://documents.worldbank.org/curated/en/714401531237858109/How-would-cross-border-electricity-trade-stimulate-hydropower-development-in-South-Asia

[10] R. Poudyal, P. Loskot, R. Nepal, R. Parajuli, and S. K. Khadka, ''Mitigating the current energy crisis in Nepal with renewable energy sources,'' *Renew. Sustain. Energy Rev.*, vol. 116, Dec. 2019, Art. no. 109388.

[11] K. Ogino, S. K. Dash, and M. Nakayama, ''Change to hydropower development in Bhutan and Nepal,'' *Energy Sustain. Develop.*, vol. 50, pp. 1–17, Jun. 2019.

[12] D. Bogdanov, A. Gulagi, M. Fasihi, and C. Breyer, ''Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination,'' *Appl. Energy*, vol. 283, Feb. 2021, Art. no. 116273.

[13] S. K. C., S. K. Khanal, P. Shrestha, and B. Lamsal, ''Current status of renewable energy in Nepal: Opportunities and challenges,'' *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 4107–4117, Oct. 2011.

[14] M. Islar, S. Brogaard, and M. Lemberg-Pedersen, ''Feasibility of energy justice: Exploring national and local efforts for energy development in Nepal,'' *Energy Policy*, vol. 105, pp. 668–676, Jun. 2017.

[15] *Energy Statistics Pocketbook*, United Nations, Washington, DC, USA, 2019. [Online]. Available: https://unstats.un.org/unsd/energy/pocket/2018/2018pb-web.pdf

[16] L. P. Ghimire and Y. Kim, ''An analysis on barriers to renewable energy development in the context of Nepal using AHP,'' *Renew. Energy*, vol. 129, pp. 446–456, Dec. 2018.

[17] *Nepal Energy Sector Assessment, Strategy, and Roadmap*, Asian Development Bank, Mandaluyong, Philippines, 2017. [Online]. Available: https://www.adb.org/sites/default/files/publication/356466/nepal-energy-assessment-road-map.pdf

[18] A. Gurung, O. P. Gurung, and S. E. Oh, ''The potential of a renewable energy technology for rural electrification in Nepal: A case study from tangting,'' *Renew. Energy*, vol. 36, no. 11, pp. 3203–3210, Nov. 2011.

[19] *World Development Report 2010: Development and Climate Change*, The World Bank, Washington, DC, USA, 2009, p. 771, vol. 326, no. 5954.

[20] *Data and Statistics*, International Energy Agency, Paris, France, 2020. https://www.iea.org/data-and-statistics/data-tables?country=NEPAL&energy=Balances&year=2018

[21] H. Katuwal and A. K. Bohara, ''Biogas: A promising renewable technology and its impact on rural households in Nepal,'' *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2668–2674, Dec. 2009.

[22] A. Sapkota, H. Yang, and J. Wang, ''Securing rural livelihoods and climate change through sustainable use of biogas and improved cooking stoves in rural households in Nepal,'' *Environ. Sci. Technol.*, vol. 47, no. 1, pp. 330–331, Jan. 2013.

[23] B. Mainali and S. Silveira, ''Renewable energy markets in rural electrification: Country case Nepal,'' *Energy Sustain. Develop.*, vol. 16, no. 2, pp. 168–178, Jun. 2012.

[24] D. Rupakheti, N. T. Kim Oanh, M. Rupakheti, R. K. Sharma, A. K. Panday, S. P. Puppala, and M. G. Lawrence, ''Indoor levels of black carbon and particulate matters in relation to cooking activities using different cook stove-fuels in rural Nepal,'' *Energy Sustain. Develop.*, vol. 48, pp. 25–33, Feb. 2019.

[25] *Annual Report*, Centre Rural Technol. Nepal, Kathmandu, India, 2017. [Online]. Available: https://docplayer.net/91632098-2016-17-2073-74-bs-annual-report-crt-centre-for-rural-technology-nepal-crt-n-towards-action-for-development-since-1989.html

[26] *World Energy Outlook*, Int. Energy Agency, Paris, France, 2017. https://www.iea.org/reports/world-energy-outlook-2017

[27] D. Yangka and M. Diesendorf, ''Modeling the benefits of electric cooking in Bhutan: A long term perspective,'' *Renew. Sustain. Energy Rev.*, vol. 59, pp. 494–503, Jun. 2016.

[28] B. Acharya and S. Adhikari, ''Household energy consumption and adaptation behavior during crisis: Evidence from Indian economic blockade on Nepal,'' *Energy Policy*, vol. 148, Jan. 2021, Art. no. 111998.

[29] Nepal Electricity Authority. (2016). *A Year in Review: Fiscal year 2015/16*. Government of Nepal, Kathmandu, India. [Online]. Available: https://www.nea.org.np/annual_report

[30] Bhutan Power Corporation. (2016). *Power Data Book—2015*. Government of Bhutan, Thimphu, Bhutan. https://www.bpc.bt/downloads/

[31] *World Development Indicators: Population*, The World Bank, Washington, DC, USA, 2017.

[32] A. Ansar, B. Flyvbjerg, A. Budzier, and D. Lunn, ''Should we build more large dams? The actual costs of hydropower megaproject development,'' *Energy Policy*, vol. 69, pp. 43–56, Jun. 2014.

[33] P. Ljung, *Energy Sector Reform: Strategies for Growth, Equity and Sustainability*. Stockholm, Sweden: Swedish International Development Cooperation Agency, 2007. [Online]. Available: http://www.energytoolbox.org/cec/bibliography/SIDA_Energy_Sector_Reform_2007.pdf

[34] H. Nautiyal and V. Goel, ''Sustainability assessment of hydropower projects,'' *J. Cleaner Prod.*, vol. 265, Aug. 2020, Art. no. 121661.

[35] R. Poudyal, S. K. Khadka, and P. Loskot, ''Understanding energy crisis in Nepal: Assessment of the country's energy demand and supply in 2016,'' in *Proc. Int. Electr. Eng. Congr. (iEECON)*, Mar. 2017, pp. 1–4.

[36] *A Vision for Nepal—Policy Notes for the Government*, The World Bank, Washington, DC, USA, 2014. [Online]. Available: https://www.worldbank.org/en/news/feature/2014/09/01/a-vision-for-nepalpolicy-%0Anotes-for-the-government/%0A

[37] *Goal 7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for all*, United Nations, New York, NY, USA, 2016. http://www.un.org/sustainabledevelopment/energy/

[38] A. Sapkota, Z. Lu, H. Yang, and J. Wang, ''Role of renewable energy technologies in rural communities' adaptation to climate change in Nepal,'' *Renew. Energy*, vol. 68, pp. 793–800, Aug. 2014.

[39] *Electric Power Consumption (Kwh Per Capita) Data*, World Bank, Washington, DC, USA, 2014. [Online]. Available: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[40] *Nepal—Systematic Country Diagnostic (English)*, World Bank, Washington, DC, USA, 2018. [Online]. Available: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/361961519398424670/nepal-systematic-country-diagnostic

[41] Department of Renewable Energy. (2016). *Bhutan Energy Data Directory 2015*. Ministry of Economic Affairs, Government of Bhutan, Thimpu, Bhutan. [Online]. Available: www.moea.gov.bt/wp-content/uploads/2018/07/Bhutan-Energy-Data-Directory-2015.pdf

[42] *Power Data 2017*, Dept. Hydropower Power Syst., Dept. Energy, Government Bhutan, Thimpu, Bhutan, 2018.

[43] [SARI/EI]—South Asia Regional Initiative For Energy Integration. (2016). *Impact of Cross-Border Electricity Trade on Bhutan*. Integrated Reserach and Action for Development, New Delhi, India. [Online]. Available: https://www.irade.org/Bhutan Working Paper.pdf

[44] [SARI/EI]—South Asia Regional Initiative For Energy Integration. (2020). *Prospects of Regional Energy Cooperation and Cross Border Energy Trade in the BIMSTEC Region*. Integrated Reserach and Action for Development, New Delhi, India. [Online]. Available: https://irade.org/BIMSTEC Background Paper_February2020.pdf

[45] M. Kamei, T. Wangmo, B. D. Leibowicz, and S. Nishioka, ''Urbanization, carbon neutrality, and gross national happiness: Sustainable development pathways for Bhutan,'' *Cities*, vol. 111, Apr. 2021, Art. no. 102972.

[46] Royal Government of Bhutan. (2017). *National Transport Policy of Bhutan 2017—Policy Protocol Report*. Thimphu, Bhutan. [Online]. Available: https://www.moic.gov.bt/wp-content/uploads/2017/08/Draft-Final-PPR.pdf

[47] [ADB]—Asian Development Bank. (2013). *Bhutan Transport 2040 Integrated Strategic Vision*. Asian Development Bank, Manila, Philippines. [Online]. Available https://www.adb.org/sites/default/files/publication/30268/bhutan-transport-2040.pdf

[48] [NEC]—National Environment Commission. (2012). *National Strategy and Action Plan for Low Carbo Development*. Government of Bhutan, Thimpu, Bhutan. [Online]. Available: http://www.nec.gov.bt/wp-content/uploads/2020/04/National-Strategy-and-action-plan-for-Low-Carbon-Development-2012.pdf

[49] A. Zhou, W. Zhou, and P. Manandhar, *A Study on the Prospect of Hydropower to Hydrogen in Nepal*. Manila, Philippines: Asian Development Bank, 2020. [Online]. Available https://www.adb.org/sites/default/files/publication/631781/study-hydropower-hydrogen-nepal.pdf

[50] F. Alam, K. Saleque, Q. Alam, I. Mustary, H. Chowdhury, and R. Jazar, ''Dependence on energy in south Asia and the need for a regional solution,'' *Energy Procedia*, vol. 160, pp. 26–33, Feb. 2019.

[51] K. R. Adhikari, B. K. Bhattarai, and S. Gurung, ''Estimation of global solar radiation for four selected sites in Nepal using sunshine hours, temperature and relative humidity,'' *J. Power Energy Eng.*, vol. 1, no. 3, pp. 1–9, 2013.

[52] P. Gilman, S. Cowlin, and D. Heimiller. (2009). *Potential for Development of Solar and Wind Resource in Bhutan*. Colorado. [Online]. Available: http://www.nrel.gov/docs/fy09osti/46547.pdf

[53] *Renewable Energy Resource Assessment Report*, Dept. Renew. Energy, Internal Document Prepared Fichtner GmbH & Co, Thimphu, Bhutan, 2016.

[54] A. Gulagi, P. Choudhary, D. Bogdanov, and C. Breyer, ''Electricity system based on 100% renewable energy for india and SAARC,'' *PLoS ONE*, vol. 12, no. 7, Jul. 2017, Art. no. e0180611.

[55] S. R. Shakya, ''Benefits of low carbon development strategies in emerging cities of developing country: A case of Kathmandu,'' *J. Sustain. Develop. Energy, Water Environ. Syst.*, vol. 4, no. 2, pp. 141–160, Jun. 2016.

[56] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, S. J. Coughlin, C. A. Hay, I. P. Manogaran, Y. Shu, and A.-K. von Krauland, ''Impacts of green new deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries,'' *One Earth*, vol. 1, no. 4, pp. 449–463, Dec. 2019.

[57] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. De Souza Noel Simas Barbosa, M. Fasihi, S. Khalili, T. Traber, and C. Breyer, ''Low-cost renewable electricity as the key driver of the global energy transition towards sustainability,'' *Energy*, vol. 227, Jul. 2021, Art. no. 120467.

[58] *Population Projections Bhutan 2017–2047*, National Statistics Bureau, Thimpu, Bhutan, 2019. [Online]. Available: https://bhutan.unfpa.org/sites/default/files/pub-pdf/Bhu_Pop_proj.pdf

[59] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, ''The future cost of electrical energy storage based on experience rates,'' *Nature Energy*, vol. 2, no. 8, Aug. 2017, Art. no. 17110.

[60] M. Fasihi, D. Bogdanov, and C. Breyer, ''Techno-economic assessment of power-to-liquids (PtL) fuels production and global trading based on hybrid PV-wind power plants,'' *Energy Procedia*, vol. 99, pp. 243–268, Nov. 2016.

[61] B. Nykvist and M. Nilsson, ''Rapidly falling costs of battery packs for electric vehicles,'' *Nature Climate Change*, vol. 5, no. 4, pp. 329–332, Mar. 2015.

[62] *Bhutan Power Corporation 2016–2019, Tariff Review Report*, Bhutan Electr. Authority, Thimphu, Bhutan, 2017. [Online]. Available: http://www.bea.gov.bt/wp-content/uploads/2017/03/BPC_Tariff_Review_Report_2016-19.pdf

[63] C. Breyer and A. Gerlach, "Global overview on grid-parity: Global overview on grid-parity," *Prog. Photovolt., Res. Appl.*, vol. 21, no. 1, pp. 121–136, Jan. 2013.

[64] J. Farfan and C. Breyer, "Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator," *J. Cleaner Prod.*, vol. 141, pp. 370–384, Jan. 2017.

[65] *Annual Report 2016*, Bhutan Power Corp. Ltd., Thimphu, Bhutan, 2016. [Online]. Available: https://www.bpc.bt/wp-content/themes/2020/assets/downloads/Annual-Report-2016.pdf

[66] P. Stackhouse and C. Whitlock, *Surface Meteorology and Solar Energy (SSE) Release 6.0 Methodology*. Langley, VA, USA: National Aeronautic and Space Administration (NASA), 2008.

[67] P. Stackhouse and C. Whitlock, *Surface Meteorology and Solar Energy (SSE) Release 6.0 Methodology*. Langley, VA, USA: National Aeronautic and Space Administration (NASA), 2009.

[68] D. Stetter, *Enhancement of the REMix Energy System Model: Global Renewable Energy Potentials Optimized Power Plant Siting and Scenario Validation*. Stuttgart, Germany: Univ. Stuttgart, 2012.

[69] D. Bogdanov and C. Breyer, "North-East Asian super grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options," *Energy Convers. Manage.*, vol. 112, pp. 176–190, Mar. 2016.

[70] S. Afanasyeva, D. Bogdanov, and C. Breyer, "Relevance of PV with single-axis tracking for energy scenarios," *Sol. Energy*, vol. 173, pp. 173–191, Oct. 2018.

[71] T. N. O. Mensah, A. S. Oyewo, and C. Breyer, "The role of biomass in sub-saharan Africa's fully renewable power sector—The case of Ghana," *Renew. Energy*, vol. 173, pp. 297–317, Aug. 2021.

[72] *Technology Roadmap—Bioenergy for Heat and Power*, Int. Energy Agency, Paris, France, 2012. [Online]. Available: http://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf

[73] [IPCC]—Intergovernmental Panel on Climate Change. (2011). *Special Report on Reneable Energy Sources and Climate Change Mitigation*. UNEP, Geneva, Switzerland. [Online]. Available: https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf

[74] A. Sadiqa, A. Gulagi, and C. Breyer, "Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050," *Energy*, vol. 147, pp. 518–533, Mar. 2018.

[75] A. Aghahosseini, D. Bogdanov, and C. Breyer, "A techno-economic study of an entirely renewable energy-based power supply for north America for 2030 conditions," *Energies*, vol. 10, no. 8, p. 1171, Aug. 2017.

[76] Government of Nepal. (2020). *Department of Electricity Development*. Kathmandu, India. [Online]. Available: https://www.doed.gov.np/

[77] Water and Energy Commission Secretariat. (2017). *Electricity Demand Forecast Report (2015–2040)*. Kathmandu, India. [Online]. Available: https://www.moewri.gov.np/storage/listies/May2020/electricity-demand-forecast-report-2014-2040.pdf

[78] UNFPA Nepal. (2017). *Population Situation Analysis of Nepal (With Respect to Sustainable Development)*. Kathmandu, India. [Online]. Available: https://nepal.unfpa.org/sites/default/files/pub-pdf/Nepal Population Situation Analysis.pdf

[79] National Statistics Bureau. (2015). *Statistical Yearbook of Bhutan 2015*. Thimpu, Bhutan. [Online]. Available: www.nsb.gov.bt>publication>publications

[80] T. Lhendup, S. Das, T. Tshering, U. Penjor, D. Choden, P. Chodon, and C. Dorji, "Status of energy consumption and energy efficiency schemes in Bhutan's domestic sector," in *Proc. IEEE Int. Conf. Comput. Intell. Commun. Technol.*, Feb. 2015, pp. 557–562.

