Manish Ram

SOCIOECONOMIC IMPACTS OF COST OPTIMISED AND CLIMATE COMPLIANT ENERGY TRANSITIONS ACROSS THE WORLD

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 1029

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Abstract

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There are undeniable signs from all over the world demonstrating that climate change is already upon us. Numerous scientific studies have warned of dire consequences should humankind fail to keep average global temperatures from rising beyond 1.5°C. Drastic measures to eliminate greenhouse gas emissions from all economic activities across the world are essential. Major emphasis has been on the energy sector, which contributes the bulk of GHG emissions. Inevitably, energy scenarios describing future transition pathways towards low, and zero emissions energy systems are commonly proposed as mitigation strategies. However, there is growing awareness in the research community that energy transitions should be understood and analysed not only from technical and economical perspectives but also from a social perspective. This research explores the broader ramifications of a global energy transition from various dimensions: costs and externalities of energy production, democratisation of future energy systems and the role of prosumers, employment creation during energy transitions at the global, regional and national levels and the effects of air pollution during energy transitions across the world.

This research builds on fundamental techno-economic principles of energy systems and relies firmly on a cost driven rationale for determining cost optimal energy system transition pathways. Techno-economic analyses of energy transitions around the world are executed with the LUT Energy System Transition Model, while the corresponding socioeconomic aspects are expressed in terms of levelised cost of electricity, cost effective development of prosumers, job creation, and the reduction of greenhouse gas emissions along with air pollution.

Findings during the course of this original research involved novel assessments of the levelised cost of electricity encompassing externalities across G20 countries, cost optimal prosumer modelling across the world, estimates of job creation potential of various renewables, storage and power-to-X technologies including the production of green hydrogen and e-fuels during global, regional and national energy transitions. The novel research methods and insights are published in several articles and presented in this thesis, which highlight robust socioeconomic benefits of transitioning the current fossil fuels dominated global energy system towards renewables complemented by storage and flexible power-to-X solutions, resulting in near zero emissions of greenhouse gases and air pollutants. These research findings and insights have significant relevance to stakeholders across the energy landscape and present a compelling case for the rapid transformation of energy systems across the world. However, the research does have limitations and is based on energy transition pathways that are inherent with uncertainties and some socioeconomic challenges. Nonetheless, actions to enhance and accelerate the ongoing energy transition across the world must be prioritised, if not for technical feasibility or economic viability, but for the social wellbeing of human society and future generations.

Keywords: Energy transition, socioeconomic impacts, levelised cost of electricity, prosumers, employment, jobs, air pollution

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Evaluations of this dissertation by the pre-examiners has further enhanced the quality and scientific rigour. My sincere thanks to Professor Claudia Kemfert and Professor Neven Duić.

All my friends and family have encouraged and supported me through this journey, and I am ever grateful to each and every one of them, especially Dad, Mom and Sista.

Manish Ram
June 2022
Lappeenranta, Finland

This dissertation is dedicated to inspiring colleagues, daring activists, dedicated boffins and passionate folks striving relentlessly to make this planet a better place for all of us. May the science be with you!

Contents

List of publications

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

I. 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.org/10.1016/j.jclepro.2018.07.159

II. Keiner, D., Ram, M., Barbosa, L.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*, 185, pp. 405-423. doi.org/10.1016/j.solener.2019.04.081

III. Ram, M., Aghahosseini, A., and Breyer, C. (2020). Job creation during the global energy transition towards 100% renewable power system by 2050. *Technological Forecasting and Social Change*, 151, 119682. doi.org/10.1016/j.techfore.2019.06.008

IV. Ram, M., Osorio-Aravena, J.C., Aghahosseini, A., Bogdanov, D., and Breyer, C. (2022). Job creation during a climate compliant global energy transition towards 100% renewable energy across the power, heat, transport and desalination sectors by 2050. *Energy*, 238, 121690. doi.org/10.1016/j.energy.2021.121690

V. Oyewo, A.S., Aghahosseini, A., Ram, M., Lohrmann, A., and Breyer, C. (2019). Pathway towards achieving 100% renewable electricity by 2050 for South Africa. *Solar Energy*, 191, pp. 549-565. doi.org/10.1016/j.solener.2019.09.039

VI. Oyewo, A.S., Aghahosseini, A., Ram, M., and Breyer, C. (2020). Transition towards decarbonised power systems and its socioeconomic impacts in West Africa. *Renewable Energy*, 154, pp. 1092-1112. doi.org/10.1016/j.renene.2020.03.085

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

Author's contribution

Manish Ram is the main author and investigator in **Publications III and IV**. In **Publication I**, Michael Child carried out the analysis, and contributed to writing the article, Manish Ram framed and wrote the article and contributed to the data and analysis. In **Publication II**, Dominik Keiner contributed with the modelling and analysis and Manish Ram was the corresponding author with framing and writing the article. In **Publication V and VI**, Ayobami Solomon Oyewo carried out the research, including the development of methods, analysing the results and writing the manuscript, Manish Ram contributed with the sections on job creation, socioeconomic analysis and assisted in writing the articles.

Lists of all publications

All the publications during the course of this research are:

1. 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.org/10.1016/j.jclepro.2018.07.159
2. Keiner, D., Ram, M., Barbosa, L.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*, 185, pp. 405-423. doi.org/10.1016/j.solener.2019.04.081
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7. Ram, M., Child, M., Aghahosseini, A., Bogdanov, D., Lohrmann, A., and Breyer, C. (2020). Authors' reply to the letter to the editor: Response to '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*, 242, 118530. doi.org/10.1016/j.jclepro.2019.118530
8. Gulagi, A., Ram, M., and 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), pp. 254 – 262.

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9. Gulagi, A., Ram, M., Solomon, A.A., Khan, M., and Breyer, C. (2020). Current energy policies and possible transition scenarios adopting renewable energy: A case study for Bangladesh. *Renewable Energy*, 155, pp. 899-920. doi.org/10.1016/j.renene.2020.03.119
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11. Oyewo, A.S., Solomon, A.A., Bogdanov, D., Aghahosseini, A., Mensah, T.N.O., Ram, M., and Breyer, C. (2021). Just transition towards defossilised energy systems for developing economies: A case study of Ethiopia. *Renewable Energy*, 176, pp. 346-365. doi.org/10.1016/j.renene.2021.05.029
12. Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L.S.N.S., Fasihi, M., Khalili, S., Traber, T., and Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, *Energy*, 227, 120467. doi.org/10.1016/j.energy.2021.120467
13. Ram, M., Bogdanov, D., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L.S.N.S., Fasihi, M., Khalili, S., Traber, T., and 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, 123419. doi.org/10.1016/j.energy.2022.123419

Nomenclature

Abbreviations

A-CAES	Adiabatic Compressed Air Energy Storage
ATCE	Annual Total Cost of Energy
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BPS	Best Policy Scenario
CAPEX	Capital Expenditure
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
COP	Coefficient of Performance
CPS	Current Policy Scenario
CHP	Combine Heat and Power
CSP	Concentrated Solar Thermal Power
DACCS	Direct Air Carbon Capture and Storage
DCR	Demand Cover Ratio
DHW	Domestic Hot Water
DoD	Depth of Discharge
DSC	Direct Self-Consumption
ECOWAS	Economic Community of West African States
ESM	Energy System Model
EU	European Union
FIT	Feed-in-tariff
FLH	Full Load Hour
G20	Group of Twenty
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HC	Heating Cartridge
HCR	Heat Cover Ratio
HP	Heat Pump
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
LUT	Lappeenranta-Lahti University of Technology LUT
MSW	Municipal Solid Waste
OPEX	Operational Expenditure
P2P	Peer-to-Peer

PHES	Pumped Hydro Energy Storage
Pph	People per household
PtX	Power-to-X
PtG	Power-to-Gas
PV	Photovoltaic
RE	Renewable Energy
SCOP	Seasonal Coefficient of Performance
SCR	Self-Consumption Ratio
SDGs	Sustainable Development Goals
SH	Space Heating
SHS	Solar Home System
SoC	State of Charge
SSA	Sub-Saharan Africa
TES	Thermal Energy Storage
UN	United Nations
USD	United States Dollar
VRE	Variable Renewable Energy
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
WACC	Weighted Average Cost of Capital

1 Introduction

1.1 Climate change driven energy transitions

Climate change has evolved over the years from being percived as rather pernicious to now an imminent existential threat. Continued dependence of modern human society on fossil fuels is warming the planet at a unprecedented pace that has not been witnessed in the past 2,000 years and its effects are already apparent, as record wildfires, droughts, and floods devastate communities around the world (Tollefson, 2021). These are just some of the events from different parts of the world and yet provide extremely alarming and painful reminders of just how devastating climate change could be, with warming of just 1°C above pre-industrial levels. For many years, limiting average global temperature rise to no more than 2°C above preindustrial levels was the defacto target for global policymakers. However, ensuing evidence has warned that the 2ºC limit is not adequate for avoiding some of the more severe longterm impacts of climate change (IPCC, 2018). Evidently, the 6th Assessment Report (IPCC, 2021) has further stressed that unless there are immediate, rapid and significant reductions in greenhouse gas (GHG) emissions, limiting warming to close to 1.5°C or even 2°C could be beyond reach. At the centre of this climate conundrum is the imprudent nature of producing and consuming energy that is still persistent around the world.

Global energy consumption is by far the largest source of human-induced GHG emissions, responsible for the majority with 76% (37.2 $GtCO_{2eq}$) of worldwide emissions in 2018 (WRI, 2021). The energy sector includes electricity and heat, transportation, buildings, manufacturing and construction, fugitive emissions and the combustion of other fuels. Figure 1 offers a comprehensive view of global GHG emissions and further identifies various sources and activities across the global economy that produce GHG emissions, as well as the type and share of gases associated with each activity. Other key sectors that produce GHG emissions are agriculture, with activities such as livestock and crop cultivation along with the rampant use of chemical fertilizers emitting 12% (5.8 $GtCO_{2eq}$) and also significant quantities of nitrous oxides; industrial processes of chemicals, cement and more contributing 5.9% (2.9 $GtCO_{2eq}$); waste, including landfills and wastewater emitting 3.3% (1.6 $GtCO_{2eq}$); and land use, land use change and forestry, including deforestation activities contributing 2.8% (1.4 $GtCO_{2eq}$) of total emissions in 2018 (WRI, 2021). It is evident that the energy sector is the prime contributor to growing GHG emissions. Wherein, generation of electricity and heat is responsible for most of the GHG emissions with around 32% (15.6 $GtCO_{2eq}$), followed by transportation emitting about 14.2% (6.9 $GtCO_{2eq}$) and manufacturing and construction activities contributing to 12.6% (6.2 $GtCO_{2eq}$) of the total emissions in 2018 (WRI, 2021).

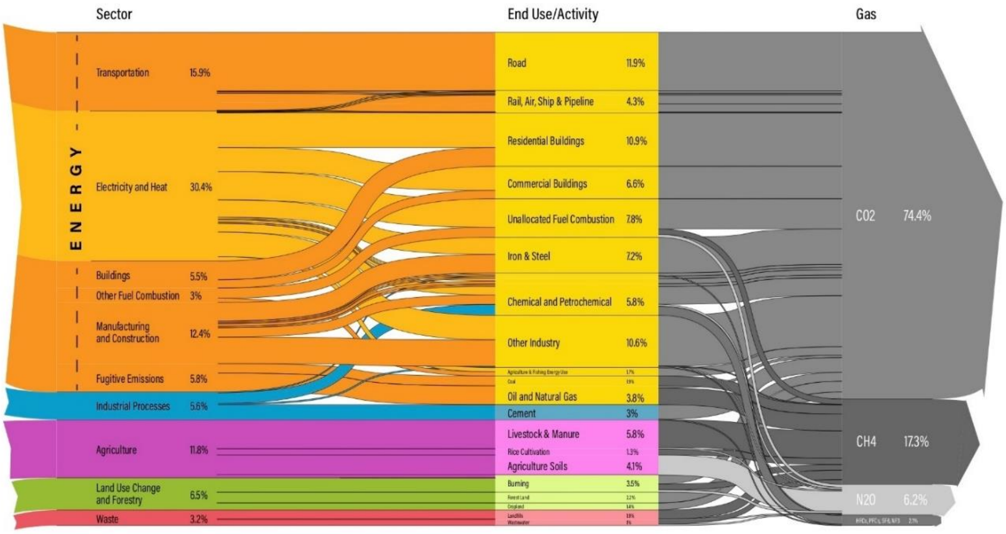

Figure 1: Global GHG emissions across the various sources and end use activities. Adopted from Climate Watch platform (WRI, 2021).

Consumption of energy and fossil fuels have intrinsically grown rapidly in the last few decades. With the global population swelling and rampant industrialisation in emerging and developing nations, the appetite for energy remains unquenched. The burgeoning demand for energy and a tenacious addiction to fossil fuels leaves the global society in a precarious position. Balancing global aspirations with energy resources from a broader alternative mix is a critical element of limiting the impacts of runaway climate change. Although the change to sustainable sources of energy cannot be done at the 'flick of a switch', it is rather an evolutionary energy transition that is already well underway. It is also imperative that over 750 million unelectrified people across the world (IEA et al., 2021) get access to modern electricity supply in a sustainable manner. Developments in renewable energy technologies are driving sustainable development across the world (Østergaard et al., 2020a, 2020b) and are expected to play a vital role in ensuring access to modern and sustainable electricity to all.