[81] A. Toktarova, L. Gruber, M. Hlusiak, D. Bogdanov, and C. Breyer, "Long term load projection in high resolution for all countries globally," *Int. J. Electr. Power Energy Syst.*, vol. 111, pp. 160–181, Oct. 2019.

[82] S. Khalili, E. Rantanen, D. Bogdanov, and C. Breyer, "Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world," *Energies*, vol. 12, no. 20, p. 3870, Oct. 2019.

[83] A. Aghahosseini and C. Breyer, "Assessment of geological resource potential for compressed air energy storage in global electricity supply," *Energy Convers. Manage.*, vol. 169, pp. 161–173, Aug. 2018.

[84] [UNFCC]—United Nations Framework Convention on Climate Change. (2015). *Adoption of the Paris Agreement*. United Nations, Paris, France. [Online]. Available: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[85] R. Bhandari and S. Pandit, "Electricity as a cooking means in Nepal—A modelling tool approach," *Sustainability*, vol. 10, no. 8, pp. 1–17, 2018.

[86] W. Clements, K. Silwal, S. Pandit, J. Leary, B. Gautam, S. Williamson, A. Tran, and P. Harper, "Unlocking electric cooking on Nepali microhydropower mini-grids," *Energy Sustain. Develop.*, vol. 57, pp. 119–131, Aug. 2020.

[87] R. Bhandari and I. Stadler, "Electrification using solar photovoltaic systems in Nepal," *Appl. Energy*, vol. 88, no. 2, pp. 458–465, Feb. 2011.

[88] C. Cader, P. Bertheau, P. Blechinger, H. Huyskens, and C. Breyer, "Global cost advantages of autonomous solar–battery–diesel systems compared to diesel-only systems," *Energy Sustain. Develop.*, vol. 31, pp. 14–23, Apr. 2016.

[89] B. R. Paudyal and S. R. Shakya, "Dust accumulation effects on efficiency of solar PV modules for off grid purpose: A case study of Kathmandu," *Sol. Energy*, vol. 135, pp. 103–110, Oct. 2016.

[90] P. Greim, A. A. Solomon, and C. Breyer, "Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation," *Nature Commun.*, vol. 11, no. 1, p. 4570, Dec. 2020.

[91] S. R. Shakya and R. M. Shrestha, "Transport sector electrification in a hydropower resource rich developing country: Energy security, environmental and climate change co-benefits," *Energy Sustain. Develop.*, vol. 15, no. 2, pp. 147–159, Jun. 2011.

[92] A. Gulagi, M. Ram, A. A. Solomon, M. Khan, and C. Breyer, "Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh," *Renew. Energy*, vol. 155, pp. 899–920, Aug. 2020.

[93] A. Gulagi, D. Bogdanov, and C. Breyer, "The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India," *J. Energy Storage*, vol. 17, pp. 525–539, Jun. 2018.

[94] R. Nepal, "Roles and potentials of renewable energy in less-developed economies: The case of Nepal," *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 2200–2206, May 2012.

[95] Ministry of Population and Environment. (2016). *Renewable Energy Subsidy Policy, 2073 BS*. Government of Nepal, Kathmandu, India. [Online]. Available: https://policy.asiapacificenergy.org/node/2650

[96] M. Ram, A. Aghahosseini, and C. Breyer, "Job creation during the global energy transition towards 100% renewable power system by 2050," *Technol. Forecasting Social Change*, vol. 151, Feb. 2020, Art. no. 119682.

ASHISH GULAGI received the master's degree in environmental engineering and technology. He is currently pursuing the Ph.D. degree with LUT University, Finland. He is currently a Researcher with the Group of Solar Economy, LUT University. His area of research is the renewables-based energy system optimization under economic and environmental constrains. This work includes energy systems modelling and analysis with a special focus on energy storage. His expertise lies in the area of energy transition in Southeast Asia and South Asian region. His special focus lies on India and its energy transition to a fully renewable energy-based system. He has published results on energy transition in leading scientific journals for India, Pakistan, Bangladesh, Southeast Asia, and SAARC. His main areas of interests are renewable energy and sustainability, smart grids, and energy system transformation.

SANJEEV PATHAK received the bachelor's degree in construction engineering and the master's degree in sustainability science from LUT University. He has been a Researcher with the Group of Solar Economy, LUT University. His area of research is the renewables-based energy system optimization for Himalayan countries. His special emphasis is the prosperous development of the Himalayan countries with sustainable energy for all respecting the limits of the environment.

DMITRII BOGDANOV received the B.S. and M.S. degrees in automation and control engineering from the Saint Petersburg Electrotechnical University, and the M.S. degree in industrial electronics from LUT University, Finland, where he is currently pursuing the Ph.D. degree. He is currently a Researcher with the Solar Economy Laboratory. His fields of research include renewable energy, energy systems modeling, and integration of high shares of renewable energy generation into energy systems. He is responsible for the development of the LUT Energy System Transition Model and its applications on global level and for regions in Europe, Eurasia, and Northeast Asia. He has authored or coauthored more than 45 scientific publications in leading scientific journals. His research interests include energy systems modeling, renewable energy, smart grids, and energy system transformation.

CHRISTIAN BREYER received the Diploma degree in general business, physics, and energy system engineering, and the Ph.D. degree in economics of hybrid PV power plants. He is currently an Inaugural Professor in solar economy with LUT University, where he started to work, in March 2014. His major expertise is the integrated research of technological and economic characteristics of renewable energy systems specializing in hybrid energy solutions, energy system modeling, and 100% renewable energy scenarios on a local but also global scale. He has been the Managing Director of the Reiner Lemoine Institut, Berlin, Germany, which focuses on research about renewable energy supply of up to 100%, and worked previously with the Research And Development and Market Development Department of Q-Cells, a former World Market Leader with PV Industry. He has authored or coauthored about 270 scientific publications, of which more than 100 have been published in peer-reviewed journals. He is a member of international working groups, like ETIP PV and IEA-PVPS Task 1, the Chairman for renewable energy with the Energy Watch Group, a Scientific Advisory Board Member of Global Alliance Powerfuels and CO_2 Value Europe, and a Founding Member of the DESERTEC Foundation.

• • •

Publication VII

Gulagi, A., Ram, M., Bogdanov, D., Sarin, S., Mensah, T. N. O., and Breyer, C.
The role of renewables for rapid transitioning of the power sector across states in India

Reprinted with permission from
Nature Communications
Vol. 13(1), pp. 1-19, 2022

nature communications

Article

https://doi.org/10.1038/s41467-022-33048-8

The role of renewables for rapid transitioning of the power sector across states in India

Received: 10 November 2021

Accepted: 25 August 2022

Ashish Gulagi [1], **Manish Ram** [1], **Dmitrii Bogdanov** [1], **Sandeep Sarin** [2], **Theophilus Nii Odai Mensah** [1] & **Christian Breyer** [1]

Recent events like heatwaves and abnormal rainfall are a glimpse of the devastating effects of human induced climate change. No country is immune to its effects, but a developing country like India is particularly vulnerable. This research, for the individual states of India, explores the technical feasibility and economic viability of a renewable transition pathway for the power sector. Based on the assumptions of this study, we show that a renewables-based power system by 2050 is lower in cost than the current coal dominated system, has zero greenhouse gas emissions and provides reliable electricity to around 1.7 billion people. Electricity generation will be based on solar PV, wind energy, and hydropower, while batteries and multi-fuel reciprocating internal combustion engines based on synthetic fuels provide the required flexibility to the power system. This transition would address multiple imperatives: affordability, accessibility, and sustainability without compromising economic growth.

Recent changes in the extremity and abnormality of weather events like heatwaves in the northern hemisphere and extreme rainfall in Europe and Asia have renewed focus on climate change[1–4]. These extreme and abnormal weather-related events are felt far and wide, as no country is immune to their devastating effects, but a developing country like India is more vulnerable. India has its own share of extreme and untimely rainfalls, heatwaves and droughts, which are growing by every passing year[5–7], a result of human-induced climate change. The consequences are extreme; socially and financially. The latest climate report from the Intergovernmental Panel on Climate Change (IPCC) finds that 'it is now unequivocal that human-caused emissions from burning fossil fuels are responsible for recent warming'[5]. Though countries have ratified the Paris Agreement and pledged their Intended Nationally Determined Contributions (INDCs), recent climate events show that more ambitious targets are needed. Therefore, the first and foremost step is a shift away from the dependence on fossil fuels, especially in the power sector towards renewable energy at a faster rate than ever.

In this context, India's path towards achieving the 1.5 °C target needs to be in synergy with its development imperatives; energy affordability and accessibility, mitigating air pollution, while maintaining rapid economic development[8]. Even though, historically, India has had lower per capita emissions than other developed countries, it has been at the forefront of the global climate debate[9]. In this regard, India has committed to reducing the greenhouse gas (GHG) emissions intensity of its GDP by 33-35% below 2005 levels and achieving 40% of cumulative installed power generation capacity from non-fossil sources by 2030[10,11]. To further its global climate commitment and leadership, it has pledged at the UN Climate Summit in 2019 a target of 450 GW of renewable energy (RE) to be achieved by 2030[12]. However, the challenge for India going forward will be to align its renewable growth trajectory with its social and economic development priorities. It is vital to set long-term goals and envision a net zero emission energy system across the country, which will not only ensure economic benefits but also place India in a position of global climate leadership. In recent years, India has taken remarkable strides in reforming its power sector, with electricity shortages declining and an electrification of

---

[1]LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland. [2]Wärtsilä Corporation, Hiililaiturinkuja 2, 00180 Helsinki, Finland.
e-mail: Ashish.Gulagi@lut.fi; Christian.Breyer@lut.fi

99.9% of the households across the country[13]. However, there is still a long way to go in reaching the standards of the developed world in terms of reliability and per capita consumption. The per capita electricity consumption within the Indian states and union territories differs a lot but is less than the global average of almost 3000 kWh[14]. As of 2020[15], the average per capita electricity consumption in India is only 1200 kWh. A dynamic growth in future electricity demand is projected over the coming years, escalated by the growing economy and end-use services[16], despite the government's efforts to pursue strong energy efficiency standards[17]. This research focuses only on the power sector, while other sectors such as heat and transport will further increase the electricity demand. In its INDC, it is mentioned that 'half of the India of 2030 is yet to be built'[11]. Thus, India's power generation choices will have implications on its long-term emissions locally and globally.

Historically, the power sector in India has been the largest contributor to energy-related GHG emissions. The dependence on low-quality coal used in highly inefficient power plants has resulted in air pollution, predominant in cities and aggravating other environmental issues[18]. Additionally, many of these coal power plants are operating at lower plant load factors (PLF), thus reducing their profitability and compounding their already dwindling financial returns[14]. Already, solar PV-based electricity generation ranges between 1.99 and 2.36 INR/kWh (24.8–29.5 €/MWh), as compared to electricity from domestic coal-fired power plants costing 3.5–5 INR/kWh (43.7–62.5 €/MWh). To complicate the matter further, under-construction coal power plants will add to the financial burden of already cash-strapped distribution companies, as these inflexible assets cannot compete with low-cost solar-based electricity[19]. On the other hand, private investors are shying away from coal investments due to the associated risks and are shifting towards sustainable technologies[20]. This has resulted in many coal power projects being scrapped or abandoned[21].

Another issue with coal power plants is the use of freshwater for cooling. India, currently, is placed 13th among the world's 'extremely water stressed countries' and most of its states are facing depleting freshwater resources. It is projected that two-thirds of the country's power plants will face high water stress by the end of 2030[22]. About 40% of coal power plants are located in these water-stressed areas across the country, while the total water requirement for thermal cooling makes up more than half of the domestic water demand[23,24]. Consequently, water shortages or drought-like situations have resulted in thermal power plant shutdowns, resulting in a loss of 1.4 bUSD (1.3 b€) between 2013 and 2016, due to lack of fresh water available for cooling[25]. With the population predicted to grow, there will be an increase in irrigation requirements, which will put tremendous pressure on already scarce water resources[26]. Competing uses of freshwater for vital irrigation and electricity generation in thermal power plants cause immense challenges for decision-makers. These factors, together with India's ambitious climate change goals and record low solar and wind energy prices, have made thermal power plants unviable in the long term, with high risks of being stranded assets. Therefore, with a view on these impacts, in this study, it is assumed that there will be no new coal or fossil fuel-based power plants built in the future to focus on a least cost and best policy scenario.

India is one of the countries that has been aggressively pursuing renewable capacity installations. For the past few years, significant growth has been observed in solar and wind installations. To put this in context, solar capacity has grown 13 times in the last six years[27], reaching approximately 45.6 GW by August 2021[28]. This growth aptly reflects the government's plan to cash in on the declining costs and significant solar potential available in the country. Even in its integrated energy policy, the government has put forth that solar energy is the way forward for India[29]. This indicates that the trend of growing renewable capacity installations will continue amid sharp falling costs and supportive policies from the central as well as state governments. Saraswat and Digalwar[30] assessed the sustainability of various energy resources in India, with empirical investigations and validation of sustainability indicators. Solar energy ranked as the most sustainable energy resource, followed by wind energy, while the least sustainable energy resources were thermal and nuclear. As highlighted by Child et al.[31], the benefits of utilising renewables go beyond the energy sector, and solar and wind are the foremost technologies to achieve sustainability goals.

However, to achieve the ambitious target of 450 GW of renewables, more needs to be done in some of the states and policies need to be aligned with the ambitions of the central government. The role of renewables in electricity generation is highly variable within the states of India. For example, the share of renewables in electricity generation from renewable energy-rich states like Andhra Pradesh, Gujarat, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Punjab, Rajasthan, Tamil Nadu and Telangana is considerably higher than the national average of 8.2%[17]. Figure 1 shows the share of solar and wind electricity in total generation across all major states of India in 2020. The states of Karnataka, Tamil Nadu, and Rajasthan have considerable generation from solar and wind, while other states are still lagging in capacity and generation. Clearly, action will be required at both the state and national level to achieve the goals

As India plans to achieve its ambitious economic goals and climate change targets, the power sector assumes an important role, as decarbonization of the power sector is key for reducing CO_2 emissions by mid-century. According to Bistline et al.[32], power sector decarbonization will play a vital role in the complete decarbonization of the energy system through direct electrification of the processes and indirect electrification – electricity derived fuels. Likewise, a recent study on an energy transition pathway for India acknowledges the huge role of electricity as a key vector in final energy demand to achieve net-zero emissions by 2050[33]. As a result, failure to deeply decarbonize the power sector before mid of this century will seriously jeopardize ongoing global climate mitigation efforts[34].

Various long-term transition studies on the emission reduction pathways for India have been conducted. Most of these studies, however, first, focus only on a national level[35], second, lack a high temporal and spatial resolution of resources and power demand[36,37], third, contain no or limited storage and flexibility options[38], fourth, lack a transition pathway, showing how the current system will 'transition' towards a system with high shares of renewables[39], and finally, consider limited share of renewable penetration[39,40]. Some of the key studies such as WWF and TERI[41], Teske et al.[42,43], Jacobson et al.[44], Lawrenz et al.[36], Gulagi et al.[45] and Bogdanov et al.[46,47], consider 100% renewable energy penetration, however, they lack in one or the other aspects mentioned above.

Considering the importance of the power sector, this study explores a rapid transition pathway for the power sector of India in a resolution of states from the current power system till 2050 in a 5-year time interval towards integrating large shares of renewables. There is a clear need for a transition pathway of the power sector beyond India's target of 2030. This paper presents a cost-optimal transition pathway integrating various generation options, storage technologies and interstate transmission to meet the hourly power demand for an entire year. This paper answers two important questions, first, is a 100% renewable energy-based power system technically possible and is it the least cost option in 2050? Second, how much and what are the generation capacities, storage, and flexibility requirements on a state and national level during the transition?

To explore the power sector transition pathway, India was divided into 22 states/regions (henceforth, the individual states and the states combined together will be called as 'states'), which are grouped into four major regional grids (Northern, Western, Southern and a combined Eastern and North Eastern) that are further interconnected to form a national transmission network, as highlighted in Methods Fig. 9. The North Eastern grid is combined with the Eastern grid due to the

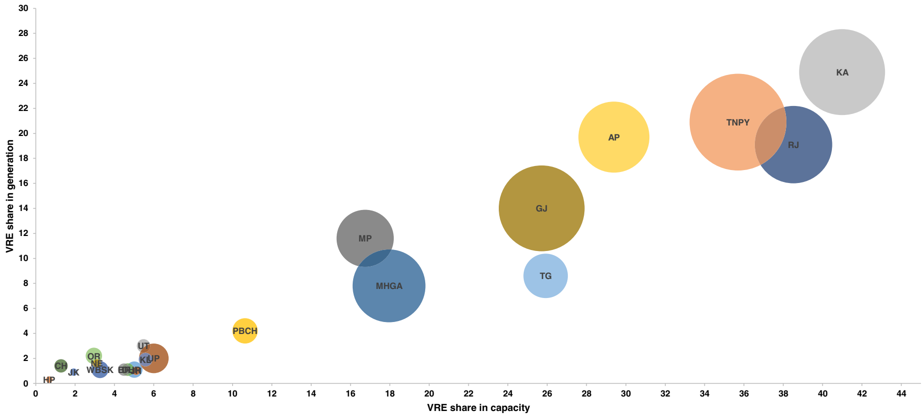


Fig. 1 | Variable Renewable Energy (VRE) share by state in capacity and generation, 2019[97]. The x and y axis represent VRE share of capacity and generation in each state's total capacity and generation respectively. The bubble size represents the share of electricity generation by VRE in each state with respect to the total electricity generation in India. Tamil Nadu has the highest share of VRE in total India generation. Karnataka has the highest share of capacity and generation among all the states. Abbreviations: AP Andhra Pradesh, BR Bihar, CH Chhattisgarh, DL New Delhi, GJ Gujarat, Daman and Dadra, HP Himachal Pradesh, HR Haryana, JH Jharkhand, JK Jammu-Kashmir, KA Karnataka, KL Kerala, MHGA Maharashtra and Goa, MP Madhya Pradesh, NE North Eastern states, OR Odisha, PBCH Punjab and Chandigarh, RJ Rajasthan, TG Telangana, TNPY Tamil Nadu and Puducherry, UP Uttar Pradesh, UT Uttarakhand, WBSK West Bengal and Sikkim.

relative size of its power system in the total electricity demand. Similarly, states in the Northeast of India are combined into one region of 'Northeast' and the Union Territories except Delhi, are combined with the adjacent states.

Results and Discussion

Capacity expansion during the transition

The cost optimal electricity generation capacities, which satisfy hourly demand in each of the regions are summarised in Fig. 2. The results show significant growth in optimal capacities of solar PV and wind power across all the states.

During the first decade of the transition, significant growth in solar PV capacities is observed in the larger states of Uttar Pradesh (82 GW) and Maharashtra (78 GW), a reflection of excellent solar resource availability and huge capacities required as replacement for decreased coal generation to satisfy the growing power demand. However, the highest average annual growth rates of solar PV installations are observed in Himachal Pradesh (228%), Jammu and Kashmir (125%) and Delhi (111%) in the Northern grid, Kerala (122%) in the Southern grid, West Bengal (121%) and Jharkhand (102%) in the Eastern grid. As hydropower is seasonal and increasing its capacity is comparatively expensive and time-consuming, the northern states, dependent on it, start investing and building solar PV at a faster rate than other states. On the other hand, the Eastern states dependent on coal, start investing in new solar PV capacities as it is the cheapest source of new electricity, saving on carbon emission costs for these states and corresponding GHG emissions. Growth in rooftop PV installation is observed across all states, particularly in Delhi, where land area is limited, and a large potential for rooftop PV is available. During the same period, wind resource-rich states observe the largest increase in wind energy installations. In absolute capacities, Gujarat (38 GW) and Maharashtra (30 GW) install wind turbines due to the availability of excellent wind resources. Installation of wind capacities is also observed in other states like Himachal Pradesh, Punjab, Haryana, and Uttar Pradesh, where the current installed capacities are negligible. Newer turbines with higher hub heights increase the capacity factors at these locations to make them more cost-competitive compared to other fossil and renewable sources of electricity generation. Additionally, during this period, as batteries are yet to be cost competitive and the dependence of solar PV on batteries to supply night-time demand, enables wind energy to see the highest growth.

From 2030 onwards, solar PV has a steady average annual growth rate of 35% across the states of India, as solar PV supported by batteries dominate the installed capacities, reaching almost 3000 GW by 2050. On the other hand, annual growth in wind capacities slows down during this period due to better cost competitiveness of solar PV. With excellent resource availability across the length and breadth of India and a continuous decrease in cost, solar PV emerges as the major source of electricity generation in all the states in 2050, as seen from the Supplementary Information Fig. 5. Total wind capacity in the country by 2050 is about 410 GW. Regions with good exploitable hydropower potential, like the Northern and Eastern states, will see the maximum growth in hydropower capacities during the transition. Detailed data on installed capacities for each of the states for all generation technologies till 2050 in every 5-year interval is given in Supplementary Information Table 5.

Shares of fossil fuels and coal decline through the transition, with installed capacities of coal at risk of becoming stranded assets. These coal power plants have very low full load hours during the transition years, as the share of renewables increases, which will lead to reduced revenues and profitability. At the same time, if these coal power plants were made to operate flexibly, additional new investments would be required[17]. These additional investments should be compared, first, against other flexibility sources such as batteries, multi-fuel reciprocating internal combustion engines (ICE) and grids, which can support very high shares of VRE with faster ramp rates, and second, against climate change goals. Even retrofitting old coal power plants to operate flexibly will result in emissions. From the results, gas turbines and reciprocating multi-fuel ICE are installed by 2030 to provide flexibility to the system, which is already over 60% renewable energy based. These flexible generation sources ramp up and down, providing instantaneous demand cover, especially for the evening peaks. The increase in utilisation and capacity of interstate transmission networks adds an additional dimension of flexibility to the power system.

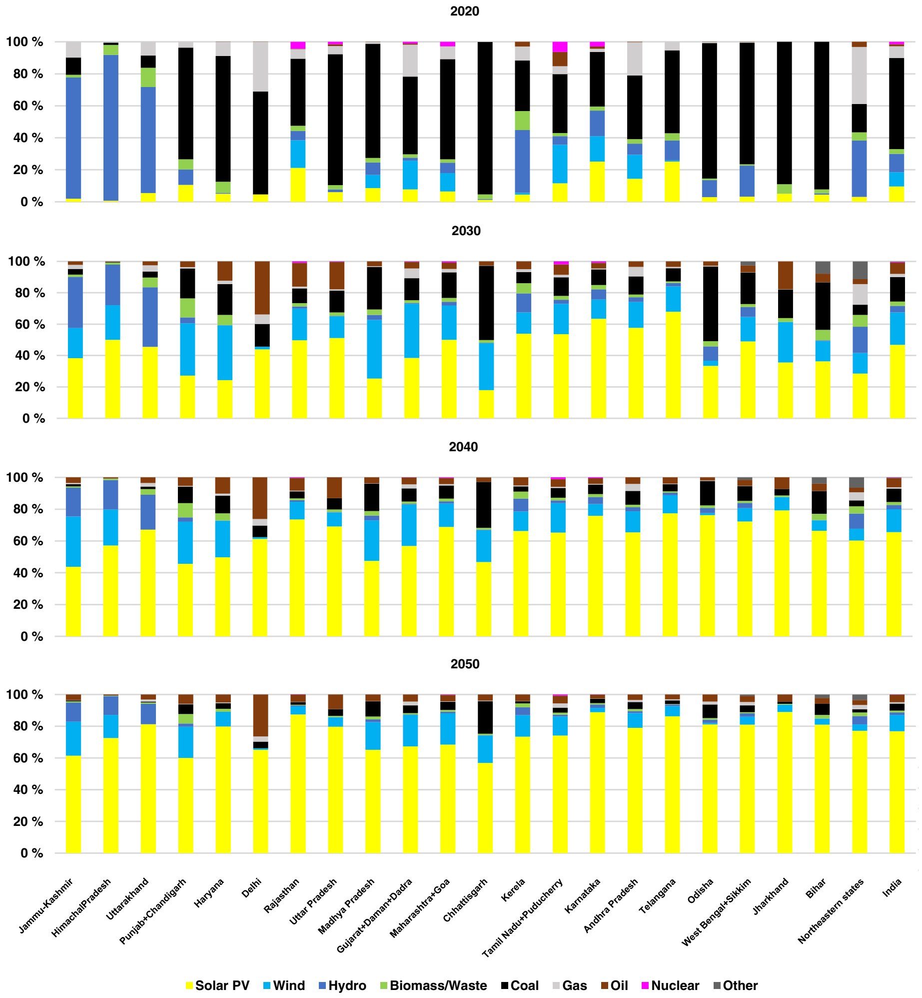


Fig. 2 | State-wise installed capacity share of different technologies in 2020, 2030, 2040 and 2050 for the individual states and aggregated all India. Solar PV capacity increases in all the states during the transition and is the main source of electricity generation, with a share of about 77% in the total installed capacity across India in 2050.

Expansion of the transmission system smooths out the resource variability and provides access to low-cost electricity from other states[48]. As a result, local storage requirements and curtailment are reduced. The total grid capacity increases to 308 GW for a full renewable energy-based power system in 2050. Grid capacity expansion of all the transmission lines considered in this study for every 10-year period of the transition is given in Supplementary Information Table 6. On the other hand, it is assumed that as the inter-state transmission grid grows during the transition, simultaneously, necessary upgrades and improvements are made within each state's grid network, as low cost electricity is available to each of the end-users.

Electricity generation during the transition

The cost-optimal contribution of different generation sources in all states across India is illustrated in Fig. 3. The share of coal in electricity generation decreases across most of the states by more than 60% in 2030. Notably, more than 80% decrease is observed in Punjab, Haryana, and Delhi in the Northern grid, Kerala, and Karnataka in the Southern grid and Northeastern states. However, states with high electricity demand, such as Gujarat and Maharashtra, and states within the traditional coal belt; Odisha, West Bengal and Jharkhand, still have a considerable share of coal generation in comparison to the rest of the states in India. On a national level, beyond 2020, as the share of coal

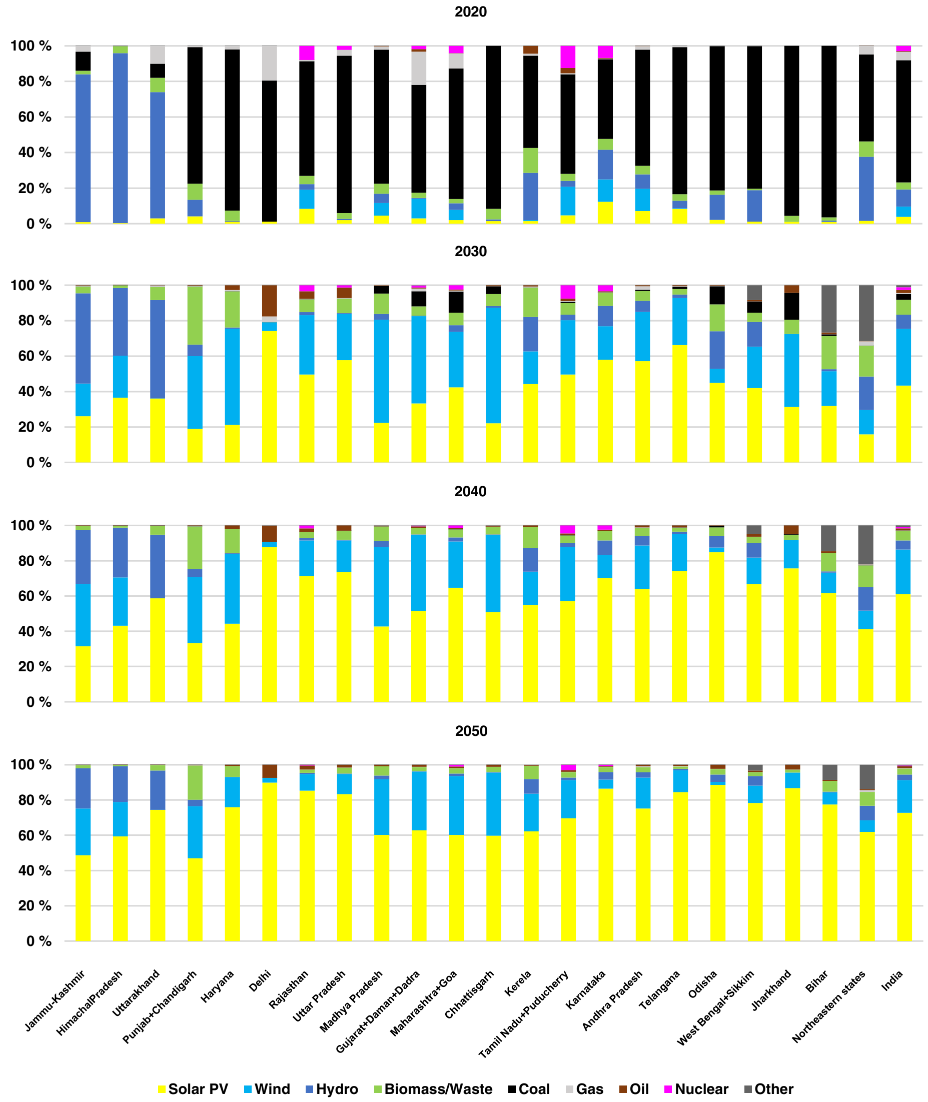


Fig. 3 | Contribution of different technologies to electricity generation in 2020, 2030, 2040 and 2050 for the individual states and aggregated all India. Transition from a coal-based to renewable energy based power system is rapid during the first decade. Electricity generated from solar PV has a share of about 73% in the total electricity generation across India in 2050.

continues to drop, first the share of wind energy in 2025 (27%) and then solar PV in 2030 (43%), increase in total electricity generation, as they become more cost competitive. This is also observed at the individual state level, where, first, electricity generation from wind energy picks up due to its high capacity factors and its availability at night. However, after 2030, as the cost competitiveness of hybrid PV-battery systems increases, solar PV will account for the largest share of electricity generation. Round-the-clock Power Purchase Agreements (PPAs) are already on the rise across different parts of India to capture the cost decrease of hybrid PV-battery power solutions and provide night-time demand[49]. The higher share of solar electricity generation could enhance the resource complementarity across the states in an

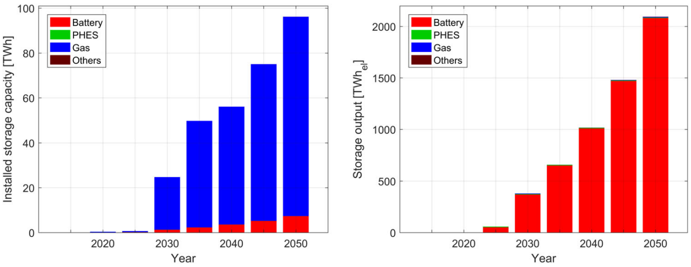


Fig. 4 | Aggerated storage capacity (a) and storage output (b) during the transition from 2015 to 2050 across India. The installed storage capacities are based on gas storage and the output is based on batteries, which is a consequence of structurally different charge-discharge cycles of short-term and seasonal storage technologies.

interconnected power system, thus neutralising the effects of the monsoon season[48]. On a national level in 2050, the major contribution to total power production are from solar (73%), wind (19%), with hydropower (3%) and nuclear power (0.4%) complementing VRE.