The total final energy consumption (TFEC) across the world was around 115,579 TWh (9938 Mtoe) in 2020 (IEA, 2020a). As shown in Figure 2, transport is responsible for the bulk of the energy consumption with 51%, heat and power generation consume 32% and 17% of the TFEC respectively. The share of renewables in TFEC has been growing steadily with around 10% in 2020, whereas fossil fuels still dominate the TFEC with over

80%. Clearly, the transition needs to gather steam and a rapid shift towards renewables across all sectors will be required. The glimmer of hope is from the global power sector, wherein renewable electricity generation has been gaining pace and has reached over 27% of total electricity production by end of 2020.

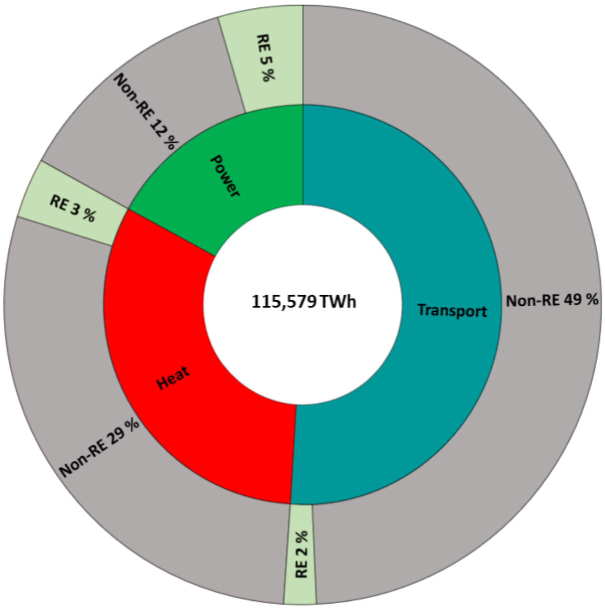

Figure 2: Global final energy consumption across the different sectors and corresponding shares of renewable and non-renewable energy. Data sourced from IEA (IEA, 2021a) and REN21 (REN21, 2021).

Despite the COVID-19 pandemic induced disruptions in the development of the global energy sector, renewable energy set a record in new power capacity addition with 256 GW in 2020 (REN21, 2021) and was the only source of electricity generation to register a net increase in total capacity. In total, renewable power generation capacity has grown globally to over 2800 GW by the end of 2020 (REN21, 2021). Wind and solar photovoltaics (PV) have been growing significantly in the last decade and have reached over 740 GW (GWEC, 2021) and 760 GW (IEA-PVPS, 2021) respectively, in terms of total installed capacities worldwide in 2020. In terms of investments in low carbon energy infrastructure, the largest sector in 2020 was renewable energy based power capacity additions, which attracted 303.5 billion USD for new projects and small-scale systems (BNEF, 2021). One of the key factors driving this booming capacity additions of renewable power is the costs. Renewable electricity generation costs have fallen steeply over the past decade, enabled by continuously improving technologies, economies of scale, competitive production and supply chains, improving speed of installations and developer experience and overall public acceptance. Costs for electricity from utility-scale solar PV fell 85%, wind onshore fell 56% and wind offshore fell 48% between 2010 and 2020 (IRENA, 2020a). Furthermore, newly built solar PV and wind power projects are not only competitive but also increasingly undercutting even the cheapest fossil fuelled power plants (mainly coal, natural gas and nuclear). Currently, over 77% of the global coal operating fleet is at higher costs than new renewables (Carbon Tracker, 2021). It is rather apparent that in the new normal for energy development with limited global carbon budgets, the relative competitiveness of renewables versus fossil fuels is rapidly gaining ground. Moreover, with more stringent climate regulations expected in the near future, there is little room for fossil fuels to continue operating.

Pathways limiting global average rise in temperature to 1.5°C necessitate rapid and far-reaching transitions in energy, land use, urban infrastructure (including transport and buildings), and industrial sectors (IPCC, 2018). These systems transitions will be unprecedented in terms of scale, but not necessarily in ambition; however, it entails deep emissions reductions across all energy sectors. A broad portfolio of mitigation options with significant upscaling of investments is a prerequisite. Integrated Assessment Models (IAMs) that integrate socioeconomic, energy-technical and climate systems to investigate how different assumptions about future developments and trends will influence mitigation options play a vital role in informing global decision making. While all IAMs incorporate continued progress in energy intensity of economic development into their model structures, primary energy demand and electrification of energy services is a crucial aspect to be considered. There are a few pathways with low energy demand development mapping potential technological transformation, but predominantly from energy efficiency and demand side perspectives. However, Bogdanov et al., (2021) have highlighted a high electrification scenario as both benefiting and enabling the overall energy transition. IAM pathways are generally more pessimistic in the projections of GHG emissions and carbon intensity reductions of the transport and industrial sectors. This certainly poses pertinent challenges and points to considerations of rapid growth in electric vehicle sales (IEA, 2020b), and more attention towards structural changes in this sector. Development of storage technologies, sector coupling, and flexible energy systems are rapidly changing the dynamics of the entire energy system (Østergaard et al., 2021) along with the production of green hydrogen, e-fuels and e-chemicals (Ram et al., 2020). Very few of the mitigation pathways assessed by the International Panel on Climate Change (IPCC) have considered these solutions in a comprehensive manner (IPCC, 2018). One of the fundamental challenges with the IAMs is their lack of capturing current market based cost trends of key energy technologies, in particular solar PV and battery storage technologies, which calls for adopting and upgrading to advanced tools by the IPCC. Creutzig et al., (2017) have very clearly pointed out the significant underestimation of the role of solar PV as an effective climate mitigation solution, which is further substantiated by recent research (Jaxa-Rozen and Trutnevyte, 2021; Victoria et al., 2021; Xiao et al., 2021). The least cost source of energy in the 21st century is practically missing from the solutions space of the IAMs, which is a result of the unreasonable PV costs in 2050 that are around 3-4 times higher in IAMs than in realistic projections (Vartiainen et al., 2020). For example, the IAM assumptions for solar PV costs in 2050 are over twice the current costs in India, which is a fundamental flaw. Even the International Energy Agency (IEA) has acknowledged that electricity costs form solar PV are the most competitive in many parts of the world, currently and even more so in the future (IEA, 2020c). Consequently, flexible technologies such as Power-to-X solutions are missing in the IAMs, while fossil fuels based carbon capture and storage, bioenergy with carbon capture and storage along with nuclear are considered as viable climate mitigation options. However, real potential of renewables is much higher than the projections shown in IPCC scenario analyses (ranging from 70-85 % of renewable electricity by 2050), as the models (IPCC, 2018) they are based on are failing to capture the true pace and nature of this transformation. Whereas numerous sectoral, regional and global studies find potential for scaling up to 100% renewable energy quite feasible (Bogdanov et al., 2021; Breyer et al., 2021; CAT, 2018; Jacobson et al., 2019; Löffler et al., 2017; Teske, 2019).

Mitigation pathways generally fail to account for negative externalities created by the consumption of fossil fuels, beyond the impacts of climate change, as highlighted by the growing menace of air pollution across the major cities of the world. Internalising, or taking fully into account, the health impacts of fossil fuel combustion as well as other socioeconomic benefits in energy transition pathways and cost analyses could provide more socially relevant insights. Contextually, this research thesis explores the socioeconomic dynamics of climate compliant energy transitions by further investigating the aspects of costs of energy generation across technologies with emphasis on externalities and their social implications, particularly across G20 countries; the role of solar PV prosumers in enabling decentralised and democratised energy systems across the world; employment generation from the power sector as well as all energy sectors through transition pathways in countries, regions and the world towards zero emissions, which is a vital socioeconomic indicator; discussing air pollution, corresponding health impacts and economic repercussions during energy transition pathways towards zero emissions across the world. On the whole, this research thesis presents comprehensive analyses beyond the usual technical-costs oriented exposition and embeds climate compliant energy transitions within a socioeconomic elucidation.

1.2 Socioeconomic dimensions of energy transitions

The ways in which societies produce and consume energy have continually changed over the course of human history, are changing currently, and certainly will continue to change in the future. These long-term energy transitions are often shaped by economic development, technological disruptions, and evolving policies among other factors (Cherp et al., 2018). In recent times, energy systems are often treated as self-contained systems, which are usually disconnected from the fundamental socioeconomic structures that they are built upon. Therefore, cognisance of enabling environments and structural elements will help maximise the benefits of energy transitions, further discern potential barriers and inform necessary remedies to be pursued for sustainable development around the world (Duić et al., 2015; Garcia-Casals et al., 2019). This research aims to further dwell into socioeconomic aspects that substantially influence socio-political decisions shaping energy pathways around the world.

This research builds on the concepts of identifying and demarcating planetary boundaries (Steffen et al., 2015), pursuing new consciousness driven sustainable energy transitions interlinked with societal wellbeing (Breyer et al., 2017) and acknowledging perpetual sustainability guardrails (Child et al., 2018). The framing of this research is highlighted in Figure 3, wherein a highly electrified energy transition towards complete sustainability is at the heart of climate mitigation and crucial to balancing economical and societal interactions with ecological facets that ensure sustained harmony of the planet. The power system is undergoing a rapid transition towards renewable sources, which in turn drives the transition across all energy sectors (including heat, transport and industry). This has economic, social and ecological consequences. It is evident from previous research (Breyer et al., 2017b; Greim et al., 2020; Junne et al., 2020) that there could be some challenges with resource availability, however there should not be any major technical limits to enable a global energy supply that is entirely based on renewables, rather the limitations are in policy making and political will. It has to be acknowledged that additional efforts in advancing material circularity concepts with increase in recovery rates are needed along with the promotion of urban mining and waste recycling, as resources on planet Earth are eventually finite (Valero et al., 2021). Even with the consideration of resources available in the solar system that are in the vicinity of the planet Earth, current economic growth could lead to the exhaustion of these in a few centuries as estimated for the case of iron resources within the solar system (Elvis and Milligan, 2019). Socioeconomic benefits of transitioning to sustainable energy systems can drive societal stance exerting political impetus on climate mitigation. This research explores, quantifies, analyses and comprehensively presents the socioeconomic benefits of energy transitions towards complete sustainability across the world.

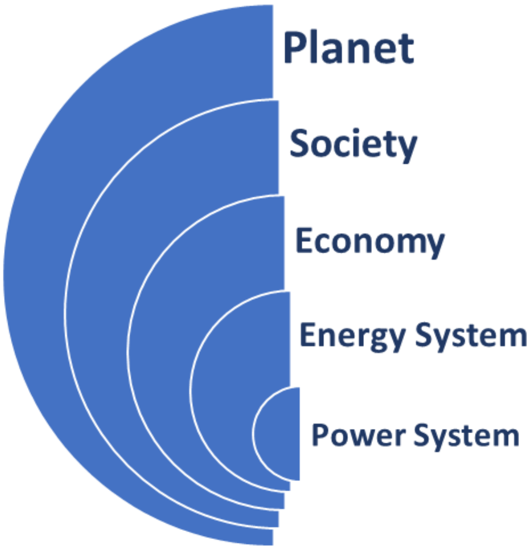

Figure 3: Research framework assessing highly electrified energy system transitions and corresponding socioeconomic aspects within ecological and planetary confines.

Currently, countries around the world are pursuing growth driven socioeconomic development, wherein costs are a critical factor in shaping developmental agendas. Similarly, energy costs are a vital factor in determining energy choices and planning across most countries of the world, more so in developed economies where levelised cost of energy has a significant bearing on deciding the energy mix (Hansen, 2019). Thereby, this research estimated and analysed the levelised cost of electricity (LCOE) of key energy generation technologies across G20 countries in 2015 and 2030, further juxtaposing LCOE from renewables and LCOE from fossil fuels and nuclear energy. In addition, externalities representing social and environmental costs that are induced by different energy technologies are estimated and internalised with the LCOE, as highlighted in **Publication I**.

The energy transition is enabled not only by the switch to renewables but also by systemic disruptions with increasing digitisation, decentralisation, and democratisation of the energy system (Pfenninger et al., 2014). The power system is rapidly transitioning away from fossil fuels and large thermal power plants towards a flexible system based on decentralised renewable energy and storage technologies. Conventional transmission and distribution grids are being upended by smart and intelligent grids enabled by digitalisation that complements bi-directional flows of electricity for the benefit of end users. At the consumption end, smart energy meters, energy monitoring devices and digital applications, along with renewable energy technologies, particularly solar PV complemented with battery storage empower energy consumers to evolve into prosumers: the producers as well as consumers of energy (Kotilainen, 2020). These prosumers, also referred to as active consumers and energy citizens, are envisioned to play an enabling role in the transition towards a sustainable energy future (Child et al., 2020). Prosumer driven systems offer democratic energy choices across society and enable active societal participation in energy transitions across the world. In this context, this research assessed cost optimal potential of solar PV prosumers across the world, as presented in **Publication II**.

Jobs are fundamental for achieving economic as well as social development, in the process contributing to broader societal goals of poverty alleviation, increasing welfare and social cohesion in every country of the world. Beyond the obvious relevance of jobs for individuals and families, jobs are critical in sharing knowledge and skills, as well as to pursue and realise equality around the world. With contributions to establishing well-functioning economies and enhancing societal stability, jobs are of critical interest to policy makers and governments around the world. Employment creation is a top concern for policy makers particular in the context of energy transitions (IRENA, 2020b). Pertinent questions of where will jobs be gained, and where will they be lost? And how will this affect the wider economy and communities that rely on these jobs? A key pillar of this research is understanding the trends in energy employment that are already underway in many regions around the world, assessing and quantifying future employment generation from transitioning to sustainable energy systems across countries, regions and the world, which are highlighted in **Publications III – VI**.