Multi-fuel ICEs, in 2050, have a share of 1.1% in electricity generation, driven by higher efficiency and lower cost, while having full load hours of over 800, mainly utilised for peak supply and balancing. Detailed generation data from different technologies is provided in the Supplementary Information Table 9.

It is quite evident that the Indian power sector is undergoing a rapid transition away from coal towards solar PV as the prime source of electricity generation as electricity from solar PV is the least cost. The trends during the last few years with record low tariffs across the country are already disrupting the economics of the power sector. With low-cost storage solutions, this trend is expected to be further amplified.

Storage deployment during the transition

Supplementary Information Table 9 summarises the installed capacities and output during the transition in a cost-optimal power system for all storage technologies considered. The table shows that storage plays a vital role in enabling a smooth and secure hourly power supply across all the states during the transition. As of 2020, pumped hydro energy storage (PHES) is the only storage option that is available and used, albeit in only some of the states. However, the installed capacity and output is low and future projects have been stalled for various reasons, such as social and environmental[50]. During the transition, cost-optimal investments are made in batteries and gas storage on a large scale rather than PHES. Large scale storage requirements start in 2030. However, this could very well take shape earlier with the right policy framework and incentives. In this research, storage capacities are initiated when the capacity share of renewables is more than 60%. Batteries perfectly complement the large share of solar PV in the generation due to their modularity, finally forming utility-scale hybrid PV-battery systems, while gas storage is used seasonally. The installed electricity storage capacity increases from about 22 TWh in 2030 to around 95 TWh by 2050, as shown in Fig. 4. Utility-scale and prosumer batteries contribute to a major share of the electricity storage output, with more than 98% by 2050, due to their low cost and high round trip efficiency, as diurnal storage requirements increase considerably by 2050.

On the other hand, gas storage, which is e-methane produced via the power-to-gas process, has large capacities but very few discharge cycles as compared to batteries. In a power-to-gas process, renewable electricity is used to capture carbon dioxide (CO_2) from the air using direct air capture units and in the process of electrolysis, separating hydrogen (H_2) from water. In the next step, these two gases are combined in a methanation process to produce synthetic methane (e-methane). The low capex of gas storage results in large capacities being installed during the transition, but only contributes to the vital seasonal storage through the transition. On a national level, it plays an important role when solar resource is at its lowest. Gas storage discharges slowly over the late monsoon and winter periods and is completely discharged till the end of winter. The excess electricity generated during the summer months is used to produce e-methane and charge the gas storage. Gas storage is completely charged till the end of summer. Hydropower reservoirs are charged completely during the monsoon and, similar to gas storage, provide complementarity to solar and wind generation but are mainly used for seasonal balancing. The state-of-charge (SoC) profiles for 2050 are provided for batteries, gas storage, and hydropower reservoirs in Supplementary Information Fig. 4.

On a regional level, in a fully renewable energy system in 2050, the storage capacities are well distributed across the regions of India. The installed storage capacities are dominated by gas storage that is mainly to provide seasonal storage, while the output is dominated by utility-scale and prosumer batteries (refer to Supplementary Information Fig. 6). Figure 5 shows the share of storage output in electricity generation across each region. Rajasthan has the largest share, with 70% of storage output in electricity generation among all the states. Given its geographic location with continuous and cheap solar availability throughout the year, batteries are needed on a diurnal cycle, while gas storage acts as an additional source of flexibility for balancing mainly seasonal unavailability of solar energy in events such as sandstorms. At the national level, battery output contributes an average of over 35% of electricity generation in 2050, as shown in Fig. 5. Rajasthan and Delhi have the largest shares of battery discharge in each of the regions' total electricity generation. Utility-scale batteries form the major share in Rajasthan, while in Delhi it is prosumer batteries that are installed. Both reflect the type of solar PV capacity installed in these states.

Electrolysers play a vital role in the production of hydrogen during the transition of the power system across the states of India and reach an installed capacity of 407 GW_{el} in 2050. The major capacities are in the solar-rich states of Rajasthan, Karnataka and Uttar Pradesh, with minor capacities in the rest of the states across the country, as shown in Supplementary Information Fig. 5. Electrolysers not only produce hydrogen, which is a fuel as well as feedstock for the production of e-fuels, but also provide crucial flexibility to the power system through the transition.

Import and Export of electricity in 2050

In a cost-optimised power system across India, transmission and distribution play a vital role in mitigating the variability of renewable resources. Thus, all states benefit from reduced investments in storage

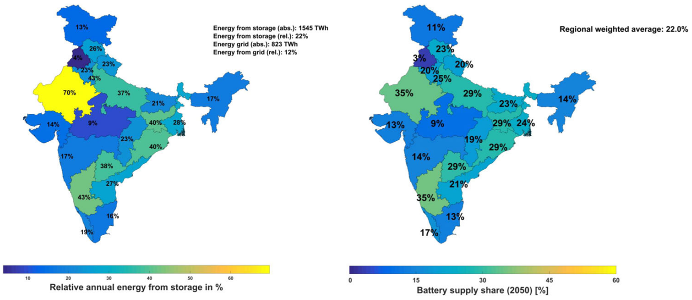


Fig. 5 | Regional distribution of relative storage output in individual states' electricity generation (a) and battery supply share (b) in 2050. The aggregated average storage supply share is 22% of the total electricity generated, while the battery supply share is 99% of the total storage output.

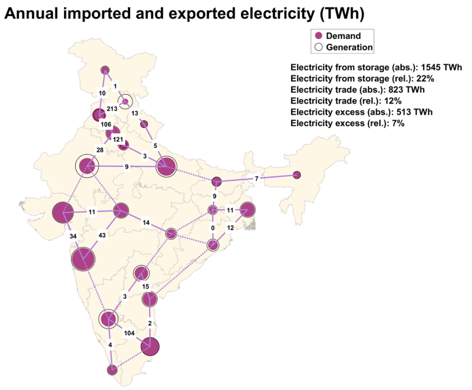


Fig. 6 | Inter-regional electricity exports and imports across India in 2050. The annual net exchange of electricity across India is around 823 TWh, which is 12% of the electricity generated in 2050.

and other flexibility options while at the same time reducing the overall system costs. A strong regional grid is vital for all states to benefit from the low-cost renewable energy resources across the entire country. The power transmission capacity increases by more than six times from 2020 to 2050, as shown in Supplementary Information Fig. 8. The interregional exchange of electricity across India in 2050 is shown in Supplementary Information Fig. 9. On a seasonal scale, grid utilisation is predominantly high during the monsoon season[48], while on a daily and weekly basis, high utilisation (hourly electricity transfer/(grid capacity·8760 h)) is observed during the morning and night hours. During a regular day, with good solar resource availability across the country, the least utilisation is observed during the noon hours, as direct electricity is used to satisfy the demand (refer to Supplementary Information Fig. 8).

Himachal Pradesh (227 TWh), Rajasthan (103 TWh) and Karnataka (116 TWh) are major net exporters of electricity, while Punjab and Chandigarh (116 TWh), Delhi (122 TWh), Maharashtra and Goa (110 TWh) and Tamil Nadu and Puducherry (116 TWh) are major net importers. Export states have excellent low-cost renewables-based electricity generation, particularly solar, wind and hydropower, which are exported, thus reducing the overall cost of storage and curtailment in these export states. Delhi, one of the largest populated cities by 2050, but with limited area and renewable energy resources, depends on neighbouring states to satisfy its electricity demand in 2050. The transmission line between Delhi and Haryana has the highest utilisation of 79% through the entire year, supplying about 121 TWh of electricity. These electricity imports play a crucial role in ensuring a steady supply of electricity throughout the year.

The share of inter-state traded electricity reaches about 12% of the total generation in 2050, clearly indicating that the majority of electricity demand across the individual states is supplied within the respective states. This implies that despite the overall interconnectedness of states across the country, each state utilises locally available renewable resources to a large extent, ensuring robust power systems even at the state level. Figure 6 gives detailed information on the power exchange between states in 2050. Supplementary Information Tables 6-8 gives information on the capacity, electricity exchange and utilisation of each transmission line respectively.

Seasonal power system analysis

A fully renewables-based power system across India has distinctive operational characteristics, which vary according to the states and seasonal patterns. Two important and distinctive seasonal variations, summer and monsoon, are considered to show the operational characteristics of a fully renewable energy based power system across India in 2050. Figure 10 in the Supplementary Information shows a representative week in summer and the monsoon season for an aggregated all India power system.

During the summer period, the major generation is from solar PV, complemented by wind energy. Significant curtailment (shown as excess) of solar and wind energy is seen on a daily basis. In the summer months, hourly curtailment can be as high as 33% of VRE-generated electricity. However, when integrated over an entire year, overall curtailment is down to 8.7%. This curtailment of electricity can be reduced by an integrated energy system, enhanced by the coupling of heat, transport and industrial sectors[51]. Storage plays an important role, especially, batteries, which are used on a daily basis, charging during the day and discharging during the evening and night hours to meet peak consumption, as highlighted in Fig. 10 of the Supplementary Information.

During the monsoon period, solar PV generation decreases, while wind generation increases and becomes the main source of electricity generation. Notably, excess electricity generation also decreases. Other renewable energy sources such as hydropower and dispatchable bioenergy support the lack of solar PV and wind generation. Reciprocating multi-fuel ICE are utilised in periods of low VRE generation, especially at the beginning of the week when wind generation is low

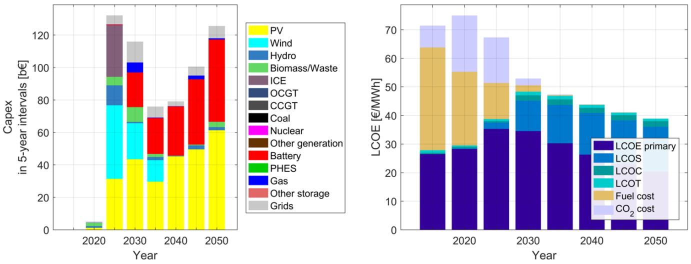


Fig. 7 | Capital expenditures for 5-year intervals (a) and levelised cost of electricity (b) during the energy transition from 2015 to 2050 across India. The highest investments take place in 2025, when the system needs to invest the most in building a new renewable energy based power system, as fossil fuels based technologies are decommissioned and restrictions on new installations. A fully renewable energy based power system in 2050 is cheaper in cost than the current fossil fuel based system.

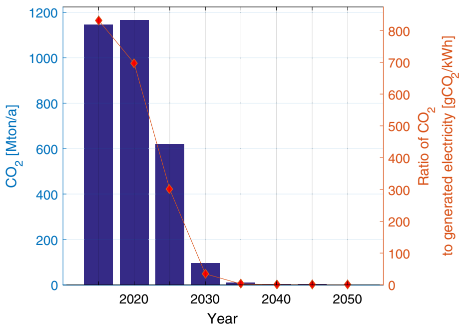


Fig. 8 | GHG emissions from the power sector during the energy transition from 2020 to 2050 across India. Deep defossilisation of the power sector is possible by 2030 and a steady decline of emissions is possible beyond 2030 up to 2050.

and when solar generation is also low in the mid and end of the week, as shown in Supplementary Information Fig. 10.

Imports and exports of electricity between states of the country play a vital role in the monsoon season, while electricity exchange is rather limited in summer. The amount of excess electricity is lower in the monsoon season as compared to the summer season.

Implications on costs and investments during the transition

The operating costs of the entire power system, including capital investments, operational expenditures, fuel costs, grid expansion costs and CO_2 emission costs during the transition are given in Fig. 7. On a national level, capital expenditures increase through the transition, with wind and reciprocating multi-fuel ICE, and later with solar and batteries being dominant. During the initial years, wind energy, due to its cost competitiveness and higher capacity factors, and solar PV are installed. However, after 2030, solar PV and batteries will become cost competitive to other generation sources, due to rapidly decreasing costs. Investments in building new transmission lines start as early as 2025 and 2030, to provide the required flexibility to a rapidly changing power system.

The levelised cost of electricity declines from around 71 €/MWh in 2020 (includes CO_2 emissions costs) to around 38 €/MWh by 2050 (refer Fig. 7) and is increasingly dominated by capital costs as fuel costs continue to decline through the transition period, which could mean increased self-reliance in terms of energy for India by 2050. Notably, the levelised cost of a fully renewable power system decreases by 46% compared to a system with 70% coal generation. Even without CO_2 emission costs[52], the decrease is about 30%. This indicates that a rapid transition of the Indian power system is simply a case of sound economics, but with additional benefits of reducing air pollution, corresponding health costs and creating jobs, which translate to further economic gains[53,54]. A steady growth in capital investments in the power sector indicates that fuel imports into the country and the respective negative impacts on trade balances will fade out through the transition, giving rise to increasing energy security.

The average cost across India is an accurate representation of the cost of the power sector, as effective cooperation among the states in terms of generation, transmission and storage enables a least-cost power system for India as well as the individual states. Direct investments, power purchase agreements (PPAs) for round-the-clock supply across the different states from central and state avenues will generate income and employment for all states and also enable least cost electricity for consumers in the country.

Reduction in GHG emissions during the transition

The reduction in GHG emissions as a function of increasing shares of renewables during the transition is shown in Fig. 8. The results indicate a rapid decline in GHG emissions in the power sector, reaching almost zero well before 2050 (2040) in comparison to current levels of about 1200 $MtCO_{2eq}$/a in 2020, on a national level. This reduction in GHG emissions is in line with the Paris Agreement target of limiting temperature rise to 1.5°C above pre-industrial levels by 2050, with zero GHG emissions across all energy sectors. As the power sector drives the transition across other energy sectors (heat, transport and industry) with increased electrification, which is a growing trend even in India, particularly with increased impetus on electric vehicles, a rapid transition will be a fundamental enabler of a climate compliant energy pathway for India.

Due to large share of coal in its electricity generation, the CO_{2eq} intensity of electricity generation in India is one of the highest in the world. During the transition, CO_{2eq} intensity rapidly declines as coal is replaced by renewables, which indicates a deep defossilisation by 2030. The level of air pollution is also expected to decline throughout India during the transition to near zero by 2040, therefore reducing associated health impacts, which has both societal as well as economic benefits.

Challenges and Uncertainties

In this research, we show a best policy scenario for the transition of the Indian power sector. Within the scope of this study, the available renewable resources in each state are adequate to satisfy the growing power demand in each state. Brown et al.[55] clearly respond to major barriers and concerns that are often associated with 100% renewables-based power systems. Nevertheless, challenges and uncertainties do exist in the modelling of future power systems.

- The primary challenges are the stability of the power system with comparatively low inertia and the inability of the power system to balance short-term variability between generation and demand. However, lack of inertia from rotating masses in a 100% renewables-based power system can be mitigated by integration of synthetic inertia and improved algorithms for power inverters for generation and batteries[47,56], as described by Oyewo et al.[57] for a 100% renewables-based power system for sub-Saharan Africa.
- The cost developments of the different renewable energy technologies considered in the study will be uncertain due to various factors, such as the recent price hike in silicon due to COVID-19 related value chain distortions. While the costs of solar PV and batteries have fallen rapidly by almost 70–80% in the last decade, this trend is expected to continue during the transition period, based on the historic learning rates of the renewable energy technologies.
- The criticality of certain raw materials like silver, copper, aluminium and lithium is seen as a potentially limiting factor in the fast growth of renewable energy and storage technologies. However, solutions do exist, and a growth in the circular economy would reduce primary production.
- Social acceptance of technologies and political will are the most uncertain aspects of the transition. These aspects change overtime and are hard to integrate into techno-economic analysis. However, qualitative assessments can be made, and we assume that society and government policies will follow a low-cost, sustainable, and a climate compliant pathway.

Renewables – Key enabler of the power sector transition

In this study, a best policy scenario was devised to analyse an energy transition pathway towards integrating 100% renewable energy by 2050 for the various states in India. It is acknowledged that challenges and uncertainties do exist in such a transition.