There is unequivocal scientific evidence that air pollution harms health across entire lifespans of people. It causes and aggravates diseases, leads to disabilities and even death, and impairs people’s quality of life (K, 2019; Tong, 2019). More specifically, it damages brains, skin, lungs, hearts and other vital organs; increasing the risk of diseases and disabilities, affecting almost the entire human body (Science of South Africa et al., 2019). From an economic perspective, costs of air pollution from fossil fuels were estimated to be around 2.9 trillion USD in 2018 (CREA, 2020). This translates to about 3.3% of the global GDP, far exceeding the likely costs of rapid reductions in the consumption of fossil fuels (CREA, 2020). In 2018, 4.5 million people were estimated to have died of exposure to air pollution from fossil fuels and on average, each of the deaths was associated with an approximate loss of 19 years of life (CREA, 2020). It is evident that there are massive social, health and economic benefits of reducing air pollution, which are estimated in various research studies (Galimova et al., 2022; Garcia-Casals et al., 2019; Jacobson, 2017).

1.3 Scope, objectives and limitations of the research

The overall scope of this research is to assess socioeconomic impacts, both quantitatively and comprehensively across energy technologies and the corresponding transition towards high levels of sustainability. Firstly, underpinning the economics of energy generation from various technologies with estimating LCOE across the G20 countries including considerations of externalities in 2015 and 2030. Secondly, probing the decentralised and democratised proposition of solar PV prosumers with a cost optimal longterm assessment of a combination of PV prosumer households (with solar PV systems and heat pumps, battery and heat storages and a couple of battery electric vehicles) across different countries and regions of the world. Thirdly, developing methods to estimate net employment effects of various energy technologies during energy transitions across the power sectors of South Africa, West Africa and the world. Further, advancing the methods to estimate jobs across the other energy sectors including heat, transport and industry including energy demand for desalinated water. Lastly, air pollution and corresponding health and economic impacts across the various regions of the world during energy transitions towards high levels of sustainability are discussed.

Specific research objectives are:

- Energy costs are a vital indicator for governments and energy planners around the world to make informed decisions, hence, the research presented in **Publication I** analyses the costs of electricity generation across the G20 countries in 2015 and from a future perspective for 2030. It involves determining the LCOE for different electricity generation and storage technologies for all the G20 member countries in 2015 and in 2030. It also considers the impacts of externalities such as, additional GHG emissions costs, health induced costs amongst other adverse societal costs including the subsidies on the levelised costs of electricity generation across the G20 countries.

- The modularity of solar PV systems has propelled a disruptive shift towards decentralised prosumerism, with increasing residential household participation across the world. A combination of solar PV, batteries, heat pumps (HP), thermal energy storage (TES) and battery electric vehicles (BEVs) in a residential household based energy system is rapidly emerging as an effective option to meet the energy demand at the household level. In this regard, the research presented in **Publication II** explores various settings along with different scenarios that constitute the basis for a cost optimal self-consuming sustainable household. Therefore, creating a solar PV prosumer model that optimises energy usage and annual energy costs of representative average residential households located across the different regions of the world.

- Apart from reducing the negative effects of the energy sector on the environment, renewable electricity generation technologies are enabling wealth creation and evolving into an important job creating sector in the 21st century. Net employment creation or loss induced by energy transitions are vital social indicators that effectuate policy ramifications worldwide. The research presented in **Publication III** focuses on net employment effects of an accelerated uptake of renewable electricity generation across the power sectors of nine major regions across the world that derives 100% of its electricity from renewable energy sources in 2050. An analytical net employment and job creation assessment for the global power sector is presented on a regional basis across nine major regions during the transition from 2015 to 2050. Taking forward the hypothesis, the research presented in **Publication IV** evaluates the socioeconomic impacts from transitioning to a completely sustainable future powered with renewables and complementary energy technologies. Thereby estimating the net employment effects of 100% renewable energy supply to the global energy sector comprising energy demand from the power, heat, transport and desalination sectors in a high electrification scenario. The analysis covered the world structured in nine major regions based on 145 regions during a global energy transition from 2020 to 2050. The proposition of employment creation is particularly of high relevance in developing countries and regions. Therefore, comprehensive job creation assessments for best policy scenarios, representing rapid cost optimal energy transitions to high shares of renewable electricity and current policy scenarios, representing legacy policies resulting in obtuse transitions with high costs and emissions are researched in **Publication V** for South Africa and in **Publication VI** for West Africa. The comprehensive research highlighted in **Publications III to VI** presents valuable insights regarding the employment impacts of a diverse set of energy technologies including energy generation, storage, fuel production, and transmission and distribution across the value chain.

- Rampant use of pollutant emitting fossil fuels subjects' vulnerable populations to even higher levels of exposure to toxic pollution, most predominant in the urban centres of the world. This has significant impacts on health of societies and bears high costs on economies with increased health expenditures and reduced productivity. On the contrary, in regions and countries where renewable energy installations have grown substantially are witnessing the benefits of cleaner air with reduced levels of pollution. Apparently, mitigating climate change and reducing air pollution have the same goal of enabling sustainable development across the world. Hence, air pollution, induced health impacts and corresponding damage costs are discussed extensively.

Despite comprehensive assessments of socioeconomic aspects that are intrinsically linked with energy transitions across the different regions and countries of the world, there are some limitations in this research. Determining social and environmental costs are challenging and often subject to circumspect in the context of conventional economic thinking, wherein costs are influenced by demand and supply of products, goods and services and not on the social and environmental consequences of producing these. Technological disruptions are sometimes unpredictable and diffusion of these could be much faster or slower than empirical evidence. This research is limited to assessing impacts of costs and corresponding externalities, increased decentralisation, net employment impacts and discussing air pollution impacts of energy transitions, however, not much has been covered on the impact of water, material criticality and other resources. **Publication V** explores the water-energy nexus in the context of the transition in the South African power sector and other research has explored this on the global scale (Lohrmann et al., 2019) and from an European perspective (Lohrmann et al., 2021). Inclusion of water availability as a socioeconomic parameter is necessary, especially for assessing impacts in water stressed regions around the world. Additionally, in depth analyses on sustainability of materials to drive energy transitions around the world could help strengthen socioeconomic assessments further.

Some of the specific limitations of this research are:

- Estimating social and environmental costs associated with energy generation is a near impossible task, which often leads to confusions and objections. Measuring the full socioeconomic impacts of emissions (GHG and others) is inherently flawed and thus subject to debate and interpretations. The range of impacts and effects included or excluded in cost estimations play a vital role. It could be argued that these costs are rather conservative in **Publication I**, which in turn builds a more viable case for accelerating the transition to renewables even further.

- Growth of solar PV prosumers around the world is greatly influenced by local market conditions and retail prices of electricity. Residential household conditions vary drastically within countries as well as across different countries and regions of the world. While **Publication II** considers representative household characteristics across the different regions of the world for a global assessment of cost optimal potential of prosumers, it could be suggested that more local assessments capturing local factors are required in the case of prosumers.

Furthermore, recent developments enable potential seasonal storage at the household level with small scale electrolysers, hydrogen storage and fuel cells, which need to be comprehensively analysed, while economic benefits at the household level may be challenging in comparison to large-scale industrial installations.

- Direct energy jobs and net employment impacts of energy transitions are comprehensively presented across the **Publications III to VI**. However, uncertainties do persist, and challenges of factoring technological megatrends raise pertinent questions. Estimating the range of disruption caused by autonomous technologies, resulting impacts on jobs and varying penetration levels across the different regions of the world could have significant repercussions for society as a whole, including energy transitions to higher shares of renewables.

- Like issues in **Publication I**, estimating air pollution levels and the corresponding health and economic impacts pose challenging questions and varying interpretations. Placing a value on life lost and loss of productivity is near impossible. However, these are pertinent aspects of the energy transition and thereby discussed in this research.

In spite of these limitations, the results of the research presented in **Publications I to VI** overwhelmingly confer the immense socioeconomic benefits of transitioning rapidly towards energy systems entirely powered by renewables and other complementary technologies across the world.

1.4 Contributions and novelty of the research

This research has extensively and comprehensively assessed the socioeconomic benefits of various energy technologies and across a range of transition scenarios in countries, regions and worldwide. Furthermore, novel and original research insights are presented and highlighted across the **Publications I to VI**. These were enabled by unique features of the global-local LUT Energy System Transition Model (Bogdanov et al., 2021; 2019), which has capabilities of enabling in-depth analyses of energy transition scenarios around the world in high temporal (hourly) and geospatial (145 regions) resolutions.

Some of the key novelties are:

- **Publication I** conducted novel research that estimated LCOE (with and without external costs including GHG emissions costs) for the most relevant electricity generation and storage technologies for individual G20 countries from the recent past (2015) and in the future (2030). Furthermore, illustrating comparative analyses between the costs of renewable electricity generation combined with storage, and the costs of electricity from fossil fuels and nuclear sources.

- **Publication II** is a novel research attempt to evaluate the potential of solar PV prosumers with a suite of complementary solutions covering residential household energy demands across the world in the most cost optimal manner. Moreover, the study presented an innovative solar PV prosumer model that optimises energy generation and consumption based on the annual energy costs incurred by average residential households across the different regions of the world.

- **Publication III** is the foremost research to quantify and present the job creation potential across various storage technologies in a global transition to 100% renewable power. Similarly, **Publication IV** is the foremost research to quantify and present job creation potential across different power-to-X technologies including green hydrogen and e-fuels production. **Publications V and VI** present unique comparitive analyses of job creation in best policies and current policies driven energy transitions, for the case of South Africa and West Africa respectively.

1.5 Overview of the structure

The thesis is structured as follows: **Chapter 1** of this thesis contextualises, states the objectives and scope, and further elaborates contributions of this research. The different dimensions and the corresponding implications on the research are presented in **chapter 2**. **Chapter 3** presents the applied methods, introduces the modelling, assessment and analysis tools and describes the main assumptions in the research. Key findings and results from the publications that comprise this thesis are presented in **chapter 4**. **Chapter 5** discusses the results and broader implications of the research. Conclusions are drawn in **Chapter 6**. References and the original publications that comprise this thesis are included at the end.

2 Socioeconomic parameters

Energy transitions taking place around the world cannot be considered in isolation from socioeconomic systems in which they are embedded. Interdependencies between the energy sector and social, ecological as well as economic systems alter the socioeconomic footprint (Garcia-Casals et al., 2019) and generate impacts that influence the GDP, employment rates, sustainability and human welfare across the world. Thus, in order to identify technically feasible, economically viable, socially equitable and ecologically sustainable transition pathways, the coupling of techno- and socioeconomic perspectives is vital. This research evaluates energy technologies and energy transitions with key socioeconomic parameters: levelised cost of electricity with externalities, solar PV prosumers driving systemic disruptions with decentralisation and democratisation of energy, net employment effects of national, regional and global energy transitions and discusses corresponding GHG emissions and air pollution impacts.

2.1 Levelised cost of electricity with externalities

Despite the propitious momentum achieved by increasing renewable energy deployment in recent years, substantial challenges and barriers persist that need to be considered by the global community. One such issue that is rather pressing is detrimental externalities of electricity generation, mainly from fossil fuels and nuclear sources. The ideal parameter to compare costs of electricity production across various technologies is LCOE, but conventionally externalities induced costs (comprising social and environmental costs) have been neglected in estimating LCOE of various electricity generation technologies. Furthermore, as LCOE is a vital indicator for policy and regulatory decision making, it is necessary to juxtapose actual costs of renewable electricity and storage technologies against conventional electricity generation technologies.

Generally, LCOE is defined as the estimated cost incurred by a particular power plant to generate a standard quantity of electricity (kWh or MWh) over its technical lifetime. Despite all the critiques of LCOE as a tool for comparing energy costs across electricity generation technologies, such as Hirth et al. (2015), Schmalensee (2016) and Synapse Energy Economics (2016) and others. LCOE remains a robust tool, as it offers several advantages of a cost metric, with its ability to normalise costs into a consistent structure across decades and technology types for enhanced comparison. Moreover, in the context of renewable electricity generation, costs are substantially influenced by different policies and market structures (Brown and Reichenberg, 2021). Additionally, LCOE provides ample flexibility allowing incorporation of many factors and parameters that provide comprehensive and detailed cost perspectives. Consequently, it has emerged as the de-facto standard for energy cost comparisons amongst several stakeholders including policymakers, practitioners, analysts, and advocacy groups (Rhodes et al., 2017).

Even though LCOE is a well-developed and standard technique in evaluating energy sector economics, there persists various approaches to model formulation, so as to ensure the model fulfils research objectives and data availability (Foster et al., 2014). Previously, there have been efforts to comprehensively integrate external costs in the form of social and environmental costs of electricity generation as part of LCOE estimations, some adopt interesting approaches such as in Rhodes et al. (2017), wherein a geographically resolved method to calculate LCOE of new power plants on an individual county basis is adopted, while including estimates for some environmental externalities across the USA. Küchler and Meyer (2012) estimate the full cost of electricity generation and systematically compare the state subsidies for conventional (nuclear, hard coal, and lignite) with those for renewables across Germany. In addition, Siemens Wind Power (2014) showcases LCOE, which includes societal and economic benefits for the different electricity generation technologies across the UK and Germany. These studies comprehensively address the aspects of externalities in electricity generation costs from national perspectives, however, there is still a necessity for a broader global context to inform policy discourse. In this regard, findings of **Publication I** highlight the LCOE of key electricity generation technologies across the G20 member countries with and without the consideration of external and GHG emissions costs. Most LCOE estimations lack in assessing long term perspectives of cost development that can assist developing plans and agendas.

In order to compare annualised costs of electricity generation form the different energy technologies on an equal footing, LCOE estimations are often employed (Short et al., 1995). LCOE estimation includes all costs of constructing, installing and operating a power plant in relation to the electricity generation over its technical lifetime. Costs associated with the transmission and distribution of electricity are not usually included in plant level LCOE estimations. Invariably, socioeconomic and ecological externalities are often excluded in LCOE estimations beyond the consideration of market prices of CO_2 emissions. However, the analysis presented in **Publication I** attempts to include the full costs of electricity generation by internalising them as justifiably as possible. In this context, a wider range of electricity costs both upstream and downstream from power plants are estimated to depict a more accurate representation of the full costs of electricity generation. These include costs related to the effects on human health, the environment, global warming or climate change, waste disposal and long-term management, power plant decommissioning, financing and budget overruns.

LCOE estimations merely depict the overnight costs of power plants in most cases, which do not fully indicate the true costs and differ significantly from originally planned and budgeted costs. Since the financing of power plant construction may occur over many years and there could be significant delays and budget overruns (Sovacool et al., 2014). It is generally accepted that many values representing these components vary significantly on a global level. Hence, low, median and high values of LCOE for each of the energy technologies have been calculated for all the G20 countries in 2015 and 2030, as highlighted in **Publication I**.

2.2 Prosumers disrupting the energy landscape

Decentralised electricity systems offer advantages of improving the resilience of residential, commercial and industrial facilities and even cities that are facing energy scarcity. Furthermore, reducing the influence from external factors such as intermittent supply, dependence on fossil fuel imports amidst speculative price oscillations, increasing resource diversity and others, while developing energy infrastructure in line with a more democratic and just clean energy transition (Carley and Konisky, 2020). Rooftop solar PV as decentralised energy systems has so far demonstrated to be very effective in producing benefits from social, economic, and environmental aspects. It can further boost local energy security and contribute towards enhancing local air quality (Buonocore et al., 2016). Decentralised rooftop solar PV are a very effective alternative to largescale PV power plants on extended agricultural lands. From a social perspective, producing electricity with household rooftop PV installations empower citizens in terms of energy sovereignty, with control over their own energy supply, in the reduction of their carbon footprint, their bills and they can pay off their investments within just a few years (Gómez-Navarro et al., 2021). The transition in the prosumer space from incentivised to self-consumption driven solar PV systems has led to various business models and corresponding innovative policies along with regulatory frameworks to foster decentralised solar PV systems around the world (IEA-PVPS, 2016a).

Options that enable and encourage consumers to generate their own electricity with solar PV (mostly on rooftops) at the point of consumption and feed any excess into the grid network, are emerging as attractive alternatives for households around the world. Even more in countries with steep retail prices for electricity. Prosumers are end-use consumers of electricity that happen to produce their own electricity at the point of consumption. Thereby meeting their own electricity demands and feeding the excess electricity into the distribution grid (Gómez-Navarro et al., 2021). PV prosumers are electricity consumers that interact with the grid network by withdrawing as well as feeding some quantities of electricity. An increasing number of PV prosumers could disrupt the electricity system and transform the way in which electricity consumers interact with it. This disruptive transformation is already taking shape in a number of countries such as Australia, Germany and many of the EU countries as well as states such as California in the US, that are promoting policies for enhanced self-consumption through residential PV installations (IEA-PVPS, 2021). While in California, it is mandated by regulations that new homeowners must have solar PV systems that will offset part of their energy bills (California Energy Commission, 2021). In addition to the capability of prosumers to self-generate and connect with the grid, prosumers have the potential to help mitigate the growth of energy supply and demand gaps as well as reduce electricity system losses. These potential benefits are particularly important for cities and urban centres, where almost two-thirds of global energy is consumed, which is set to rise with rapid rates of urbanisation around the world (UN-Habitat, 2020).

Solar PV prosumers could evolve to be the most important enablers of the energy transition across most regions of the world and provide a means for people's direct participation in climate mitigation. Various research (Miller and Senadeera, 2017; Ruotsalainen et al., 2017) propose a decentralised peer to peer society as an emancipatory and transformative socio-cultural vision for the era of renewable energy systems and have showcased the significant role of solar PV prosumers in countries such as Finland (Child et al., 2020; 2017). PV prosumers gain the most by maximising self-consumption, while avoiding feeding-in large quantities of excess electricity into the distribution grid (IEA-PVPS, 2016a). As these concepts are rapidly evolving with various options to optimise self-generation as well as consumption are still being explored across different regions of the world. However, there is a lack of comprehensive research on PV prosumer models that combine all the aspects of electricity, heat, storage and electric mobility integrated into residential household energy systems. Prosumer models for the different regions of the world as well as on a global scale are still lacking and is emerging as an issue that needs more attention from the global scientific community. Additionally, electricity and heat storage technologies along with HPs and BEVs are complementary in achieving the highest possible self-consumption shares for residential PV prosumer systems. These are expected to reach grid-parity within this decade across most regions of the world. However, grid-parity is relative to market conditions and depends on local retail electricity prices in the different countries and regions of the world, with some being more favourable for PV prosumers. Whereas, the others still posing substantial barriers and challenges with inappropriate market designs and regulatory policies (Breyer and Gerlach, 2013; IEA-PVPS, 2016a). The research in **Publication II** explores and presents the cost optimal combinations of various complementary technologies including heat pumps, batteries, thermal energy storage and electric vehicles, for PV prosumers across the world in four distinct settings and scenarios. Moreover, it explores the different self-consumption ratios (SCR) and demand coverage ratios (DCR) for solar PV prosumer systems from 2015 until 2050.

2.3 Employment in energy transitions

The environmental credentials of renewables as drivers of the zero emissions economy have long been touted as a solution to the current climate crisis. However, what is increasingly evident is that they are also contributing positively to overall global employment and hence socioeconomic growth around the world. Similar to other techno-economic and social shifts, transitioning to low or zero GHG emission economies will result in existing jobs being transformed, new jobs being created, jobs being substituted and jobs being eliminated or redundant (Worldwatch Institute and Cornell University, 2008). There is substantial research that indicate net positive effects on employment from the transition towards high shares of renewables (Dominish et al., 2019; Jacobson et al., 2019; Pai et al., 2021).

The effects of energy transitions on employment form a crucial element of energy policy decisions, as highlighted by Fischer et al., (2016) for the case of Germany, wherein jobs are one of the five most controversial issues in the debate on the "Energiewende". In recent times, employment effects of renewable energy technologies in the context of energy transitions have received significant attention from many stakeholders including academia, multilateral and intergovernmental agencies, private sector, and civil society (IEA, 2021; Adekoya and Faraz, 2021; Dominish et al., 2019; Greenpeace, 2015; IRENA, 2020b; Jacobson et al., 2017; Lund and Hvelplund, 1998; NREL, 2013; Pai et al., 2021). Employment trends can vary significantly for different energy technologies through their value chains including extraction, production, generation, storage, transmission and distribution, and flexibility options. In general, there are different types of jobs associated with the energy industry; the most commonly adopted categorisation is 'direct', 'indirect' and 'induced' jobs. Direct energy jobs are the ones associated directly to an activity in the value chain of a particular energy technology, whereas, indirect and induced jobs entail those jobs that are either created by auxiliary activities or activities that are an outcome of enabling energy availability (IRENA, 2011).

Employment impacts of energy transitions are emerging as vital indicators for energy policy and decision makers around the world. As the shift to renewable energy technologies is gathering pace, however in widely varying proportions across the different countries of the world, the employment impacts both in terms of jobs created and jobs lost are generating keen political interest. Direct energy jobs associated with the different energy technologies and net employment effects in the course of the transition to zero emissions are vital socioeconomic indicators. These are assessed for the global power sector in **Publication III** and for the global energy sector (including power, heat, transport and energy demand for desalinated water) in **Publication IV**. To further highlight the additional impacts, direct energy jobs created are assessed for two distinct energy pathways, one that enables an accelerated uptake of renewables and the other following current practices with moderate uptake of renewables across South Africa presented in **Publication V** and West Africa presented in **Publication VI**.

2.4 Air pollution induced externalities

Air pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), heavy metals typically represented as particulate matter (PM), and CO (carbon monoxide) have direct impacts on human health and the environment, implying that air pollution must be dealt with similar urgency as climate change. However, mitigating climate change and reducing air pollution are coherently interlinked and have the same goal of enabling sustainable development globally. It is increasingly evident that air pollution is linked to cardiovascular diseases, strokes, acute respiratory diseases and cancer (Landrigan et al., 2018; Lelieveld et al., 2019). It is estimated that 9 out of 10 people breath highly polluted air resulting in more than 8 million deaths a year, of which around 4.2 million are attributed to ambient air pollution and over 3.8 million from household air pollution (Burnett et al., 2018; Lelieveld et al., 2015; Vohra et al., 2021; WHO, 2021).

Fossil fuels and traditional uses of bioenergy are major sources of local and regional air pollution across the world. Consequently, not only causing human health effects, but also inducing reduced agricultural yields, severe damage to forests and fisheries in the form of acid rain, which also damages buildings and infrastructure. As research (Vandyck et al., 2018) indicates that air quality co-benefits on morbidity, mortality, and agriculture could globally offset the costs of climate policy. The economic costs of air pollution for humanity have been increasingly damaging. Air pollution can have huge economic consequences for people and their communities, including reduced work hours and shifts, increased health care costs from disabilities and chronic respiratory diseases, lost household incomes from caregiving for ill family members. For communities, the economic costs induced by air pollution can mean lowered economic productivity from work absences and overall reduced life expectancy.

Exhausts from the burning of fossil fuels results in three times as many deaths as road traffic accidents worldwide and it is estimated that air pollution effectuated an economic cost of 2.9 trillion USD, equating to 3.3% of the global GDP (Coady et al., 2016; CREA, 2020; IMF, 2015). Moreover, air pollution has induced increase in health care expenditures as a share of GDP across OECD countries over the last few years (Mujtaba and Shahzad, 2021). There were 4.5 million deaths with $PM_{2.5}$ pollution also responsible for 1.8 billion days of work absence, 4 million new cases of child asthma and 2 million preterm births (CREA, 2020). Disabilities from chronic diseases cost the global economy 200 billion USD in 2018, with sick leave and preterm births costing 100 billion USD and 90 billion USD respectively (CREA, 2020). In the context of Europe, on average every inhabitant of a European city suffered a welfare loss of over 1,250 €/year owing to direct and indirect health losses associated with poor air quality, which translates to around 3.9% of income generated across European cities in 2018 (CE Delft, 2020). These detrimental social and economic costs cannot be ignored anymore and must be accounted for and reflected in short-term as well as in the long-term energy decisions. Research (Reis et al., 2022) indicates that accounting for air pollution impacts reduces climate mitigation costs and inequality and increases global and regional welfare. There is a growing need to understand the change in external costs that can be achieved through increased use of modern renewables, in comparison to fossil fuels and traditional uses of bioenergy. This is particularly important for socioeconomic analyses of different energy technologies and energy transitions. Since consideration of external effects influences investment risks and the financial attractiveness of the different energy technology options.

2.5 Climate compliant, cost optimal and just energy systems

Rapid and deep reductions in GHG emissions are a prerequisite to avoid dangerous climate change. This necessitates transitions across electricity, transport, heat, industrial, forestry, and agricultural systems around the world to net-zero emissions. Consequently, the future of energy systems is one of the central policy challenges facing developed, developing and underdeveloped countries (Duić, 2015). This challenge is complex and multifaceted (Carley and Konisky, 2020; Geels et al., 2017; Miller and Richter, 2014). Not only does such an energy transition imply changes in energy generation, storage, distribution and consumption, but also a complex set of interconnected social, economic, ecological and political rearrangements. It is in the convergence of energy transitions and socioeconomic concerns where the concept of a 'just energy transition' arises (Axon and Morrissey, 2020).

Most energy decision making around the world is deduced by reducing energy systems to narrow configurations of energy technologies, the prices at which these technologies deliver energy in a useful form, and in recent years, the corresponding carbon emissions released. The result is stunted energy policies that systematically underemphasise the meaning and consequences of energy systems (Duić, 2015) and their transitions for human societies. Contextually, this research thesis emphasising socioeconomic impacts is built on fundamental energy system transition analyses (Bogdanov et al., 2021; 2019) that are cost optimal as well as climate compliant.

The value of analysing energy transitions through the lens of social-economic-technological systems stems from the ability to reveal important aspects of energy transformations that go unrecognised and unacknowledged in other analytical approaches. These include the socioeconomic processes that stimulate and manage energy transitions as highlighted by **Publication I** considering energy costs and **Publication II** assessing the role of solar PV prosumers. The socioeconomic changes that accompany shifts in energy technologies, which are highlighted by changes in job creation in **Publications III to VI** and changes in air pollution levels and corresponding impacts are discussed. The socioeconomic outcomes that emanate from organising and operating sustainable energy systems are highlighted across the **Publications I to VI**.

Energy systems can only transform when and if people make the corresponding choices, whether these agents of change are in the roles of business managers, policy officials, scientists and engineers, or ordinary consumers (Miller et al., 2013). In turn, changes in energy systems reshape social norms, values, interrelations, and institutions, such as new business models, forms of work, and ways of living. Therefore, the current energy transition should not be viewed through just one lens. It is not merely an issue of technology, or resource availability. It is about history, democracy, economics and society (Grayson, 2017). Thereby the global community must strive for energy transitions to be socially, economically, ecologically and politically just. This entails 21st century energy system modelling and analyses to consider social parameters in shaping future energy systems (Kılkış et al., 2021; Krumm et al., 2022; Pfenninger et al., 2014).