Despite the challenges and uncertainties, the findings of this study, based on the financial and technical assumption used, show that a cost optimal rapid transition away from coal and towards 100% renewable energy based electricity generation across the different states of India can be achieved by integrating large shares of solar PV, batteries, wind energy and supported by a strong transmission and distribution infrastructure. This transition not only decreases the cost of electricity generation by phasing out fossil fuels but also enables a rapid decrease in CO_2 emissions and losses in the power sector. Future analysis could capture various uncertainties associated with such a transition pathway.

The total installed capacity of solar PV reaches 3000 GW by 2050, contributing almost 73% to the total power generation of India. On the other hand, wind plays a supporting role, which complements perfectly during the monsoon season. The contribution of wind energy to total power generation reaches 19% in 2050. Solar PV and wind energy are already low-cost in India. With the prices of batteries continuously decreasing[58], a rapid transition of the power sector towards utilising 100% renewables is a possibility. Additionally, utilising the huge resource potential of solar and wind energy should be the preferred strategy that India should focus on. This will not only solve the increasing toxic air pollution and water stress issues[59], but also reduce the growing fossil fuel import bill that has been over 100 bUSD for the last few years[60]. Additionally, this transition could decrease the system's energy transformation losses to as low as 9.3% in 2050, from a high of 57% in 2020 (refer to Supplementary Information Figs. 11 and 12).

As the share of renewables increases across the different states, storage technologies, especially batteries and the transmission grid provide much needed flexibility during the transition, without increasing the total cost of the system. The system's LCOE decreases from 71 €/MWh in 2020 to 38 €/MWh by 2050. The CO_2 emissions cost enables a faster transition. However, without such a cost, the LCOE still decreases by 30%, compared to the 2020 levels. Additionally, if the cost structure of 2020 is frozen to satisfy the power demand of 2050 (a non-transition scenario), this would lead to an LCOE of 268 €/MWh, which is almost six times higher than a 100% renewable energy based power system. This shows that a rapid transition of the power system across the states in India is not only based on the direct cost competitiveness of renewables but also on indirect economic benefits, such as reducing air pollution and corresponding health costs and creating additional jobs. Finally, pathways showing fully renewable power systems fulfil wide ranging environmental, socio-economic, and ethical sustainability criteria in a comprehensive manner. Therefore, fully renewable energy system scenarios should be regarded as real policy options and set as a reference for alternative pathways.

Policy implications - Opportunity for India to be a trendsetter

The growth in electricity use, among all energy carriers, is the fastest, confirming the role of electricity as the backbone of the current as well as future energy systems, globally as well as in India. This was amplified further due to the disruptions caused by the COVID-19 pandemic. Electricity as an energy vector kept societies functioning without major disruptions[61]. Also, the growing trend of 'electrification' of energy sectors reiterates the importance of renewable energy based electricity as an enabler of a sustainable and low-cost energy transition. This increasing trend of electrification obligates India to develop a low-cost resilient future power system, decoupling it from external price shocks of imported fossil fuels and increasing its energy security.

The power sector in India has undergone a massive transformation during the last decade. Government led reforms such as establishing a single national power grid by connecting regional grids, expanding electricity access to all households, and a massive increase in renewable energy installations have created momentum for increased electricity use and a clean energy transition[62]. A recent example can be seen from the growth in VRE installations in Karnataka. Favourable state government policies for renewable project developers, involving local farmers and reducing dependence on coal imports, resulted in a conducive atmosphere for VRE development on a large scale[63,64].

India will see the largest increase in energy demand in the next couple of decades, as a result of its expanding economy, population, urbanisation and industrialisation[65]. There is huge potential for India to leapfrog polluting technologies and satisfy the growing energy demand with renewable energy and storage technologies. Doing so without increasing CO_2 emissions.

Currently, India does not directly implement a tax on carbon or GHG emissions. However, it does implement implicitly a form of taxation known as 'fuel excise tax'. In 2021, this was 14.4 €/tCO_2[66]. However, this is lower compared to the GHG emissions cost considered in this study, which is based on a proactive climate perspective. In this context, India could consider some additional taxes on emissions or similar mechanisms to internalise the adverse effects of fossil fuels. Additionally, the revenue collected could be used towards the development of renewable energy and sustainable technologies.

Already, India has one of the most ambitious renewable energy capacity expansion targets by 2030[12]. Some of the renewable energy rich states have renewable energy penetration levels larger than some of the developed countries[17]. However, even faster growth and steeper targets will be needed in the next few decades to stop the ill effects of climate change[5]. The average annual growth rate of renewables in India has been around 15%, while solar PV installations have grown by 26%

annually since 2018. However, more needs to be done in the case of India to achieve its targets of renewable capacity installation. On the other hand, globally, renewable capacity installation grew by 45% in 2020[67]. China installed 136 GW of renewables in 2020, about 50 GW of solar PV and 73 GW of wind energy. The growth of renewables in Vietnam has been phenomenal, especially solar PV, growing by almost 1000%, with 11.7 GW of solar PV installed in 2020. Similarly, Australia had an annual growth in solar PV capacity of 35% in 2020, while per capita installed capacity of renewables was more than 250 W/person/year in 2020[68].

This study shows that a faster and a cost optimal transition is possible with solar PV, wind energy and batteries. An ambitious long term target will give a clear message to investors and stakeholders that investing in fossil fuel based electricity generating technologies will result in stranded assets.

About 137 countries have already announced their net zero targets[69]. Among top carbon emitting countries, the US and the European Union have set a target of carbon neutrality by 2050, while China has set a target of 2060[69]. India, as the third largest GHG emitter, announced their net zero emissions target by 2070 at the recently concluded COP26. The results of this study show that a rapid transition pathway for achieving net zero emissions in the power sector can accommodate India's development imperatives of energy affordability, accessibility and mitigating air pollution in its cities, while maintaining robust economic growth.

Every country will have a different pathway towards net zero emissions, more so for India due to its uniqueness. However, one thing is clear: electricity will be the backbone of the entire energy system, with solar PV and batteries emerging as the most dominant technologies in the transition. The COVID-19 pandemic has shown us that electricity kept societies functioning when everything else stopped.

Methods

LUT energy system transition model

The LUT Energy System Transition Model is developed to assess various possible techno-economic energy transition pathways on global, national, and regional levels. The model has been previously used to study the transition of the global[46,47], regional[70–72] and national[45,73,74] power and energy systems. The specific characteristics of individual countries or regions are captured with corresponding model input parameters and assumptions.

The primary objective of this study is to define a least-cost power system incorporating renewables for all the specified years during the transition across the different states of India, using specific initial assumptions for key technologies. The transition from the current coal dominated to a fully renewable energy-based power system by 2050 is not only cost competitive but also rapidly reduces GHG emissions. This pathway provides an alternative scenario of affordability, sustainability, and emissions reduction, mainly utilising solar, wind and batteries, further complemented by hydropower.

To evaluate an energy transition pathway from 2015 to 2050, the LUT Energy System Transition modelling tool[47,75] is applied to the power sector across the states of India. A hierarchical modelling approach has been applied to reduce the complexity and allow simulation at high regional resolution in India. This method is described in Bogdanov et al.[76]. The model linearly optimises a set of given constraints on an hourly resolution for an entire year (further details of the model along with the respective mathematical representation of the target functions and constraints can be found in the next section). According to Prina et al.[77], the LUT model is one of the most sophisticated among all the investigated long term energy system models.

Two important constraints are applied to the model. First, no new power capacity installed after 2015 for coal, nuclear and conventional fossil oil-based power plants; the exception here being capacities commissioned and grid connected between 2015 and 2019, as mentioned briefly earlier. Second, in a specific year, growth in the share of installed capacity of renewable energy technologies cannot exceed more than 4% of the total installed capacity per annum from 2020 onwards. Additional information on the constraints can be found in the next section.

The model defines a cost-optimal capacity mix of generation, storage, transmission, and flexibility technologies to match the hourly power demand for each of the 22 states for a reference year. The costs of operating a power system for an entire year are calculated as a sum of the annualised capital expenditures (Capex), the Weighted Average Cost of Capital (WACC), Operational Fixed (Opex fixed) and Operational Variable (Opex var) expenditures, ramping costs for thermal generators, fuel costs and the cost of GHG emissions for all available technologies. The detailed financial and technical assumptions for all technologies are given in the Supplementary Information Table 1–4.

In addition to the energy system transition modelling, the power sector incorporates distributed self-generation and consumption of residential, commercial, and industrial PV prosumers. A prosumer is an individual entity generating their own electricity by installing rooftop solar PV and optional batteries and can also consume electricity from the grid (and supply excess generated electricity to the grid if regional policy allows). These prosumers are optimised exogenously with a different model describing rooftop PV capacities and battery development[78]. The prosumer modelling determines the cost-optimal solar PV capacities installed on rooftops with the battery energy storage, individually for residential (all roofs used for residential purposes such as residential houses, apartments, individual houses, etc.), commercial (all roofs used for commercial purposes such as commercial buildings, malls and government buildings) and industrial prosumers (all rooftop available from the industrial complexes).

The hourly profiles for solar PV consumption, battery charging and discharging, electricity supply from the grid, and feed-in of excess electricity to the grid are determined through the target function of minimisation of annual electricity costs. The details of the target function used for prosumers is given in the next section. The resulting output from the prosumer model defines the demand of the centralised power system. As a result of the integration of prosumers into the larger energy system, prosumers reduce the daily peak demand and, in turn, reduce the centralised system's power plant capacities. Integration of large scale prosumers will require bidirectional smart meters, and it is assumed to be part of the prosumer setup.

The capacity built, electricity generated, storage and grid deployed are all based on the results of the applied target function and constraints. It is acknowledged that there could be various pathways to achieve a zero GHG emission power system by 2050, such as integrating large shares of nuclear energy, carbon capture and storage and biomass. However, in this study, a least cost scenario is highlighted by utilising abundant potential of solar and wind energy[79].

The power sector transition modelling for India is performed by using the LUT Energy System Transition Model tool[47,75]. Under the assumption of perfect foresight of renewable energy power generation and power demand, the power system is linearly optimised on an hourly resolution for an entire year under a set of applied constraints. The optimisation is performed using a third-party solver. In this study, MOSEK ver.8 is used as an optimiser, but other solvers (Gurobi, CPLEX, etc.) can also be used. The model is compiled in the Matlab environment in LP file format so that the model can be read by most of the available solvers. After simulation, the results are parsed back into the Matlab data structure and post-processed.

A multi-node approach used in this study enables the description of any desired configuration of states and power transmission interconnections. To decrease the simulation time, a hierarchical modelling approach has been applied[76]. The modelling is performed in two steps. First, modelling of the system in a reduced regional resolution (4 regional grids). Second, modelling of each of the regional grids in full

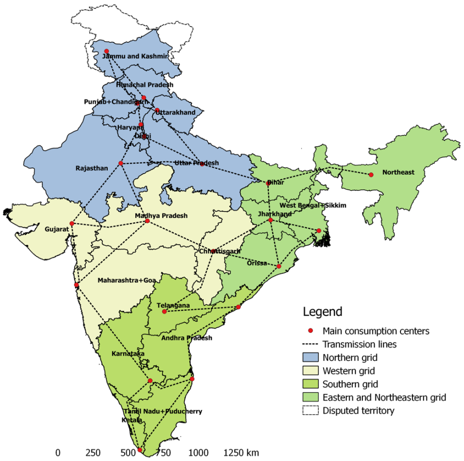


Fig. 9 | The four major regions constituted by the corresponding states/regions. India has five regional grids. In this analysis, we have combined the Eastern and Northeastern grids to form an Eastern grid, so we have four regional grids. All the major states are considered as shown, while smaller states and union territories are combined to the nearest state, except Delhi. The individual states within each of the regional grids are interconnected, and the regional grids are interconnected with each other. These transmission lines enable imports and exports between the states. It is assumed that the existing network of alternating current (AC) lines within the individual states will provide electricity to all end consumers.

state resolution, considering the power flows between the regional grids simulated in the first step. The results represent the operations of the integrated power system in full resolution, where power can flow between all the states. Figure 9 describes the detailed regional configuration.

The main constraints for the optimisation are the matching of all types of generation and power demand for every hour of the applied year, and the optimisation criteria is to have a least annual cost of the power system. The hourly resolution of the model significantly increases the computation time; however, it guarantees that for every hour of the year, the total supply within a region covers the local demand and enables a more precise system description, including synergy effects of different system components.

Target function

The target of the system optimisation is to minimise the total annual cost of an integrated power system, calculated as the sum of the annual costs of installed capacities of different technologies, the costs of power generation and ramping technologies. This target function includes the annual costs of the power sector. The target function of the applied energy model for minimising annual costs is presented in Eq. (1) using the abbreviations: states/regions (*r*, reg), generation, storage and transmission technologies (*t*, tech), capital expenditures for technology *t* in region *r* ($\mathrm{CAPEX}_{r,t}$), capital recovery factor for technology *t* in region *r* ($\mathrm{crf}_{r,t}$), fixed operational expenditures for technology *t* in region *r* ($\mathrm{OPEXfix}_{r,t}$), variable operational expenditures technology *t* in region *r* ($\mathrm{OPEXvar}_{r,t}$), installed capacity in the region *r* of technology *t* ($\mathrm{instCap}_{r,t}$), annual generation by technology *t* in region *r* ($\mathrm{E}_{gen,t,r}$), cost of ramping of technology *t* ($\mathrm{rampCost}_t$) and sum of power ramping values during the year for the technology *t* in the region *r* ($\mathrm{totRamp}_{r,t}$).

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}\left(\mathrm{CAPEX}_{r,t}\cdot crf_{r,t}+OPEXfix_{r,t}\right)\cdot instCap_{r,t}+OPEXvar_{r,t}\cdot E_{gen,r,t}+rampCost_t\cdot totRamp_{r,t}\right) \tag{1}$$

The target function only considers the cost assumptions for the given step of transition as the previously built capacity is defined as a lower limit for the total capacity ($\mathrm{instCap}_{t,r}$), and thus the previously built capacity costs do not affect the optimisation.

The rooftop prosumer system (solar PV and batteries) is realised in an independent sub model with a slightly different target function. The prosumer system is optimised for each region and each power demand segment (residential, commercial and industrial) independently, even if the states or regions are interconnected with each other. The target function includes annual costs of the prosumers power generation and storage and the cost of electricity bought from the distribution grid. The cost of electricity sold to the distribution grid is deducted from the total annual cost. The target function of the applied prosumer model for minimising annual costs is presented in Eq. (2) using the abbreviations: generation and storage technologies (*t, tech*), capital expenditures for technology *t* (CAPEX_t), capital recovery factor for technology *t* (crf_t), fixed operational expenditures for technology *t* ($\mathrm{OPEXfix}_t$), variable operational expenditures for technology *t* ($\mathrm{OPEXvar}_t$), installed capacity of technology *t* ($\mathrm{instCap}_t$), annual generation by technology *t* ($E_{\mathrm{gen},t}$), retail price of electricity (elCost), feed-in price of electricity (elFeedIn), annual amount of electricity bought from the grid (E_{grid}), annual amount of electricity sold from the grid (E_{curt}).

$$\min\left(\sum_{t=1}^{tech}\left(CAPEX_t\cdot crf_t+OPEXfix_t\right)\cdot instCap_t+OPEXvar_t \cdot E_{gen,t}+elCost\cdot E_{grid}+elFeedIn\cdot E_{curt}\right) \tag{2}$$

Energy balance constraints

The main constraint for optimising the power sector is matching power generation and demand for every hour of the applied year. For every hour of the year, the total generation within a region and electricity imported should cover the local electricity demand.

$$\forall h\in[1,8760]\ \sum_{t}^{tech}E_{gen,t}+\sum_{r}^{reg}E_{imp,r}+\sum_{t}^{stor}E_{stor,disch}=E_{demand}+\sum_{r}^{reg}E_{\exp,r}+\sum_{t}^{stor}E_{stor,ch}+E_{curt} \tag{3}$$

Equation (3) describes constraints for the energy flows of a region. Abbreviations: hours (*h*), technology (*t*), all modelled power generation technologies (tech), sub-region (*r*), all sub-regions (reg), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies (stor), electricity from discharging storage ($E_{\mathrm{stor,disch}}$), electricity demand (E_{demand}), electricity exported (E_{exp}), electricity for charging storage ($E_{\mathrm{stor,ch}}$), curtailed excess energy (E_{curt}). The energy loss in the high voltage direct current (HVDC) and alternating current (HVAC) transmission grids and energy storage technologies are considered in storage discharge and grid import value calculations.