3 Methods: measuring socioeconomic impacts

Methods for measuring socioeconomic impacts include; the methods for estimating LCOE with inclusion of external costs across power technologies for G20 countries in 2015 and 2030 detailed in **Publication I**; the methods for assessing cost optimal solar PV prosumer systems across the world up to 2050 and creating a residential prosumer household model with features of solar PV, HPs, battery storage, TES along with two BEVs (passenger cars), are highlighted in detail in **Publication II**; the methods for estimating direct energy jobs and net employment effects during energy transitions are highlighted in detail for a regional-global power sector transition in **Publication III**, for a regional-global energy system transition (including energy demand from power, heat, transport and desalination) in **Publication IV**, for the South African power sector transition in **Publication V** and for the West African Power Pool transition in **Publication VI**.

3.1 Estimating levelised cost of electricity with externalities

LCOE estimations comprise complete costs of constructing and operating power plants in relation to the expected electricity generation over the corresponding technical lifetimes. Costs associated with transmitting and distributing electricity are not usually considered for plant level LCOE estimations. Inadvertently, socioeconomic and ecological externalities often get excluded from LCOE estimations beyond inclusion of market prices of CO_2 emissions. However, the analysis in **Publication I** was an attempt to include the full costs of electricity generation by internalising externalities as comprehensively as possible. In this context, a broad range of costs from both upstream and downstream of power plants are included to ensure a more accurate estimation of the full costs of electricity generation. These include costs associated with the effects on human health, the environment including climate change or global warming, waste disposal and long-term management, appropriate decommissioning along with the financial planning, investments and budget overruns.

LCOE estimations were focused on 2015, which at the time of **Publication I** were based on the latest available data on a global scale and in particular for G20 countries. LCOE was also estimated for 2030 using recognised and validated projections of cost components for the different electricity generation and storage technologies. In cases wherein reliable data was unavailable for particular G20 countries, corresponding data was substituted from regionally neighbouring countries. Primarily, this approach was based on the presumption of similar economic and geographic conditions that prevail in some of the G20 countries in the vicinity of each other. More details on the regional grouping of G20 countries is highlighted in detail in **Publication I**. Accurate and reliable background data were collated for all electricity generation and storage technologies and based on validated local and international sources.

These include:

- Ahmad and Ramana (2014)
- Bongers (2015)
- Central Electricity Regulatory Commission of India (2015)
- Danish Energy Agency (2016)
- European Commission Joint Research Centre (2014)
- European Technology and Innovation Platform for Photovoltaic (2017)
- Grausz (2011)
- International Energy Agency (2016)
- International Energy Agency and Nuclear Energy Agency (2015)
- International Energy Agency – Photovoltaic Power Systems Programme (2016)
- International Renewable Energy Agency (2015)
- Lazard (2016)
- Mann et al. (2014)
- Ministry of New and Renewable Energy, Government of India (2017)
- Pöller et al. (2015)
- Rafaj and Kypreos (2007)
- Schlissel (2016)
- Schneider and Froggatt (2016)
- UBS (2017)
- World Nuclear Association (2017a)
- World Nuclear Association (2017b)

The approach to estimate LCOE employed in this analysis includes elements such as real capital expenditures (Capex) as opposed to overnight costs, decommissioning costs, both fixed operational and maintenance expenditures (Opex fixed) and variable operational and maintenance expenditures (Opex variable), storage costs, fuel costs, GHG emissions costs, waste disposal and management costs, and a range of socioeconomic costs encompassing externalities. Additional key aspects of LCOE estimations are power plant technical lifetimes and annual operation in the form of full load hours (FLH).

Estimated LCOE (expressed in €/MWh_{el}), adopting a discounted cash flow approach with constant annual cash flows (Short et al., 1995), in **Publication I** is illustrated by the following equation (1):

$$LCOE = \frac{(Capex_{Real} * crf) + Opex_{fixed} + \frac{Decommissioning\ costs}{N}}{FLH} + Opex_{variable} + LCOS + Fuel\ costs + Waste\ disposal\ costs + External\ costs + GHG\ costs \quad (1)$$

wherein, $Capex_{Real}$ is capital expenditures (€/MW_{el}), which include low and high estimates corresponding to investments and budget overruns; $Opex_{fixed}$ is the cost for fixed operation and maintenance (as a percentage of annual Capex); $Opex_{variable}$ are the annual variable operation and maintenance costs (€/MWh_{el}) depending on the hours of operation; *Decommissioning costs* expressed as a percentage of Capex for all technologies except nuclear power plants, for which they are based on actual costs from literature expressed in €/MW_{el}; *N* is the operational lifetime of a particular energy technology (in years); *LCOS* is the levelised cost of storage in €/MWh_{el}; *Fuel costs* are expressed in €/MWh_{el}; *Waste disposal and management costs* are expressed in €/MWh_{el}; *External costs* (annual) include a range of socioeconomic and environmental costs related to electricity generation (€/MWh_{el}); *GHG costs* (annual) include the full socioeconomic costs of GHG emissions (€/MWh_{el}). Decommissioning costs are not discounted, i.e., a social discounting rate of 0% has been assumed to reflect real societal costs. Instead, are applied at the time of electricity generation.

Capex

Overnight Capex for the various energy technologies were derived from comprehensive sources, which are internationally validated and recognised for all the G20 countries. Sources with low and high Capex ranges for most of the electricity generation and storage technologies were identified. Data unavailable for a particular G20 country, was substituted with data from a neighbouring or geographically identical G20 country. The most economical option for utility-scale solar PV is sometimes a fixed optimally tilted system. This is the case, in countries such as Canada, France, Germany, Japan, Russia and the UK. However, at other times it is advantageous to operate a single-axis tracking system, as the higher yield of the system outweighs the increase in Capex. Hence, an additional 10% of the cost was added to Capex (Bolinger et al., 2017) to reflect costs of the tracking systems for all other countries. In all cases but three, the overnight Capex was the starting point for all estimations.

Investment and overruns

Solar PV and wind energy projects rarely encounter investment delays or budget overruns, hence just 1.5% – 3.5% of the Capex was considered (IEA & NEA, 2015). This indicates that solar and wind installations typically have very short construction times (around 1-2 years), however, some delays may occur due to complex procedures associated with permits. Battery technologies do not have any investment and cost overruns allocated. It was assumed that thermal power plants (coal and gas) have investments and budget overruns of 5% (low) and 15% (high), respectively. Additions from budget overruns to Capex are consistent with estimates from the IEA (IEA & NEA, 2015; IEA, 2016). Nuclear power plants are well known to have lengthy delays and prolonged construction times, thereby, an investment and budget overrun of 20% (low) was assumed, which is consistent with IEA estimates (IEA & NEA, 2015; IEA, 2016). In addition, an investment and cost overrun of 40% (high) is adopted from Koomey and Hultman (2007). Here the international trend towards longer construction times and budget overruns for nuclear power plants are comprehensively reflected, which have gotten progressively larger over time (Koomey and Hultman, 2007; Lovering et al., 2016; Schneider and Froggatt, 2021). Currently, nuclear power plants in France and Finland are over a decade past their scheduled construction time of 5 years, and budget overruns are approximately over 300% and growing (Koistinen, 2012; Le Monde, 2012; Schneider and Froggatt, 2021). In this context, assumed range of 20% - 40% of Capex for budget overruns is rather conservative, given that a scientific analysis for 180 nuclear reactors resulted in an average budget overrun of 117% with no single reactor completed within the planned budget (Sovacool et al., 2014).

$Capex_{Real}$

$Capex_{Real}$ (high and low) were calculated by adding the corresponding high and low investment and cost overruns to the high and low Capex assumptions stated earlier. In some cases, only the Capex was available, and the variance in $Capex_{Real}$ represents the corresponding variation in investment and budget overruns. Further literature analysis was adopted for extracting Capex for nuclear power plants in Argentina, China and South Korea, which is detailed in **Publication I**.

Decommissioning

Decommissioning costs were assumed to be 5% of Capex in the case of solar PV, wind, coal and gas power plants. Decommissioning costs were not considered for batteries. While an average decommissioning cost of 1100 €/kW was adopted for nuclear power plants across the G20 countries. However, the contentious aspects of accounting decommissioning costs in an accurate manner merit further discussions and comprehensive analyses of decommissioning costs across several nuclear power plants. Globally, actual experience and detailed information related to fully decommissioned nuclear power plants is quite scarce. Therefore, estimates of future costs ranging from 200 €/kW for reactors in Finland (219 million USD for 2*440 MW VVER) to 1500 €/kW for reactors in Slovakia (1.3 b€ for 2*440 MW VVER) were analysed (EC, 2016; IAEA, 2002). In the research presented in **Publication I**, it is assumed that average decommissioning costs globally will be 1100 €/kW in 2015 and remain the same up to

2030. Varying the decommissioning costs by ± 50% has an effect of just ±1 €/MWh_{el} on LCOE from nuclear power plants.

Opex

There are fixed and variable operational and maintenance expenditures. The $Opex_{fixed}$ is expressed as a percentage of annual Capex and comprises costs that are generally fixed over the lifetimes of power plants and do not depend on the operations and thus are unrelated to the FLH. These costs include material, personnel, administrative and insurance costs. On the other hand, the $Opex_{variable}$ represents costs that are directly dependent on the frequency as well as the duration of power plant operations such as fuel and emissions costs. Some operations and maintenance costs, such as those related to pumps, fans and lubricating fluids, are incurred when the power plant operates. In the case of batteries, like $Opex_{variable}$ costs are related to storage losses. These losses are a function of the energy throughput and battery operation efficiencies.

Lifetime

Power plant lifetimes considered in **Publication I** are consistent with estimates from the IEA and other international agencies. Wind power plants are assumed to have a technical lifetime of 25 years. Solar PV rooftop units and power plants are assumed to have a technical lifetime of 30 years (ETIP-PV, 2017), some facilities may have physical lifetimes up to 35 years. Increasing solar PV lifetime by 10 years would result in LCOE reduction of about 5 €/MWh_{el}. The actual lifetimes of solar PV modules and wind turbines installed currently are mostly unknown as most are yet to reach their end of technical lifetimes. More relevant to LCOE estimations, however, are the perceived technical and economic lifetimes by the international community, in particular investors. The technical lifetime of batteries, which has been set at 10 years for 2015 and 15 years for 2030 is yet to be standardised. The lifetime extension for 2030 is based on projected lifetimes of Li-ion batteries used in BEVs (UBS, 2017). Complicating this further is that batteries have both calendric and cyclic lifetimes, meaning batteries getting charged and discharged more frequently and deeply will have reduced lifetimes. Technical lifetimes of coal and gas power plants is assumed to be 40 years. While technical and economic lifetime of nuclear power plants is considered as 50 years. However, the high risk profile of nuclear power plants could lead to much shorter lifetimes in the future with exasperated societal willingness to accept risks associated with nuclear power. A growing trend across liberal western constituencies, as indicated by the Federal Constitutional Court of Germany in 2016 (Bundesverfassungsgericht, 2016).

Full load hours

FLH represents the operational hours of power plants on an annual basis. These vary drastically across the different technologies and have numerous technicalities that determine the FLH for each of the electricity generation and storage technologies. These have been presented and discussed comprehensively in **Publication I** and Ram et al. (2020a).

Fuel

Fuel costs were from Bloomberg New Energy Finance's New Energy Outlook 2015 (BNEF, 2015) and are summarised in Table 1.

Table 1: Fuel costs for coal (upper) and gas (lower) in €/MWh$_{th}$.

	€/t		**€/MWh$_{th}$**	
	2015	**2030**	**2015**	**2030**
Coal Europe	45.86	64.66	5.63	7.94
Coal China	71.43	68.42	8.77	8.40
Coal India	30.08	63.91	3.69	7.85
Average			**6.03**	**8.06**

	€/MMBtu		**€/MWh$_{th}$**	
	2015	**2030**	**2015**	**2030**
Gas Europe	5.26	9.77	17.96	33.35
Gas Japan	6.02	10.53	20.52	35.92
Gas China	9.77	9.77	33.35	33.35
Gas USA	2.26	8.27	7.70	28.22
Average			**19.88**	**32.71**

Cost of nuclear fuel was assumed to be 5.26 €/MWh$_{el}$ (IEA, 2016) for all G20 countries in both 2015 and 2030, due to ample stockpiles of nuclear fuel around the world. This corresponds to approximately 7 USD/MWh$_{el}$ and could vary by ±1 €/MWh$_{el}$ globally.

Waste disposal and management

Waste disposal and management costs form nuclear power plants is considered and derived directly from the IEA (IEA & NEA, 2015). The assumed waste disposal and management costs reflect the economic challenges that some countries face in safely disposing nuclear waste particularly in Japan, the USA and the UK. However, it is acknowledged that these costs are only indicative and in reality waste management of nuclear power plants is far more contentious and longterm, with costs escalating drastically in some cases, especially after disasters such as the Fukushima Daiichi (Ram et al., 2020a; Schneider and Froggatt, 2021).

External costs

A comprehensive review by Climate Advisers (Grausz, 2011) on the social costs of different forms of electricity generation determined that Rafaj and Kypreos (2007) conducted the most comprehensive estimation of external costs form electricity generation. These costs are the basis for LCOE estimations, which are summarised in Table 2. In the case of nuclear power, issues around liability and insurance in the event of accidents and disasters make it rather complex to determine appropriate and justifiable external costs. Over the last decade, many liability cases have been filed by citizens concerning nuclear energy across various courts worldwide (Schneider and Froggatt, 2021), more so in the wake of the Fukushima Daiichi disaster. There has also been growing evidence of activities around nuclear energy occurring beyond national and international legal jurisdictions and could even constitute nuclear as ‘criminal energy’ (Schneider and Froggatt, 2021).