Apart from this, various financial and technical assumptions that are utilised for the cost optimisation of the model are presented in the Supplementary Information Table 1–4.

The important constraints applied in the modelling are given below:

1. No new power capacity will be installed after 2015 for coal, nuclear and conventional fossil oil-based power plants, mainly due to their inability to fulfill the high sustainability criteria set in the model. The capacities commissioned and grid connected between 2015 and 2019 are an exception. It is assumed that coal and oil-

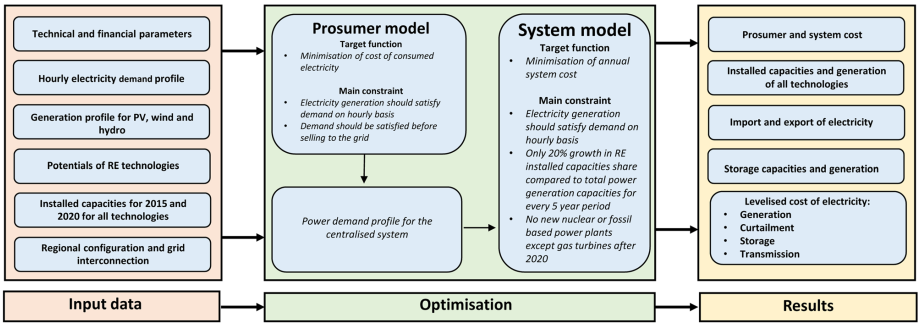


Fig. 10 | Schematics of the LUT Energy System Transition model. The model consists of various primary data as an input to the optimisation process, where, first, the prosumer target function is optimised, and in the second step, the system target function. Different optimised results are obtained as an output.

fired power plants under construction and planned capacities are scrapped and not commissioned. All fossil fuel-based power plant capacities are fully amortised until the end of their technical lifetimes to facilitate a gradual phase out. Their utilisation is cost optimised so that, in later periods for some states, full load hours or capacity factors even decline to zero, due to their higher per unit cost of electricity production. Even though these capacities do not produce electricity, they have to be amortised for political reasons, a procedure which is known as cold reserve (also called security reserve). Gas turbines and multi-fuel ICE are permitted to be installed beyond 2015 due to lower carbon emissions and the possibility to accommodate renewable electricity based methane (e-methane), bio-methane and even green hydrogen into the system. Gas-fired power plants are more flexible, not only in their ramping rates but also in utilising different e-fuels

2. In a specific year, growth in the shares of installed capacities of renewable energy technologies cannot exceed more than 4% per annum from 2020 onwards in congruence with empirical data[80]

The active capacity existing in the system is defined on each of the steps for each of the regions, based on the data of the capacity installed at previous steps and the lifetime for a given technology at given commissioning year as presented in Eq. (4) using the abbreviations: years (y, $year$), generation and storage technologies (t, $tech$), existing active capacity for technology t at modelled year (existingCap$_{t,year}$), new built capacity for technology t at previous year y (newCap$_{t,y}$), lifetime of the capacity of technology t built in year y (N$_{t,y}$):

$$\forall t \in [tech]\ \text{existingCap}_{t,year} = \sum_{y=1960}^{year} \text{newCap}_{t,y} \cdot \left((y + N_{t,y}) > year\right) \tag{4}$$

Then the model optimisation results in the optimal regional capacity of the technologies in the given year, which defines the new built capacity needed by the system as defined in Eq. (5) using the abbreviations: modelling year ($year$), generation and storage technologies (t, $tech$), new built capacity for technology t at a given year $year$ (newCap$_{t,year}$), total capacity for technology t at a given year $year$ as defined by the model optimisation ($instCap_{t,year}$), existing active capacity for technology t at modelled year (existingCap$_{t,year}$):

$$\forall t \in [tech]\ \text{newCap}_{t,year} = \text{instCap}_{t,year} - \text{existingCap}_{t,year} \tag{5}$$

The energy cost calculations in the post-processing phase are based in a hierarchical approach, where the annualised cost of the system considers the financial assumptions in the periods when these capacities were built, unlike the approach used in the optimisation and described in Eq. (1). For the variable opex calculations, the energy output of technologies is split accordingly to the capacity age structure as defined in Eq. (6) using the abbreviations: modelling year ($year$), all years from 1960 (y), generation and storage technologies (t, $tech$), annual generation by technology t by capacity built at year y ($E_{\text{genSplit},t,y}$), new built capacity for technology t built at year y (newCap$_{t,y}$), annual generation by technology t defined by the model for the modelling year $year$ ($E_{\text{gen},t,year}$), total capacity for technology t at given a year $year$ as defined by the model optimisation (instCap$_{t,year}$) lifetime of the capacity of technology t built at year y ($N_{t,y}$):

$$\begin{aligned}\forall t \in [tech], \forall y \in [1960 \ldots year]\ & E_{\text{genSplit},t,y} \\ &= E_{\text{gen},t,year} \cdot \left(\text{newCap}_{t,y} \cdot \left(\left(y + N_{t,y}\right) > year\right)\right) / \text{instCap}_{t,year}\end{aligned} \tag{6}$$

The annnualised cost of the system at a given year is calculated accordingly to the Eq. (7) using the abbreviations: modelling year ($year$), all years from 1960 (y), generation and storage technologies (t, $tech$), capital expenditures for technology t in region r and year y (CAPEX$_{r,t,y}$), capital recovery factor for technology t in region r and year y (crf$_{r,t,y}$), fixed operational expenditures for technology t in region r and year y (OPEXfix$_{r,t,y}$), variable operational expenditures technology t in region r and year y (OPEXvar$_{r,t,y}$), new built capacity for technology t built in region r at year y (newCap$_{r,t,y}$), lifetime of the capacity of technology t built at year y ($N_{t,y}$), annual generation by technology t in region r in year $year$ by capacity built at year y ($E_{\text{genSplit},r,t,y}$), cost of ramping of technology t (rampCost$_t$) and sum of power ramping values during the year for the technology t in the region r (totRamp$_{r,t}$):

$$\begin{aligned}\text{annualCost}_{year} = \sum_{r=1}^{reg} \sum_{t=1}^{tech} \sum_{y=1960}^{year} & \left(\text{CAPEX}_{r,t,y} \cdot \text{crf}_{r,t,y} + \text{OPEXfix}_{r,t,y}\right) \\ & \cdot \left(\left(\text{newCap}_{r,t,y} \cdot \left(\left(y + N_{t,y}\right) > year\right)\right)\right. \\ & \left. + \text{OPEXvar}_{r,t,y} \cdot E_{\text{genSplit},r,t,y} + \text{rampCost}_t \cdot \text{totRamp}_{r,t}\right.\end{aligned} \tag{7}$$

This historical cost calculation approach is used for other cost calculations including LCOE and split of LCOE in sub-categories.

The schematic of the LUT Energy System Transition Model with the various inputs, optimisation and results is illustrated in Fig. 10.

Table 1 | Technical and financial assumptions for key power system technologies used in the Indian energy transition from 2015 to 2050

Technology		Unit	2015/2017	2020	2025	2030	2035	2040	2045	2050	Ref
PV rooftop - residential	Capex	€/kW$_{el}$	1360	1045	842	715	622	551	496	453	98
	Opex fix	€/(kW$_{el}$ a)	20.4	9.1	7.7	6.7	5.9	5.3	4.8	4.4	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kW$_{el}$	1360	689	544	456	393	345	308	280	98
	Opex fix	€/(kW$_{el}$ a)	20.4	9.1	7.7	6.7	5.9	5.3	4.8	4.4	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kW$_{el}$	1360	512	397	329	281	245	217	197	98
	Opex fix	€/(kW$_{el}$ a)	20.4	9.1	7.7	6.7	5.9	5.3	4.8	4.4	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally tilted	Capex	€/kW$_{el}$	733	432	336	278	237	207	184	166	99–101
	Opex fix	€/(kW$_{el}$ a)	9.3	7.8	6.5	5.7	5.0	4.5	4.0	3.7	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kW$_{el}$	1150	475	370	306	261	228	202	183	100,102
	Opex fix	€/(kW$_{el}$ a)	17.3	9.0	7.0	6.0	6.0	5.0	4.0	4.0	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW$_{el}$	800.0	800	783.3	767.0	749.0	749.0	749.0	749.0	99,100
	Opex fix	€/(kW$_{el}$ a)	15.0	15.0	13	11	8.0	8.0	8.0	8.0	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
Hydro Reservoir/ Dam	Capex	€/kW$_{el}$	1650	1650	1650	1650	1650	1650	1650	1650	103
	Opex fix	€/(kW$_{el}$ a)	49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5	
	Opex var	€/(kWh$_{el}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
	Lifetime	years	50	50	50	50	50	50	50	50	
Hydro Run-of-River	Capex	€/kW$_{el}$	2560	2560	2560	2560	2560	2560	2560	2560	103
	Opex fix	€/(kW$_{el}$ a)	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8	
	Opex var	€/(kWh$_{el}$)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	
	Lifetime	years	50	50	50	50	50	50	50	50	
Coal Power Plant	Capex	€/(kW$_{el}$)	867	934	1045	1156	1267	1378	1489	1600	104
	Opex fix	€/(kW$_{el}$ a)	24.0	23.6	23.0	22.4	21.8	21.2	20.6	20.0	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	32	42	42	42	43	43	43	43	
	Lifetime	years	40	40	40	40	40	40	40	40	
Nuclear Power Plant	Capex	€/(kW$_{el}$)	4511	4571	4672	4773	4874	4974	5075	5175	105–107
	Opex fix	€/(kW$_{el}$ a)	85.0	86.1	88.0	83.0	84.8	79.3	80.9	78.8	
	Opex var	€/(kWh$_{el}$)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
	Efficiency	%	34	34	34	35	35	35	35	35	
	Lifetime	years	40	40	40	40	40	40	40	40	
CCGT	Capex	€/(kW$_{el}$)	623	637	660	683	706	729	752	775	104,108
	Opex fix	€/(kW$_{el}$ a)	23.44	23.1	22.5	21.9	21.3	20.7	20	19.375	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	52.2	52.2	52.2	52.2	53.1	54	54	54	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT HD	Capex	€/(kW$_{el}$)	450	445	440	435	430	425	420	415	104,108
	Opex fix	€/(kW$_{el}$ a)	23.4	11.3	10.6	9.9	9.2	8.5	7.8	7.1	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	28	30	33	35	38	40	43	45	
	Lifetime	years	35	35	35	35	35	35	35	35	
Open cycle Aeroderivative	Capex	€/(kW$_{el}$)	550	540	530	520	510	500	490	480	
	Opex fix	€/(kW$_{el}$ a)	11.3	11.3	10.6	9.9	9.2	8.5	7.8	7.1	

Table 1 (continued) | Technical and financial assumptions for key power system technologies used in the Indian energy transition from 2015 to 2050

Technology		Unit	2015/2017	2020	2025	2030	2035	2040	2045	2050	Ref
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	0.39	0.40	0.42	0.42	0.43	0.44	0.45	0.45	
	Lifetime	years	35	35	35	35	35	35	35	35	
RECIP oil based	Capex	€/(kW$_{el}$)	385	385	385	385	385	385	385	385	[109]
	Opex fix	€/(kW$_{el}$ a)	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	28	28	28	28	29	29	30	30	
	Lifetime	years	20	20	20	20	20	20	20	20	
RECIP Gas	Capex	€/(kW$_{el}$)	578.5	569.0	553.0	537.0	522.0	506.0	491.0	475.0	
	Opex fix	€/(kW$_{el}$ a)	15.3	15.3	14.6	13.9	13.2	12.5	11.8	11.1	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	0.47	0.48	0.48	0.49	0.49	0.50	0.50	0.51	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biomass Power Plant	Capex	€/(kW$_{el}$)	760.0	857	1019	1181	1343	1505	1668	1830	[99,100]
	Opex fix	€/(kW$_{el}$ a)	53.3	51.5	48.4	45.3	42.2	39.1	36	32.9	
	Opex var	€/(kWh$_{el}$)	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	
	Efficiency	%	35	36	37	37	38	38	39	39	
	Lifetime	years	25	25	25	25	25	25	25	25	
Battery storage	Capex	€/kWh$_{el}$	400	270	182	134	108	92	78	70	[98]
	Opex fix	€/(kWh$_{el}$ a)	24.0	9.0	5.0	3.8	3.0	2.5	2.1	1.9	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
Pumped Hydro Energy Storage (PHES)	Capex	€/kWh$_{el}$	89.0	89.0	89.0	89.0	89.0	89.0	89.0	89.0	
	Opex fix	€/(kWh$_{el}$ a)	1	1	1	1	1	1	1	1	
	Opex var	€/(kWh$_{el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	85	85	85	85	85	85	85	85	
	Self-discharge	%/h	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Selected technologies are listed. Further technologies can be found in the Supplementary Information Table 1.

Development of electricity demand

The average per capita electricity demand is assumed to rise from 1.2 MWh in 2020 to 3.5 MWh in 2050, while the population is projected to increase to 1.7 billion by 2050, as highlighted in the Supplementary Information Fig. 1. Total electricity demand of the Indian power sector is estimated to increase to about 5921 TWh by 2050, which represents a compound average annual growth rate of around 4.9% in the energy transition period, in line with the expectations of the government and other energy institutions[81]. Use of electricity in other energy sectors (such as heat, transport and industry) is not considered in this research, which could lead to an additional increase in electricity demand during the transition period. The synthetic electricity demand profiles from 2015 until 2050 are generated for each of the states, based on the methods applied by Toktarova et al.[82]. Load profile will be different for the centralised power system due to partial load covering by prosumers. The seasonal and daily variations are captured in the load profiles up to 2050 across all the 22 states in the country.

Electricity generation technologies and other resources

The model is integrated with all crucial aspects of power systems: generation, storage and transmission[83].

- **Technologies for electricity generation**: Solar PV fixed tilted, solar PV single-axis north-south tracking, solar PV rooftop, concentrating solar thermal power (CSP), wind onshore and offshore, hydropower run-of-river, hydropower reservoirs, geothermal, bioenergy (solid biomass, biogas, and waste-to-energy). The existing fossil fuels-based generation technologies considered are coal and conventional oil based power plants, open cycle gas turbines (OCGT), combined cycle gas turbines (CCGT) and nuclear technologies. In addition, new technologies like multi-fuel reciprocating ICE (gas) and heavy-duty open cycle gas turbines (OCGT HD) make up the electricity generation technologies.
- **Energy storage technologies**: Lithium-ion (Li-ion) batteries and pumped hydro energy storage (PHES) for short-term storage. Adiabatic compressed air energy storage (A-CAES) and thermal energy storage (TES) for medium-term storage. Gas storage including power-to-gas technology, which allows production of e-methane for the energy system for seasonal storage requirement.
- **Electricity transmission technologies**: The existing power grid, its future development, and impact on overall electricity transmission and distribution losses[84] is taken into account in the transition. The states are interconnected with high voltage direct current (HVDC) or high voltage alternating current (HVAC) power lines. These transmission lines provide the required flexibility by spatial distribution of renewable-based electricity, especially in the monsoon season[48], while reducing overall national system costs.

Best Policy Scenario

The LUT Power System Transition Model can be utilised to generate wide-ranging power sector scenarios across the different regions of the world on a global-local scale. However, the objective of this study is to highlight a power sector scenario for the states in India interconnected via transmission lines in the context of achieving the goals of the Paris Agreement by reaching zero GHG emissions from the power sector in a technically feasible and economically viable manner. Therefore, a Best Policy Scenario is envisioned for the power sector from 2015 towards a cost-optimal power system by 2050. The results are visualised and presented in 5-year intervals through the transition from 2015-2050 for the power system transition across the states of India.

Technical and financial assumptions

The key technical and financial assumptions, with the corresponding references, are presented in Table 1. A comprehensive list of all the assumptions used in this study is presented in Supplementary Information Table 1–4. The key assumptions are mostly taken from the Central Electricity Authority (CEA), and the Central Electricity Regulatory Commission (CERC). Table 2 presents the ramping costs for key power generation technologies. However, not all assumptions were available from these sources, therefore global assumptions were used in such cases. Each of these technical and financial assumptions are considered for 5-year time periods between 2015 to 2050. The average solar PV costs in India, in 2020 was 455 USD/kW i.e. ~424 €/kW[85]. The average lifetime is given in the range of 25-40 years in the NREL study[86]. Warranties are often used as an indicator of the economic lifetime of solar PV modules which is 25 years, while the modules can produce more than 80% of the original power after 25 years and upto 50 years[87]. Based on various project developers, and other stakeholders the useful life assumptions increased from an average of ~21.5 years in 2007 to ~32.5 years in 2019[86]. Currently, the assumptions range from 25 years to more than 35 years[86]. Increase in lifetime is expected as we go through the transition towards 2050, as observed from 2007 to 2019. For residential batteries, average cost of battery packs in India is 215 €/kWh[88]. The weighted average cost of capital (WACC) was set to 11% in 2015, declining steadily to 7% in 2050 (Table 3). However, in the case of residential solar PV prosumers, WACC is set to 4% due to lower financial return expectations. Electricity prices for residential, commercial and industrial consumers were taken from the Tariff Order for individual states, and extended to 2050 based on the methods of Breyer and Gerlach[89]. The excess electricity generated by PV prosumers is fed into the national grid and is assumed to be incentivised for a transfer price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before feeding it to the grid. The costs for biomass are calculated using data from the IEA[90] and IPCC[91]. Solid wastes gate fees are 50 €/ton in 2015, 53 €/ton in 2020, 59 €/ton in 2025, 68 €/ton in 2030, 80 €/ton in 2035, 95 €/ton in 2040, 100 €/ton in 2045 and 2050; the assumption is based that gate fees will gradually increase globally and by 2050 reach 100 €/ton as in most of the developed countries. It is assumed that the GHG emissions cost increases from 28 €/tCO_2 in 2020 to 150 €/tCO_2 in 2050[92].

Table 2 | Ramping costs for key power generation technologies

Technology	Unit	
Coal PP	€/MW	54.3
Nuclear PP	€/MW	54.3
CCGT	€/MW	25.0
OCGT	€/MW	22.9
Biomass PP	€/MW	54.3

Data adopted from Deutsches Institut für Wirtschaftsforschung[110]. Selected technologies are listed. Further technologies can be found in the Supplementary Information Table 2.

Capacity factor profiles

The hourly feed-in profiles for solar PV, wind energy and hydropower were provided as an input to the model. The dataset used for solar irradiation and wind speed is in a 0.45° X 0.45° spatial resolution for the real weather conditions. The feed-in full load hours (FLH)/capacity factors for the individual states are computed on the basis of the 0.45° X 0.45° spatially resolved single sub-area data using a weighted average formula. The individual state capacity factors are calculated using the following rule: 0–10% best sub-areas of a state are weighted by 0.3, 10–20% best sub-areas of a state are weighted by 0.3, 20– 30% best state of a region are weighted by 0.2, 30–40% best sub-areas of a state are weighted by 0.1 and 40–50% best sub-areas of a state are weighted by 0.1. The FLH/capacity factor of solar PV and wind energy estimated at a high geospatial resolution across the country are given below in Supplementary Figs.2 and 3.

Renewable energy potentials

The potential capacities, or the upper limits for solar PV and wind energy, are based on land use limitations and specific capacity densities. The area covered by solar PV plants is set at a maximum of 6% of the total land area available in each of the states. The average specific capacity density of solar PV is assumed to be 75 MW/km^2 for the entire transition period. This is based on 15% module efficiency and a 50% ground coverage ratio[93], and is confirmed by empiric data[94]. However, increase in the efficiency of the PV modules that would impact the specific capacity density is not considered. The total calculated installable potential for utility-scale solar PV in India is 14223 GW.

Table 3 | Financial assumptions for the fossil and nuclear fuel prices and GHG emission cost

Name of component	Unit	2015/2017	2020	2025	2030	2035	2040	2045	2050	Ref.
Coal	€/MWh_{th}	9.9	9.9	10.8	11.8	13.1	14.3	14.3	14.3	[111]
Fuel oil	€/MWh_{th}	101.1	101.1	114.3	127.5	126.0	124.9	124.9	124.9	[106,112]
Fossil gas	€/MWh_{th}	36.1	36.1	48.8	53.2	58.8	65.4	65.4	65.4	[112,113]
Uranium	€/MWh_{th}	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	[107]
GHG emissions	€/tCO_{2eq}	9	28	52	61	68	75	100	150	[92]
WACC		11.0 %	11.0 %	9.7 %	8.5 %	7.0 %	7.0 %	7.0 %	7.0%	[114]
GHG emissions by fuel type t_{CO2eq}/MWh_{th}										
Coal[115]			**Oil**[115]				**Fossil gas**[116]			
0.34			0.25				0.21			

The referenced values are till 2040 and are kept stable for later periods (fuels).

For onshore wind power plants, land use limitation is set to a maximum of 4%, while the average specific capacity density is assumed to be 8.4 MW/km^{2}[93]. The total calculated installable potential for onshore wind energy is 1062 GW.

For hydropower plants and pumped hydro energy storage (PHES), the potential was set to 150% and 200% of the already installed capacities of 2015. The geothermal energy potential was calculated according to the methods described in Aghahosseini and Breyer[95]. The biomass potentials were calculated based on the methodology described in Mensah et al.[96].

Data availability

The data and the main model code that support the findings of this study is available from the authors on reasonable request.

References

1. Januta, A. *Extreme weather renews focus on climate change as scientists update forecasts*. https://www.reuters.com/business/environment/extreme-weather-renews-focus-climate-change-scientists-update-forecasts-2021-07-26/ (2021).
2. United Nations News. *Water-related hazards dominate list of 10 most destructive disasters*. https://news.un.org/en/story/2021/07/1096302 (2021).
3. Sippel, S., Meinshausen, N., Fischer, E. M., Székely, E. & Knutti, R. Climate change now detectable from any single day of weather at global scale. *Nat. Clim. Chang. 2020 101* **10**, 35–41 (2020).
4. Madakumbura, G. D., Thackeray, C. W., Norris, J., Goldenson, N. & Hall, A. Anthropogenic influence on extreme precipitation over global land areas seen in multiple observational datasets. *Nat. Commun.* **12**, 3944 (2021).
5. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf (2021).
6. Ajit, N. *Climate change makes Indian monsoon season stronger and more chaotic*. https://www.dw.com/en/indian-monsoon-climate-change-rainfall/a-57187793 (2021).
7. *Assessment of Climate Change over the Indian Region*. (Springer Singapore, 2020). https://doi.org/10.1007/978-981-15-4327-2.
8. Mathur, R. & Shekhar, S. India's energy sector choices—options and implications of ambitious mitigation efforts. *Clim. Change* **162**, 1893–1911 (2020).
9. Chaturvedi, V., Koti, P. N., Sugam, R., Neog, K. & Hejazi, M. Cooperation or rivalry? Impact of alternative development pathways on India's long-term electricity generation and associated water demands. *Energy* **192**, 116708 (2020).
10. Climate Action Tracker. *Pledges And Targets - India*. https://climateactiontracker.org/countries/india/pledges-and-targets/ (2019).
11. [UNFCC] - United Nations Framework for Climate Change. *India's Intended Nationally Determined Contribution*. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/IndiaFirst/INDIA INDC TO UNFCCC.pdf (2016).
12. Prime Minister's Office. *Pledges to more than double India's renewable energy capacity target to 450 GW*. https://pib.gov.in/PressReleasePage.aspx? PRID=1585979 (2019).
13. Ministry of Power. *SAUBHAGYA- Pradhan Mantri Sahaj Bijli Har Ghar Yojana*. https://saubhagya.gov.in/ (2019).
14. Bryndis, W. & David, S. *Risks Growing for India's Coal Sector Over-Capacity, Water Shortages*. https://ieefa.org/wp-content/uploads/2019/08/Risks-Growing-for-India-Coal-Sector_September-2019.pdf (2019).
15. [CEA] - Central Electricity Authority. *Growth Of Electricity Sector In India From 1947-2020*. https://cea.nic.in/wp-content/uploads/pdm/2020/12/growth_2020.pdf (2020).
16. Sharma, V., Greig, C. & Lant, P. What is stopping India's rapid decarbonisation? Examining social factors, speed, and institutions in Odisha. *Energy Res. Soc. Sci.* **78**, 102117 (2021).
17. IEA and NITI Aayog. *Renewables Integration report in India*. https://iea.blob.core.windows.net/assets/7b6bf9e6-4d69-466c-8069-bdd26b3e9ed1/RenewablesIntegrationinIndia2021.pdf (2021).
18. Prakash, V., Ghosh, S. & Kanjilal, K. Costs of avoided carbon emission from thermal and renewable sources of power in India and policy implications. *Energy* **200**, 117522 (2020).
19. Chakravarty, S. & Somanathan, E. There is no economic case for new coal plants in India. *World Dev. Perspect.* **24**, 100373 (2021).
20. Chaudhary, A. *India's Clean Energy Got More Loans Than Coal For Third Year*. https://www.bloomberg.com/news/articles/2021-12-15/india-s-clean-energy-got-more-financing-than-coal-for-third-year (2021).
21. Lolla, A., Fernandes, A. & Raj, A. *India's Zombie Threat*. https://ember-climate.org/wp-content/uploads/2021/09/Ember-Report-Indias-Zombie-Threat.pdf (2021).
22. Gajardo, D., Goyal, A., Kuzma, S. & Goswami, S. *How Water Challenges Threaten India's Energy Security*. https://www.wri.org/insights/water-challenges-energy-sector-india (2021).
23. [CSE] - Centre for Science and Environment. *India's first-ever environmental rating of coal-based power plants finds the sector's performance to be way below global benchmarks*. https://www.cseindia.org/indias-first-ever-environmental-rating-of-coal-based-power-plants-finds-the-sectors-performance-to-be-way-below-global-benchmarks-5685 (2015).
24. IEEFA. *Seriously Stressed and Stranded: The Burden of Non-Performing Assets in India's Thermal Power Sector*. https://ieefa.org/wp-content/uploads/2019/12/The-Burden-of-NonPerforming-Assets-in-India-Thermal-Power-Sector_December-2019.pdf (2019).
25. Luo, T., Krishnan, D. & Sen, S. Parched Power: Water Demands, Risks, and Opportunities for India's Power Sector. *World Resour. Inst.* 1–40 (2018).
26. Srinivasan, S. et al. Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. *Appl. Energy* **210**, 673–684 (2018).
27. [PIB] - Press Information Bureau. *MNRE - Year End Review - 2020*. https://pib.gov.in/Pressreleaseshare.aspx?PRID=1685046 (2020).
28. [MNRE] - Ministry of New and Renewable Energy. *State-wise Installed Capacity of Renewable Energy as on 31.08.2021*. https://mnre.gov.in/the-ministry/physical-progress (2021).
29. [GOI] - Government of India. *Report of the Expert Committee for Integrated Energy Policy*. https://niti.gov.in/planningcommission.gov.in/docs/reports/genrep/rep_intengy.pdf (2006).
30. Saraswat, S. K. & Digalwar, A. K. Empirical investigation and validation of sustainability indicators for the assessment of energy sources in India. *Renew. Sustain. Energy Rev.* **145**, 111156 (2021).
31. Child, M., Koskinen, O., Linnanen, L. & Breyer, C. Sustainability guardrails for energy scenarios of the global energy transition. *Renew. Sustain. Energy Rev.* **91**, 321–334 (2018).
32. Bistline, J. E. T. & Blanford, G. J. The role of the power sector in net-zero energy systems. *Energy Clim. Chang.* **2**, 100045 (2021).
33. TERI and Shell. *India: Transforming To A Net-Zero Emission Energy System*. https://www.teriin.org/sites/default/files/2021-03/India_Transforming_to_a_net-zero_emissions_energy_system.pdf (2021).
34. Jenkins, J. D., Luke, M. & Thernstrom, S. Getting to Zero Carbon Emissions in the Electric Power Sector. *Joule* **2**, 2498–2510 (2018).
35. Gambhir, A., Napp, T. A., Emmott, C. J. M. & Anandarajah, G. India's CO2 emissions pathways to 2050: Energy system, economic and

fossil fuel impacts with and without carbon permit trading. *Energy* **77**, 791–801 (2014).