Table 2: External costs of electricity generation excluding CO_2 costs in LCOE estimations (Rafaj and Kypreos, 2007). All values are in €$_{2015}$/MWh of electricity generated and based on long-term currency conversion of 1.33 EUR/USD and 57% inflation of the USD between June 1995 and June 2015. ASIA includes all Asian countries. OECD includes Australia and all other countries not specified. NAME includes all North American countries. EEFSU includes all Eastern European and Former Soviet Union countries. LAFM includes countries of Latin America, Africa and the Middle East. Further, PP is Power Plants, CCS is Carbon Capture and Storage and CCGT is Combined Cycle Gas Turbine.

	ASIA €/MWh$_{el}$	**OECD** €/MWh$_{el}$	**NAME** €/MWh$_{el}$	**EEFSU** €/MWh$_{el}$	**LAFM** €/MWh$_{el}$
Coal PP	18.9	18.9	13.3	13.3	13.3
Coal PP + CCS	22.7	22.7	15.9	15.9	15.9
Gas PP - CCGT	19.0	5.7	14.8	13.5	13.5
Gas PP - CCGT + CCS	22.7	6.5	7.4	15.2	15.2
Nuclear PP	7.7	7.7	7.7	7.7	7.7
Solar PV	1.5	1.5	1.5	1.5	1.5
Wind turbine	1.5	1.5	1.5	1.5	1.5

GHG emissions costs

For CO_2 equivalent GHG emissions, a range of costs exist that represent the cost of a metric ton of GHG emitted. Some are market oriented, while others are determined through policies and regulations. Carbon markets are perceived as imperfect mechanisms that often transfer and consolidate power and wealth, as concluded by Sovacool (2011). The author reviewed more than 300 articles that discussed merits and drawbacks of global and regional carbon markets over the last decade (Sovacool, 2011). The distributional impacts across the developed, developing and least developed countries around the world tend to favour the developed nations to expand their carbon budgets and raises questions on legitimacy of climate mitigative actions (Ohlendorf et al., 2021). In **Publication I,** 7 €/ton of CO_{2eq} was assumed based on the market price of carbon in the EU for 2015. In 2030, 74 €/ton of CO_{2eq} was assumed based on estimates of the social cost of carbon by the Stern Review (Stern, 2007) and confirmed by the High-Level Commission on carbon pricing (Carbon Pricing Leadership Coalition, 2017). However, it should be noted that there are a range of estimates related to the actual costs of carbon from 30 to 165 €/ton of CO_{2eq} (Moore and Diaz, 2015). Jakob et al. (2016) argue that emissions pricing could be utilised to promote sustainable socioeconomic development by providing public goods that are essential for human well-being through public financing. However, global concerns over potential competitive disadvantages seem to constitute major obstacles to market mechanism climate policy diffusion and strengthening carbon pricing policies around the world (Steinebach et al., 2021).

Determining universally acceptable costs for GHG emissions is a mere impossible task, which often leads to confusions, objections and contentions. A more comprehensive analysis is presented in **Publication I** on the diversity of GHG emissions costs. Recent research (Green, 2021) provides a meta-review of ex-post quantitative evaluations of carbon pricing policies around the world since 1990 and concludes that carbon pricing has limited impact on emissions reduction. Thereby indicating more stringent actions in the form of taxation fare a better chance at achieving emissions reduction targets around the world and are much need in G20 countries.

Other technical parameters and assumptions are presented and discussed quite comprehensively in **Publication I** and Ram et al. (2020a).

3.2 Prosumer model: Methods and assumptions

The PV prosumer model is formulated on the fundamental aspects of the LUT Energy System Transition Model, which is uniquely capable of analysing energy systems on high temporal (hourly) and geospatial (145 regions) resolutions (Bogdanov et al., 2019b). The modelling involves determining cost optimised solar PV and stationary battery capacities, resulting from the least Annual Total Cost of Energy (ATCE). Simulations were performed on an iterative basis for different PV capacities, ranging from 1 – 30 kW_p and stationary battery capacities, ranging from 1 – 50 kWh_{cap}, with 1 kW_p and 1 kWh_{cap} intervals respectively. Furthermore, the simulations were carried out on a local-global scale comprising 145 regions and 92 countries (Bogdanov et al., 2019b), in 5-year intervals from 2015 until 2050. A list of all the regions with their abbreviations can be found in the Supplementary Material of **Publication II**. Figure 4 illustrates the schematic composition of the entire PV prosumer household energy system, including all the different components.

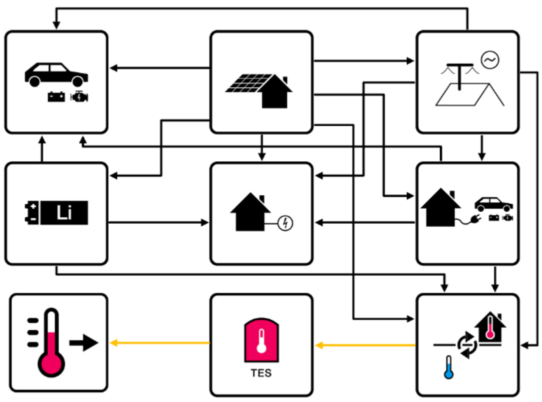

Figure 4: Composition of the PV Prosumer household model with all system components and the corresponding flows of electricity and heat. The black arrows indicate electricity flows, while the orange arrows indicate the flow of heat in the form of heated water.

Components of the household PV prosumer system are enlisted as follows,

a. Car 1: BEV with the primary functionality of daily commuting and occasionally as tertiary electricity storage. It also has an active role in charge transfers to and from Car 2 along with the stationary battery. External charging (mostly workplace charging) is not activated in this model.

b. Solar PV electricity generation system: Mostly rooftop PV that generates electricity to cover the energy demands of the entire household and feeds the excess electricity into the distribution grid network.

c. Grid integration: Enables bidirectional flow of electricity with the connected local distribution grid network and accounts for withdrawing grid electricity as well as feeding in excess solar PV generation.

d. Electricity storage: Lithium-ion batteries that can store electricity for utilisation within the household as well as power other components (BEVs and HP).

e. Household electricity demand: This is an aggregate demand from all household appliances and equipment that consume electricity.

f. Car 2: BEV with Vehicle-to-Home (V2H) capability, with low usage for commuting and available mainly as secondary electricity storage.

g. Heating demand: represents the heating needs of the household, mainly demand for hot water and space heating, particularly during winters. This is applicable to respective regions and varies globally.

h. Thermal energy storage (TES): storing thermal energy in the form of hot water in an efficient hot water tank for later consumption.

i. Heat Pump/Heating Cartridge: Heat exchange systems with primary function of converting electricity to thermal energy (heat).

Sizing of PV prosumer systems depends on average household energy demands across the different regions. While representative average households for corresponding regions were considered to factor the substantial variation in household sizes and corresponding energy demands within the regions.

GDP and Household Size

Household data was adopted from the United Nations database (UNSD, 2017). In addition, from the Gross Domestic Product (GDP) per capita, a relation between GDP per capita and people per household (pph) was established. GDP projections were adopted from Toktarova et al. (2019). For the development of pph until 2050, a linear growth of GDP per capita was assumed. Furthermore, it was assumed that the effect on pph is 25%of the GDP per capita development, which means a 100% increase in GDP per capita will induce one fourth decrease in pph. This relation portrays an appropriate development of the pph within the whole transition period and has been derived empirically. The development of pph through the transition period from 2015 to 2050 across all regions of the world can be found in the Supplementary Material of **Publication II**.

Solar Data

Solar PV electricity generation profiles for every region in hourly resolution in kWh were according to Bogdanov and Breyer (2016), as shown in Figure 5. These are adopted for a range of PV capacities in the PV Prosumer model to generate the household level PV generation profiles from 2015 until 2050 in 5-year intervals.

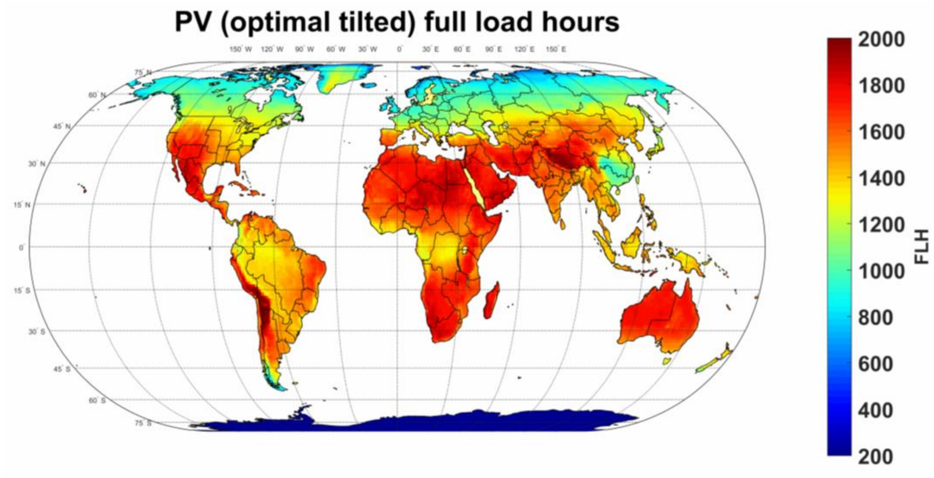

Figure 5: Global full load hours of optimally tilted solar PV systems (Bogdanov and Breyer, 2016).

Household Load Profiles

Household electricity load profiles of different countries were adopted for Brazil, Germany, Italy, Japan, New Zealand, Senegal, Thailand and the United States (Werner et al., 2012). In order to capture the local aspects of residential households, regions with similar socioeconomic and geographical conditions were categorised into ten distinct profile regions. Further aspects are comprehensively discussed in **Publication II**. The load profiles for the ten regions are shown in Figure 6. Wherein, the profiles differ quite substantially during daytimes, which has an impact on the Direct Self-Consumption (DSC) of households in the respective regions. This approach does result in rather simplified load profiles, which are ideal for the case of representative average households. However, the aspects of urban and rural household differentiation, which is quite stark in most developing countries have not been directly considered. Nonetheless, the various settings and capacity ranges explored could represent some of the variations between urban and rural households. It has been observed globally that prosumer proliferation generally originates in urban settings and then expands into the rural segments too. In the case of developing countries, there have been instances where solar PV prosumer households have propped up due to unavailability of stable electricity services (Laursen, 2017).

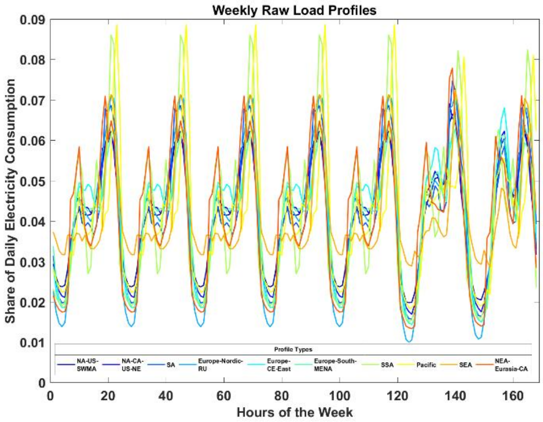

Figure 6: Weekly household load profiles as shares of energy consumption for the ten profile regions. NA-US-SWMA (South Western and Middle USA), NA-CA-US-NE (North Eastern USA and Canada), SA (South America), Europe-Nordic-RU (Northern Europe and Russia), Europe-CE-East (Central and Eastern Europe), Europe-South-MENA (Southern Europe and MENA), SSA (Sub-Saharan Africa), Pacific (New Zealand and Australia), SEA (South East Asia) and NEA-Eurasia-CA (Central and Eastern Asia).

Furthermore, the profiles encounter annual variations that occur predominantly due to the seasonal changes in activities that influence electricity demand. Country and regional electricity load profiles were adopted from Toktarova et al. (2019), which have factored in the annual seasonal variations. In turn, these electricity load profiles were adopted to derive the annual mean loads. Further, by applying weekly load profiles along with specific weekly factors as suggested by Equation (2) for every week of the year, the residential electricity load profiles across different households in corresponding regions of the world were derived.

$$load_{factorised} = load_{raw} \cdot f_{week} \qquad (2)$$

In Equation (1), $load_{factorised}$ – real load profile; $load_{raw}$ – raw load profile; f_{week} – factor of the investigated week in comparison to the country or regional annual mean load.

This weekly correction approach was applied for all weeks during the entire year and thereby deriving annual residential load profiles across households in the 145 regions. Figure 7 illustrates the factorised annual electricity load profile for Germany. The corresponding electricity load profiles are normalised to annual electricity consumption of 1 MWh. Thereafter, the electricity load profiles were corrected with annual electricity consumption per household across the different regions to determine the final factorised electricity load profiles of households.

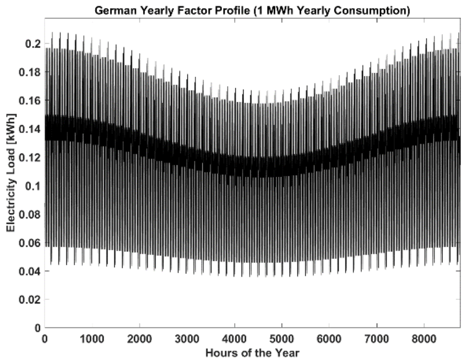

Figure 7: German yearly factored electricity load profile (normalised to annual electricity consumption of 1 MWh).

With the data for pph, total electricity consumption (IEA, 2017) and shares of residential electricity consumption across the different regions (Toktarova et al., 2019), the annual residential electricity consumption per representative average household was estimated for each of the regions. Other aspects of household and residential shares of electricity are further elaborated in **Publication II**.

Load profiles for Space Heating (SH) and Domestic Hot Water (DHW) demand were available on a regional scale form 2015 until 2050 (Keiner et al., 2021). Moreover, SH and DHW factorised load profiles were derived according to the pph and population per region. Electricity consumption, SH and DHW for households in all the regions across the different years can be found in the Supplementary Material of **Publication II**.

Battery Electric Vehicles

For a standard case of the PV Prosumer model, a residential household with two BEVs is envisioned. The capacity of batteries in the BEVs were set to specific values based on recent trends (EV Database, 2021; ICCT, 2012; UBS, 2017), with Car 1 having 80 kWh_{cap} and Car 2 having 60 kWh_{cap}. UBS (2017) presents detailed analyses of the BEV market with insights into driving ranges and battery packs of upcoming BEVs. However, recent developments in the BEV space have led to increasing battery pack sizes of vehicles available on the market and the current average is around 60 kWh_{cap} with the highest at around 200 kWh_{cap} (EV Database, 2021). More detailed discussions can be found in **Publication II**. From a 2050 perspective, 80 kWh and 60 kWh were assumed as reasonable capacities for BEVs, however, it is acknowledged that these could be rather conservative in context of recent developments. Usability and driving patterns determine the availability of the BEVs for optimal PV charging. The operational assumptions and patterns of charging and discharging of the BEVs, battery storage and solar PV generation are described comprehensively in **Publication II**. Usage of Car 1 and Car 2, as well as their driving patterns were based on the findings of Marwitz (2018). In the case of poor solar conditions, the BEVs are charged with grid electricity.

Daily trip demands were estimated from Equation (3), as follows:

$$E_{Car,trip} = \frac{Yearly\ driving\ distance}{\sum journeys} \cdot E_{cons.} \qquad (3)$$

wherein, $E_{car,trip}$ – electricity demand per car trip and $E_{cons.}$ – specific electricity consumption of BEVs. The specific electricity consumption of the BEVs was set to 20 kWh/ 100 km (Marwitz, 2012), including energy losses and discharging efficiencies. However, it is acknowledged that these consumption rates have improved in new generation BEVs (EV Database, 2021). The discharging efficiency of Car 2 to supply household demands and charge Car 1 was assumed at 96.8% (Luo et al., 2015), which represents the charging and discharging efficiency of Li-Ion batteries in the LUT Energy System Transition Model (Bogdanov et al., 2019b). Annual driving distances were assumed as 14,000 km and 10,000 km per year for Car 1 and Car 2 respectively, these were adopted from Khalili et al. (2019) and based on the ICCT (2012). Moreover, the global annual average of all cars was in the range of the average mileage of passenger car drivers in Germany at 12,800 km (Khalili et al., 2019). In addition, the study (De La and Layos, 2007) showed that the global daily driving distances are more or less in the range of European mean values, which are around 30-40 km per day.

Stationary Battery

A stationary battery is considered to be part of a standard PV prosumer household and the model based on various factors for achieving the least ATCE option, determines the capacity. A series of combinations of installed capacities of PV and stationary batteries are determined by an iterative process to achieve the ATCE for different prosumer households across the various regions of the world. As highlighted in Figure 1, the stationary battery satisfies the electricity demand of the household and the HP, as well as charges Car 1 occasionally. The model prioritises charging of the stationary battery after DSC. The primarily role of the stationary battery is to deliver electricity that meets electricity demands during evening and night hours, but also covering peak demands during daytimes when PV generation falls short, provided the stationary battery is sufficiently charged. To minimise utilisation of grid electricity, charge transfers between the stationary battery and Car 1 are prioritised over charging Car 2 with grid electricity. This does not impact the household demand and provides for the possibility of maximising the utilisation of PV electricity within the household.

A Li-ion battery is considered as the standard for the PV prosumer household, as it is increasingly common in residential applications. The DoD was assumed at 95%, while the charging and discharging efficiency was 96.8%, similar to BEVs (Luo et al., 2015). Along with charge transfers, the stationary battery is complemented by Car 2 that can cover demands during insufficiencies. Moreover, Car 2 has the provision to transfer excess charge to Car 1 assuming the functionality of the storage battery. Thereby ensuring all energy components in the household interact with each other to find the most cost optimal consumption pattern for reducing the ATCE.

Heating System (Heat Pump and Heating Cartridge)

There is no technology that is currently available to rival heat pumps in efficiently delivering residential and commercial space heating using electricity (Fawcett, 2011; IEA, 2020d; Wang et al., 2021). Ground source heat pumps (GSHP), which absorb energy from the ground with a dedicated borehole or a network of buried pipes was chosen to be part of the standard PV prosumer household. The efficiencies compared to air source HPs are much better in ideal conditions and locations with good ground heat profiles, the operational costs are lower, while the availability in comparison to water source HPs is higher. Another advantage of GSHPs is the stable Coefficient of Performance (COP) over the whole year enabled by the stored solar energy in the ground, even during the winters with very low temperatures. The choice of GSHP as part of the representative prosumer household was based on the resulting lower annual costs as compared to other HPs, as the end objective was to attain a cost optimal setting for PV prosumers. However, it could be the case that other HPs could be better in terms of performance in specific weather conditions. The detailed HP specifications are further highlighted in **Publication II**.

Heating requirements across the different regions of the world vary significantly, primarily due to climatic and geographic conditions. Therefore, heat pump systems and heating cartage systems are chosen based on the conditions of the regions. Figure 8 maps the regions across the world according to the heating systems utilised.

European standards DIN EN 806-2 (DIN, 2005) and DIN EN 1717 (DIN, 2000) recommend a temperature minimum of 60°C for the avoidance of legionella development in potable water. Therefore, operations at a nominal temperature of 65°C was adopted to operate safely within the limits.

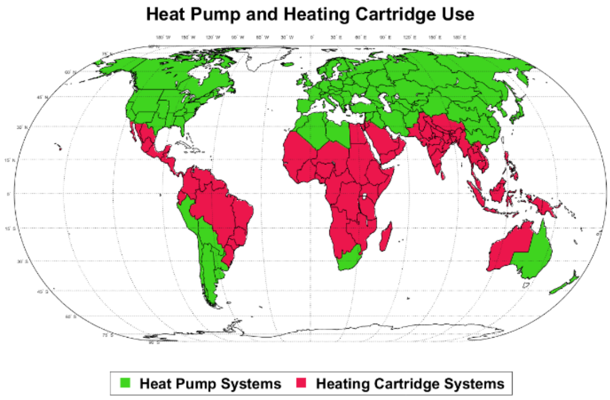

Figure 8: A global distribution of heating system options across the various regions.

Thermal Energy Storage

TES is a tank-in-tank storage with a water capacity of 800 litres for HP systems and 200 litres for heating cartridge systems. This includes storage capacities for SH and DHW in one device, as they are usually used in solar thermal applications (Sterner and Stadler, 2017; 2019). A standby of 25% was set for the TES as shown in Figure 9, which guarantees coverage of SH and DHW demands during refilling. Equation (4) describes the estimation of storable capacity of thermal energy in the TES.

$$E_{th,cap} = c_{p,water} \cdot V_{TES} \cdot \Delta T \qquad (4)$$

wherein, E_{th} – thermal energy; $c_{p,water}$ – specific heat capacity of water (0.0016 $kWh_{th}/(kg \cdot K)$, derived from 4.19 $kJ/(kg \cdot K)$); V_{TES} – storage volume of the TES; ΔT – temperature difference (45 K for nominal operation, 70 K for PV additional filling).

Figure 9 visualises the TES filling conditions, and the operational details are presented in **Publication II**.

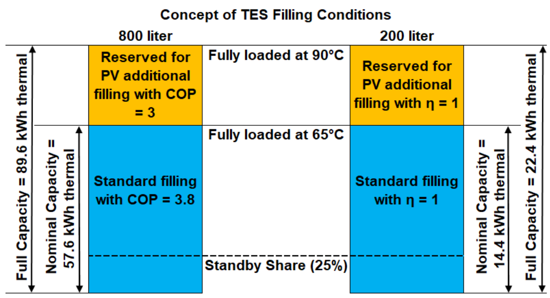

Figure 9: Capacities of TES filling for the operational modes of HP and Heating Cartridge.

The losses of thermal energy storage systems are between 1.6 kWh_{th} and 2.5 kWh_{th} per day (24 hrs) according to Viessmann Werke GmbH (Viessmann, 2018). Considering the 800 litres TES, thermal energy losses of about 0.15% per hour could be expected. This was considered independently of the SoC and TES size. The efficiency assumptions for all relevant system components are listed in **Publication II**.

Financial Target Function

The ATCE is estimated according to Equation (5), which is minimised over the year.

$$ATCE = \sum_i^{technology}(Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + cost_{grid} - income_{feed-in} \qquad (5)$$

wherein, *ATCE* – annual total cost of energy, *Capex* – investment cost for technology, *crf* – annuity factor, $Opex_{fix}$ – fixed operational expenditures, $Opex_{var}$ – variable operational expenditures, $E_{throughput}$ – energy handling of component (e.g., discharged energy of the battery), $cost_{grid}$ – cost of remaining electricity supplied by the grid, $income_{feedin}$ – income form PV electricity fed-in to the grid.

For comparing annual energy costs, Equation (6) representing a 100% grid supply energy system without PV and stationary battery is considered. This is minimised over an entire year. In the case of 100% grid supply, Car 2 is assumed as a normal BEV, as V2H application may not be beneficial. The HP operates nominally with grid supply, to minimise annual total grid energy cost (ATGEC) according to Equation (5).

$$ATGEC = \sum_i^{HP,TES}(Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + \left(\frac{E_{th,DHW} + E_{th,SH}}{COP_{nom}} + E_{el,house} + E_{el,car1} + E_{el,car2}\right) \cdot price_{grid} \qquad (6)$$

wherein, ATGEC – Annual Total Grid Energy Cost, $E_{th,DHW}$ – annual thermal energy for hot water demand; $E_{th,SH}$ – annual thermal energy for space heating; COP_{nom} – Coefficient of Performance of HP for operation at nominal value; $E_{el,house}$ – annual electricity consumption of household; $E_{el,car}$ – annual electricity demand for driving.

Financial assumptions for system components and grid/retail electricity prices across the different regions are based on the LUT Energy System Transition Model (Bogdanov et al., 2019b; ETIP-PV, 2017) and presented in Supplementary Material of **Publication II**. The costs of PV systems and battery storage systems vary quite significantly across the different regions (IRENA, 2018a) and have been converging towards regional standards (ETIP-PV, 2017; Schachinger, 2014). Standard Capex and Opex costs are considered for all technologies across the different regions of the world, as costs of these technologies are assumed to converge towards a global standard from a long-term perspective. Moreover, the retail electricity tariffs (grid electricity prices) are from various sources that are collated in Gerlach et al. (2014) and in Breyer and Gerlach (2013). In the case of BEVs, no storage costs are considered as it is assumed batteries are paid for along with the car (whose primary function is commuting). For all regions of the world, a standard feed-in tariff (reimbursement) of 0.02 €/kWh was considered. Despite the presence of significantly varying FITs across the different regions of the world, a conservative FIT is assumed from a 2050 perspective. Furthermore, the research is aimed at exploring options for residential households to optimise their self-consumption and minimise their energy costs without the aid of fiscal benefits in the form of taxes, subsidies, fees or others. Moreover, the feed-in reimbursement is assumed to be available only for up to 50% of electricity from the installed solar PV systems at households.

Operation and scenarios

Operation of the PV Prosumer model is considered to occur sequentially as represented by the flow diagrams in Figure 10. Adopting this process ensures maximising self-consumption of solar PV generation and minimising the ATCE of the PV prosumer household.

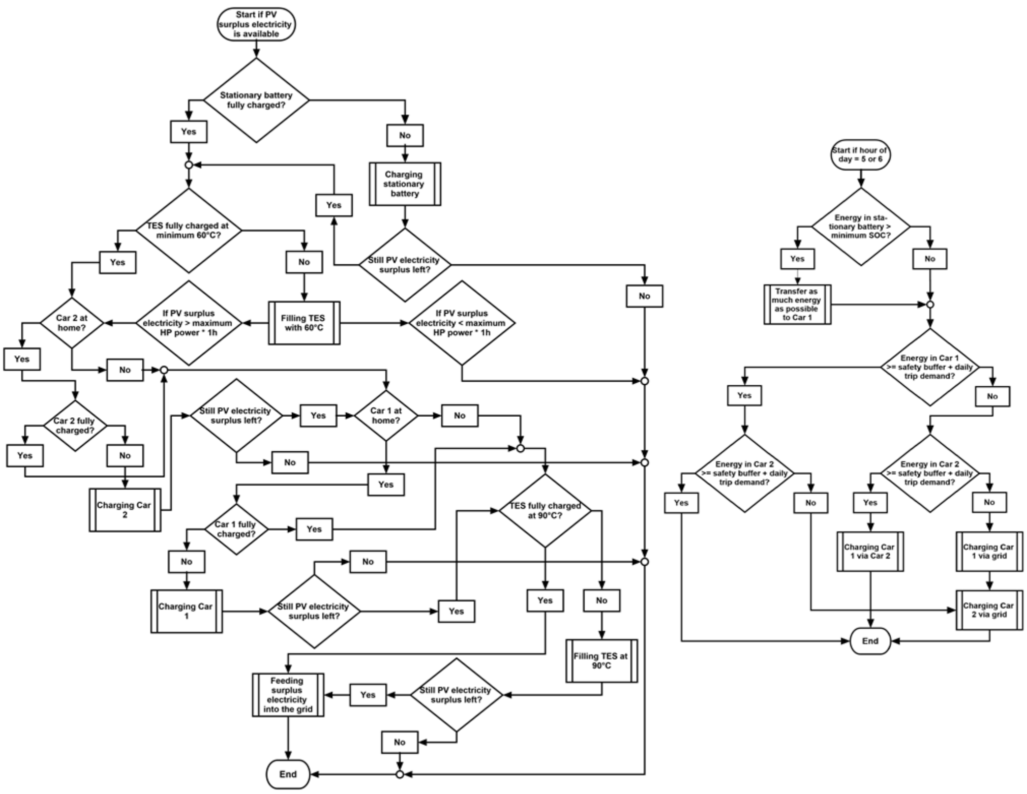

Figure 10: Flow charts illustrating the sequential operation of the components of a PV

Prosumer household. PV electricity generation and utilisation (left) and charge transfer between the BEVs (right).