36. Lawrenz, L. et al. Exploring energy pathways for the low-carbon transformation in India—a model-based analysis. *Energies* **11**, 3001 (2018).
37. Rose, A., Chernyakhovskiy, I., Palchak, D., Koebrich, S. & Joshi, M. Least-Cost Pathways for India's Electric Power Sector. 1–54 (2020).
38. NITI Aayog. *India Energy Security Scenarios 2014 Version 2.0*. http://iess2047.gov.in/ (2015).
39. Laha, P. & Chakraborty, B. Cost optimal combinations of storage technologies for maximizing renewable integration in Indian power system by 2040: Multi-region approach. *Renew. Energy* **179**, 233–247 (2021).
40. Lu, T. et al. India's potential for integrating solar and on- and offshore wind power into its energy system. *Nat. Commun.* **11**, 4750 (2020).
41. Das, S. *et al*. *The Energy Report - India 100% Renewable Energy by 2050*. http://awsassets.wwfindia.org/downloads/the_energy_report_india.pdf (2013).
42. Teske, S. *et al*. *Energy [r]evolution-A sustainable india energy outlook*. (2012).
43. Teske, S., Sawyer, S. & Schäfer, O. *energy [r]evolution: A Sustainable World Energy Outlook 2015*. https://www.greenpeace.org/static/planet4-canada-stateless/2018/06/Energy-Revolution-2015-Full.pdf (2015).
44. Jacobson, M. Z. Roadmaps to Transition Countries to 100% Clean, Renewable Energy for All Purposes to Curtail Global Warming, Air Pollution, and Energy Risk. *Earth's Futur.* **5**, 948–952 (2017).
45. Gulagi, A., Bogdanov, D. & Breyer, C. The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. *J. Energy Storage* **17**, 525–539 (2018).
46. Bogdanov, D. et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy* **227**, 120467 (2021).
47. Bogdanov, D. et al. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nat. Commun.* **10**, 1077 (2019).
48. Gulagi, A., Ram, M. & Breyer, C. Role of the transmission grid and solar wind complementarity in mitigating the monsoon effect in a fully sustainable electricity system for India. *IET Renew. Power Gener.* **14**, 254–262 (2020).
49. Gupta, U. *Indian developer signs PPA for 400 MW round-the-clock energy supply*. https://www.pv-magazine.com/2021/08/10/indian-developer-signs-ppa-for-400-mw-round-the-clock-energy-supply/ (2021).
50. Buckley, T. & Shah, K. *Pumped Hydro Storage in India*. https://ieefa.org/wp-content/uploads/2019/03/IEEFA-India_Pumped-Hydro-Storage_Mar-2019.pdf (2019).
51. Brown, T., Schlachtberger, D., Kies, A., Schramm, S. & Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* **160**, 720–739 (2018).
52. GSI. *India's Energy Transition: Mapping subsidies to fossil fuels and clean energy in India*. https://www.iisd.org/system/files/publications/india-energy-transition.pdf (2017).
53. Ram, M. et al. A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. *J. Clean. Prod.* **199**, 687–704 (2018).
54. Ram, M., Osorio-Aravena, J. C., Aghahosseini, A., Bogdanov, D. & Breyer, C. Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050. *Energy* **238**, 121690 (2022).
55. Brown, T. W. et al. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renew. Sustain. Energy Rev.* **92**, 834–847 (2018).
56. Hodge, B. M. S. et al. Addressing technical challenges in 100% variable inverter-based renewable energy power systems. *Wiley Interdisciplinary Reviews: Energy and Environment* https://doi.org/10.1002/wene.376 (2020).
57. Oyewo, A. S., Farfan, J., Peltoniemi, P. & Breyer, C. Repercussion of large scale hydro dam deployment: The case of congo Grand Inga hydro project. *Energies* https://doi.org/10.3390/en11040972 (2018).
58. Ershad, A. M., Ueckerdt, F., Pietzcker, R. C., Giannousakis, A. & Luderer, G. A further decline in battery storage costs can pave the way for a solar PV-dominated Indian power system. *Renew. Sustain. Energy Transit.* **1**, 100006 (2021).
59. Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C. & Breyer, C. Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nat. Energy* **4**, 1040–1048 (2019).
60. [PNAC] - Petroleum Planning & Analysis Cell. *Data for Crude and Products - Value in Dollars*. https://www.ppac.gov.in/content/212_1_ImportExport.aspx (2021).
61. Birol, F. *The coronavirus crisis reminds us that electricity is more indispensable than ever*. https://www.iea.org/commentaries/the-coronavirus-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever (2020).
62. Beyer, S. *India needs a resilient power sector: Lessons from the Covid-19 crisis*. https://www.iea.org/commentaries/india-needs-a-resilient-power-sector-lessons-from-the-covid-19-crisis (2020).
63. Elavarasan, R. M. et al. A Comprehensive Review on Renewable Energy Development, Challenges, and Policies of Leading Indian States with an International Perspective. *IEEE Access* https://doi.org/10.1109/ACCESS.2020.2988011 (2020).
64. Amrutha, A. A., Balachandra, P. & Mathirajan, M. Role of targeted policies in mainstreaming renewable energy in a resource constrained electricity system: A case study of Karnataka electricity system in India. *Energy Policy* **106**, 48–58 (2017).
65. [IEA] - International Energy Agency. *India Energy Outlook 2021*. https://www.iea.org/reports/india-energy-outlook-2021 (2021).
66. OECD. *Carbon pricing in India*. https://www.oecd.org/tax/tax-policy/carbon-pricing-india.pdf (2021).
67. [IEA]-International Energy Agency. *Renewable Energy Market Update 2021*. https://www.iea.org/reports/renewable-energy-market-update-2021 (2021).
68. Blakers, A., Stocks, M., Lu, B. & Cheng, C. The observed cost of high penetration solar and wind electricity. *Energy* **233**, 121150 (2021).
69. Energy and Climate Intelligence Unit. Net Zero Emission Race. https://eciu.net/netzerotracker (2021).
70. Oyewo, A. S., Aghahosseini, A., Ram, M. & Breyer, C. Transition towards decarbonised power systems and its socio-economic impacts in West Africa. *Renew. Energy* **154**, 1092–1112 (2020).
71. Barasa, M., Bogdanov, D., Oyewo, A. S. & Breyer, C. A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030. *Renew. Sustain. Energy Rev.* **92**, 440–457 (2018).
72. Gulagi, A., Choudhary, P., Bogdanov, D. & Breyer, C. Electricity system based on 100% renewable energy for India and SAARC. *PLoS One* **12**, e0180611 (2017).
73. Sadiqa, A., Gulagi, A. & Breyer, C. Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. *Energy* **147**, 518–533 (2018).
74. Gulagi, A., Ram, M., Solomon, A. A., Khan, M. & Breyer, C. Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. *Renew. Energy* **155**, 899–920 (2020).

75. Bogdanov, D., Gulagi, A., Fasihi, M. & Breyer, C. Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination. *Appl. Energy* **283**, 116273 (2021).
76. Bogdanov, D., Oyewo, A. S. & Breyer, C. Hierarchical approach to energy system modelling on the case of Japan. *Submitted* (2022).
77. Prina, M. G., Manzolini, G., Moser, D., Nastasi, B. & Sparber, W. Classification and challenges of bottom-up energy system models - A review. *Renew. Sustain. Energy Rev.* **129**, 109917 (2020).
78. Keiner, D., Ram, M., Barbosa, L. D. S. N. S., Bogdanov, D. & Breyer, C. Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050. *Sol. Energy* **185**, 406–423 (2019).
79. Jain, A., Das, P., Yamujala, S., Bhakar, R. & Mathur, J. Resource potential and variability assessment of solar and wind energy in India. *Energy* **211**, 118993 (2020).
80. Farfan, J. & Breyer, C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *J. Clean. Prod.* **141**, 370–384 (2017).
81. [IEA] - International Energy Agency. *India Energy Outlook 2015*. https://www.iea.org/reports/india-energy-outlook-2015 (2015).
82. Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D. & Breyer, C. Long term load projection in high resolution for all countries globally. *Int. J. Electr. Power Energy Syst.* **111**, 160–181 (2019).
83. [IRENA] - International Renewable Energy Agency. *Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf (2018).
84. Sadovskaia, K., Bogdanov, D., Honkapuro, S. & Breyer, C. Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally. *Int. J. Electr. Power Energy Syst.* **107**, 98–109 (2019).
85. Joshi, A. *Average Cost to Build Large-Scale Solar Projects Climbed by 23% YoY in Q3 2021*. https://mercomindia.com/average-cost-large-scale-solar-q3-2021/ (2021).
86. Wiser, R., Bolinger, M. & Seel, J. Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals. (2020).
87. Peters, I. M., Hauch, J., Brabec, C. & Sinha, P. The value of stability in photovoltaics. *Joule* **5**, 3137–3153 (2021).
88. Auroville Consulting. *Levelised Cost Of Behind-The-Meter Storage In India - A Status Report*. https://www.aurovilleconsulting.com/levelised-cost-of-btm-storage-2021/ (2021).
89. Breyer, C. & Gerlach, A. Global overview on grid-parity. *Prog. Photovoltaics: Res. Appl.* **21**, 121–136 (2013).
90. Eisentraut, A. & Brown, A. Technology Roadmap Bioenergy for Heat and Power. [IEA] - Int. *Energy Agency* 1–41 https://doi.org/10.1108/meq.2013.08324aaa.005 (2012).
91. Edenhofer, O. *et al. [IPCC] - International Panel on Climate Change, 2011: Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press* (2011). https://doi.org/10.5860/CHOICE.49-6309.
92. [BNEF] - Bloomberg New Energy Finance. *New Energy Outlook 2015 - Long-term projections of the global energy sector. Bloomberg New Energy Finance* https://doi.org/10.1017/CBO9781107415324.004 (2015).
93. Bogdanov, D. & Breyer, C. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. *Energy Convers. Manag.* **112**, 176–190 (2016).
94. Bolinger, M. & Bolinger, G. Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density. *IEEE J. Photovoltaics* https://doi.org/10.1109/JPHOTOV.2021.3136805 (2022).
95. Aghahosseini, A. & Breyer, C. From hot rock to useful energy: A global estimate of enhanced geothermal systems potential. *Appl. Energy* **279**, 115769 (2020).
96. Mensah, T. N. O., Oyewo, A. S. & Breyer, C. The role of biomass in sub-Saharan Africa's fully renewable power sector – The case of Ghana. *Renew. Energy* **173**, 297–317 (2021).
97. [CEA] - Central Electricity Authority. *Monthly Installed Capacities*. http://cea.nic.in/reports/monthly/installedcapacity/2019/installed_capacity-09.pdf (2019).
98. [ETIP-PV] - European Technology and Innovation Platform for Photovoltaics. *Photovoltaic Solar Energy: Big and Beyond: Sustainable Energy to Limit Global Warming to 1.5 degrees*. https://etip-pv.eu/publications/etip-pv-publications/ (2019).
99. Central Electricity Regulatory Commission. *Tariff Determination from Renewable Energy Sources - Regulations*. https://cercind.gov.in/2017/regulation/Noti131.pdf (2017).
100. Central Electricity Authority (CEA). *National Electrcity Plan*. http://www.cea.nic.in/reports/committee/nep/nep_jan_2018.pdf (2018).
101. Vartiainen, E., Masson, G., Breyer, C., Moser, D. & Román Medina, E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Prog. Photovolt. Res. Appl.* **28**, 439–453 (2020).
102. Bolinger, Mark; Seel, J. *Utility-Scale Solar 2015: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States. Lawrence Berkeley National Laboratory*. (2016).
103. European Commission. Joint Research Centre. Institute for Energy and Transport. & SERTIS. *Energy Technology Reference Indicator (ETRI) projections for 2010-2050*. (2014).
104. Central Electricity Authority (CEA). *DRAFT REPORT ON OPTIMAL GENERATION CAPACITY MIX FOR 2029-30*. (2019).
105. Koomey, J. & Hultman, N. E. A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. *Energy Policy* **35**, 5630–5642 (2007).
106. IEA. *World Energy Outlook*. https://www.iea.org/reports/world-energy-outlook-2017 (2017).
107. [IEA] - International Energy Agency and [NEA]-Nuclear Energy Agency. *Projected costs of generating electricity*. https://doi.org/10.1787/cost_electricity-2015-en (2015).
108. Central Electricity Regulatory Commission. *Tariff Regulations*. (2019).
109. Lazard. *Lazard's Levelised Cost of Energy Analysis (version 10.0)*. (2016).
110. Deutsches Institut für Wirtschaftsforschung. *Data documnetation: Current and Prospective Costs of Electricity Generation until 2050*. (2013).
111. Tongia, R. & Gross, S. *Coal in India -Adjusting to Transition*. (2019).
112. Government of India. *Indian Petroleum and Natural gas statistics*. (2017).
113. McKinsey. Unlocking gas potential - New business models. in Petrotech (2019).
114. [BNEF] - Bloomberg New Energy Finance. *New Energy Outlook 2019*. (2019).
115. CSIRO Division of Atmospheric Research. Lifecycle emissions and energy analysis of LNG, oil and coal. (1996).
116. Environmental Protection Agency. *Annexes to the Inventory of U.S. GHG Emissions and Sinks*. (2013).

Acknowledgements

The authors would like to thank their respective organisations for the general support to this research.

Author contributions

A.G. was responsible for data collection, methodology, simulation, results analysis, and writing, reviewing and editing original draft. M.R. was responsible for methodology, result analysis and reviewing and editing original draft. D.B. was responsible for model development, reviewing and editing original draft. S.S. contributed to methodology and reviewing and editing original draft. T.N.O.M. provided the biomass potential data. C.B. analysed the results, supervised, contributed to reviewing and editing original draft and coordinated the work.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-022-33048-8.

Correspondence and requests for materials should be addressed to Ashish Gulagi or Christian Breyer.

Peer review information *Nature Communications* thanks Rohit Bakhar, Auke Hoekstra, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

1029. RAM, MANISH. Socioeconomic impacts of cost optimised and climate compliant energy transitions across the world. 2022. Diss.

1030. AMADI, MIRACLE. Hybrid modelling methods for epidemiological studies. 2022. Diss.

1031. RAMÍREZ ANGEL, YENDERY. Water-energy nexus for waste minimisation in the mining industry. 2022. Diss.

1032. ZOLOTAREV, FEDOR. Computer vision for virtual sawing and timber tracing. 2022. Diss.

1033. NEPOVINNYKH, EKATERINA. Automatic image-based re-identification of ringed seals. 2022. Diss.

1034. ARAYA GÓMEZ, Natalia Andrea. Sustainable management of water and tailings in the mining industry. 2022. Diss.

1035. YAHYA, MANAL. Augmented reality based on human needs. 2022. Diss.

1036. KARUPPANNAN GOPALRAJ, SANKAR. Impacts of recycling carbon fibre and glass fibre as sustainable raw materials for thermosetting composites. 2022. Diss.

1037. UDOKWU, CHIBUZOR JOSEPH. A modelling approach for building blockchain applications that enables trustable inter-organizational collaborations. 2022. Diss.

1038. INGMAN, JONNY. Evaluation of failure mechanisms in electronics using X-ray imaging. 2022. Diss.

1039. LIPIÄINEN, SATU. The role of the forest industry in mitigating global change: towards energy efficient and low-carbon operation. 2022. Diss.

1040. AFKHAMI, SHAHRIAR. Laser powder-bed fusion of steels: case studies on microstructures, mechanical properties, and notch-load interactions. 2022. Diss.

1041. SHEVELEVA, NADEZHDA. NMR studies of functionalized peptide dendrimers. 2022. Diss.

1042. SOUSA DE SENA, ARTHUR. Intelligent reflecting surfaces and advanced multiple access techniques for multi-antenna wireless communication systems. 2022. Diss.

1043. MOLINARI, ANDREA. Integration between eLearning platforms and information systems: a new generation of tools for virtual communities. 2022. Diss.

1044. AGHAJANIAN, SOHEIL. Reactive crystallisation studies of $CaCO_3$ processing via a CO_2 capture process: real-time crystallisation monitoring, fault detection, and hydrodynamic modelling. 2022. Diss.

1045. RYYNÄNEN, MARKO. A forecasting model of packaging costs: case plain packaging. 2022. Diss.

1046. MAILAGAHA KUMBURE, MAHINDA. Novel fuzzy k-nearest neighbor methods for effective classification and regression. 2022. Diss.

1047. RUMKY, JANNATUL. Valorization of sludge materials after chemical and electrochemical treatment. 2022. Diss.

1048. KARJUNEN, HANNU. Analysis and design of carbon dioxide utilization systems and infrastructures. 2022. Diss.

1049. VEHMAANPERÄ, PAULA. Dissolution of magnetite and hematite in acid mixtures. 2022. Diss.

1050. GOLOVLEVA, MARIA. Numerical simulations of defect modeling in semiconductor radiation detectors. 2022. Diss.

1051. TREVES, LUKE. A connected future: The influence of the Internet of Things on business models and their innovation. 2022. Diss.

1052. TSERING, TENZIN. Research advancements and future needs of microplastic analytics: microplastics in the shore sediment of the freshwater sources of the Indian Himalaya. 2022. Diss.

1053. HOSEINPUR, FARHOOD. Towards security and resource efficiency in fog computing networks. 2022. Diss.

1054. MAKSIMOV, PAVEL. Methanol synthesis via CO2 hydrogenation in a periodically operated multifunctional reactor. 2022. Diss.

1055. LIPIÄINEN, KALLE. Fatigue performance and the effect of manufacturing quality on uncoated and hot-dip galvanized ultra-high-strength steel laser cut edges. 2022. Diss.

1056. MONTONEN, JAN-HENRI. Modeling and system analysis of electrically driven mechatronic systems. 2022. Diss.

1057. HAVUKAINEN, MINNA. Global climate as a commons — from decision making to climate actions in least developed countries. 2022. Diss.

1058. KHAN, MUSHAROF. Environmental impacts of the utilisation of challenging plastic-containing waste. 2022. Diss.

1059. RINTALA, VILLE. Coupling Monte Carlo neutronics with thermal hydraulics and fuel thermo-mechanics. 2022. Diss.

1060. LÄHDEAHO, OSKARI. Competitiveness through sustainability: Drivers for logistics industry transformation. 2022. Diss.

1061. ESKOLA, ROOPE. Value creation in manufacturing industry based on the simulation. 2022. Diss.

1062. MAKARAVA, IRYNA. Electrochemical recovery of rare-earth elements from NdFeB magnets. 2022. Diss.

1063. LUHAS, JUKKA. The interconnections of lock-in mechanisms in the forest-based bioeconomy transition towards sustainability. 2022. Diss.

1064. QIN, GUODONG. Research on key technologies of snake arm maintainers in extreme environments. 2022. Diss.

1065. TAMMINEN, JUSSI. Fast contact copper extraction. 2022. Diss.

1066. JANTUNEN, NIKLAS. Development of liquid–liquid extraction processes for concentrated hydrometallurgical solutions. 2022. Diss.

LUT
University

ISBN 978-952-335-916-1
ISBN 978-952-335-917-8 (PDF)
ISSN 1456-4491 (Print)
ISSN 2814-5518 (Online)
Lappeenranta 2023