As shown in Figure 10 (left), the stationary battery has first priority in the sequential order to utilise surplus solar PV electricity (available after covering the household electricity demand). The complete operational details are comprehensively discussed in **Publication II**.

Furthermore, the PV Prosumer model is designed to operate in four distinct scenarios to better capture the range of household compositions across the various regions of the world. Table 3 shows the four distinct scenarios, which are

- ‘Two Cars’ scenario: in this case, both BEVs are in operation along with the PV prosumer household.
- ‘Only Car 1’ scenario: in this case, just one BEV primarily used for commuting is in operation with the PV prosumer household.
- ‘Only Car 2’ scenario: in this case, just one BEV used primarily for V2H as a secondary storage is in operation with the PV prosumer household.
- ‘No Cars’ scenario: in this case, both BEVs are not in operation at the PV prosumer household.

Table 3: Scenarios based on the presence and usage of BEVs.

Scenarios	Car 1	Car 2 (V2H)
‘Two Cars’	Yes	Yes
‘Only Car 1’	Yes	
‘Only Car 2’		Yes
‘No Cars’		

3.3 Evaluating net employment effects in energy transitions

Net employment effects and estimations of direct energy jobs created during energy transitions across countries, regions and worldwide are assessed based on an analytical approach developed and presented in **Publications III and IV**. The method from **Publication IV** is presented, which is an extension of the methods highlighted in **Publication III** and adopted in **Publications V and VI**, in which direct energy jobs during energy transitions across different power sectors are estimated. The methods are further developed with modifications and improvements for more comprehensive analyses and results as well as applied to a wider range of energy technologies covering demands from the power, heat and transport sectors along with demand for desalinated water across the world in a highly electrified future energy system on 100% renewables in **Publication IV** and applied to the energy systems of Jordan (Azzuni et al., 2020) and Ethiopia (Oyewo et al., 2021).

The Employment Factor approach

Net employment effects during a regional-global energy transition from 2015 to 2050 are estimated by adopting the Employment Factor (EF) approach, which is an improved version from **Publication III**, that modified the methods from Rutovitz et al. (2015a). This approach was considered over others for its effectiveness and versatility in estimating direct employment associated with energy technologies through the value chain. Moreover, the approach allows for modifications in the methods to capture the dynamic nature of employment creation through the transition years and inclusion of different dimensions of regional trade and labour productivity. In this research, the methods from **Publication III** have been improved for the estimation of jobs in the transmission and distribution of electricity as well as the extraction, production and global trade of fossil fuels, accounting for jobs from export of coal, oil and gas, as highlighted in Figure 11.

Figure 11: Method for estimating direct energy jobs created during the energy transition. Abbreviations: Employment Factor (EF), Capital expenditure (Capex) and Operational expenditure (Opex).

The EF approach can be modified for specific contexts as well as applied over a range of energy scenarios for different regions worldwide, as highlighted for South Africa (Oyewo et al., 2019), Jordan (Azzuni et al., 2020), Ethiopia (Oyewo et al., 2021) and West Africa (Oyewo et al., 2020). Figure 11 presents an overview of the methods adopted to estimate jobs created during the global energy transition from 2020 to 2050 across the value chain associated with different energy technologies categorised into electricity, heat, fuels, and storage. It is further applied to energy transitions across nine major regions of Europe, Eurasia, Middle East and North Africa (MENA), sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America capturing the regional variations in job creation. In addition, total direct energy jobs were derived on the basis of final energy demand across 92 regions/countries of the world. Jobs in the value chain of a comprehensive number of energy technologies including electricity and heat generation, fuel production (fossil and synthetic), storage of electricity and heat and transmission and distribution of electricity. In context of this research, the total direct energy jobs are a sum of jobs in manufacturing (including exports), construction and installation, operations and maintenance, fuel production and supply (including exports), decommissioning of all technologies at the end of their lifetimes and jobs from the transmission and distribution of electricity. Job categories through the value chain are further defined as follows:

- **Manufacturing Jobs** – consists of jobs necessary to manufacture a unit of power, heat, storage, or fuel production and processing capacities. Manufacturing equipment and components for particular energy projects may require several weeks, months or possibly years. As such, they provide relatively temporary employment in comparison to the technical lifetimes of installations. However, with rapid scaling and huge demand for energy technologies, manufacturing units and associated jobs could last for long periods. Hence, they are expressed as job-years, or the full-time jobs required for manufacturing over the technical lifetimes of various technologies (IRENA, 2013). Additionally, an aspect to consider is that the manufacturing of equipment and components that are required in energy installations could occur elsewhere than the region or country in which the energy generation, fuel production or energy storage capacity is installed. Many countries around the world rely on importing technologies, in particular renewable energy technologies including components for storage and Power-to-X, as domestic manufacturing capabilities are insufficient or non-existent as yet. On the flip side, countries and regions that export renewable energy equipment and components create additional employment over their domestic energy capacity addition with additional manufacturing and production capacities for export markets. To account for imports and exports, the level of import dependence represented by local manufacturing factors are considered for each of the nine major regions, which are further highlighted below in **Publications III and IV**.

- **Construction and Installation Jobs** – consists of jobs associated with constructing and installing a unit of electricity and heat generation, energy storage or fuel production and processing capacity. It is assumed that a local workforce will undertake the construction and installation of all energy projects, as is in most cases around the world. These jobs too tend to last for a shorter duration compared to the technical lifetime of energy projects. Similar to manufacturing jobs, these are expressed in terms of job-years too, or as the total number of full-time jobs required for the construction and installation of an energy project over the technical lifetime of the corresponding installation. These jobs exist predominantly during the planning phase of energy projects (that is in the first few years) and last through the period in which the energy plants are built, until the commencement of operations. In this case, the construction and installation jobs are annualised over the technical lifetime of corresponding energy projects, which is the time required for construction and installation of a unit of energy capacity. The construction times for all technologies are presented in **Publications III and IV**.

- **Operation and Maintenance Jobs** – consists of jobs associated with operating as well as maintaining the operational condition of energy plants during the technical lifetimes. Energy plants are usually designed and built to operate for decades. Hence, operation and maintenance jobs last for relatively longer durations and are therefore interpreted as jobs for the quantity of energy generated, stored, or produced. These jobs are considered to exist over the technical lifetimes of the respective energy plants and are further annualised to derive the total number of jobs during the transition period. When energy plants are decommissioned and new energy plants replace the existing capacities, the operation and maintenance jobs continue to exist. A decline factor, which is correlated to increasing productivity and declining operational expenditures (Opex) is adopted to reflect the decline in operation and maintenance jobs as technologies and operational processes further mature with higher levels of automation. Moreover, these are locally originating jobs aiding the corresponding local economies.

- **Fuel Jobs** – consist of jobs associated with fuel production and supply to meet fuel demand from power and heat plants (nuclear, fossil and bioenergy), transport (road, rail, marine and aviation) and other applications. These are expressed as jobs per unit of primary energy, factoring the different rates of fuel consumption for energy plants and applications corresponding to the fuel utilised based on conversion efficiencies during the transition period. Furthermore, the transition from fossil fuels to e-fuels produced from low cost renewable electricity result in fuels which are categorised as plant to grid and include hydrogen, e-methane and Fischer-Tropsch (FT) fuels. Whereas fuels that are extracted including fossil oil, fossil methane, coal and biofuels are categorised as source to plant. Fuels jobs are based on these categories and originate at corresponding activities in the value chain. As fossil fuels are geographically dependent and are traded around the world from production heavy regions to consumption driven regions, the imports and exports of fossil fuels are captured in estimating the regional fuel jobs. Local production shares and import shares from corresponding import regions are factored for the nine major regions according to each fuel, fossil oil, fossil methane and coal as presented in **Publications III and IV**.

- **Decommissioning Jobs** – are jobs associated with the decommissioning of existing energy plants at the end of their technical operational lifetimes, especially if the energy plants are repowered or if certain components are recycled or reused as well as dismantled and reclaimed. These jobs are similar to construction and installation jobs and are also expressed in job-years, or the total number of full-time jobs required for decommissioning over the technical lifetimes of energy plants. These are generally short duration jobs, while in some cases, decommissioning jobs can last for a significantly longer periods, especially in the case of nuclear power plants. These jobs are further annualised through the transition period to derive the total number of decommissioning jobs created.

- **Transmission and Distribution Jobs** – consists of jobs associated with the transmission and distribution of electricity. In context of this research, electrification of the different energy sectors leads to greater shares of electricity in the final energy demand, which implies greater needs for transmission and distribution infrastructure. Therefore, transmission and distribution jobs are linked to the total electricity generated in the system, which are expressed as jobs per unit electricity generated. This factor is used to extrapolate the transmission and distribution jobs in the future with regional labour productivity considerations. Actual employment in the transmission and distribution of electricity were collected for different countries representative of each major region in the 2015-2020 period as presented in **Publications III and IV**. These jobs tend to be long term as transmission and distribution infrastructure last for decades.

- **Job Loss –** the jobs lost in fossil fuels and nuclear energy are corresponding to the decommissioned capacities of conventional power and heat plants along with corresponding fuel production plants during the transition period. Since only renewables are installed beyond 2020, new jobs do not arise in conventional energy plants and these are decommissioned at the end of their technical lifetimes, which create additional decommissioning jobs. As indicated in the results, more jobs are created than lost through the transition period, thus with a net positive in terms of job creation. Main technologies introduced in the model include electricity generation (fossil, nuclear and RE technologies), heat generation (fossil and RE technologies), energy storage, power transmission and sector coupling technologies to provide additional flexibility to the entire energy system and to enable low-cost energy system solutions strongly based on electricity. Figure 11 shows the block diagram of the energy transition model.

Parameters considered for the estimation of job creation from various power and heat generation, fuels production and storage technologies are listed below.

- **Employment Factors** – are expressed in terms of jobs per unit of capacity, comprised of activities pertaining to manufacturing, construction and installation, operation and maintenance, fuels production and decommissioning of various energy technologies and resources. It is also expressed as jobs per unit of primary energy for fuel production and supply and jobs per unit of electricity generated for transmission and distribution. EFs for the research in **Publications III and IV** were mainly adopted from Rutovitz et al. (2015a), along with some modifications and estimates from other sources, which are presented in detail in **Publications III and IV**. The different EFs for the various power and heat generation, fuel production and supply and storage technologies corresponding to the value chains are presented in **Publications III and IV**.

- **Decline Factors** – job creation potential or labour intensity can be expected to reduce as technologies and production processes constantly mature with learning effects. This maturing or learning occurs as a result of the growing experience and volume of installations in the energy industry (mainly renewables, storage and Power-to-X technologies); i.e. learning by doing and economies of scale (Cameron and Van Der Zwaan, 2015). Accounting for the maturity of different energy technologies and the corresponding reductions in employment generation with increasing production capacities, is factored through correlating EFs with the rate of reduction in capital expenditures (Capex) for the corresponding power and heat generation, fuel production and storage technologies during the transition period, in the case of manufacturing, construction and installation jobs. Whereas for operation and maintenance jobs, the EFs are correlated with the rate of decline in operational expenditures (Opex) of the corresponding power and heat generation, fuel production and storage technologies through the transition period. The Capex and Opex of the different energy technologies during the transition period from 2015 to 2050 can be referred to in Bogdanov et al. (2021).

- **Regional Employment Multiplier** – of the various regions were adopted to reflect the variation in labour intensive economic activities in the different regions (nine major regions) of the world. EFs are normalised for OECD countries, hence, the regional employment multipliers account for the additional employment that will be generated in non-OECD countries with respect to corresponding labour intensities. Moreover, adjustments for the differing stages of economic development during the transition are captured with varying reginal employment multipliers. In general, the lower the cost of labour in a country, the greater the number of workers that will be employed to produce a unit of any particular output, be it manufacturing, construction, services or agriculture. The methods from Rutovitz et al. (2015a), along with labour productivity data from the ILO (2016) were adopted to determine regional employment multipliers for the corresponding major regions.

- **Local Manufacturing Factor** – indicates the percentage of local manufacturing within the various regions of the world (the nine major regions in this context). As manufacturing of mainly renewable energy, storage and Power-to-X technologies is quite unevenly distributed across the world, many regions still rely heavily on imports of technologies to develop and scale renewable energy, storage and Power-to-X installations. The regional import and export proportions as well as current export shares with corresponding importing regions are determined according to current trends and practices. These are derived from global trade flows in the energy sector (predominantly renewables) and industrial activity in corresponding major regions adjusted to indicators from UNIDO (2013). Currently, the more industrialised regions of Northeast Asia, Europe and North America along with some shares from Southeast Asia and SAARC dominate the global export of renewable energy technologies. However, with economic growth in other regions, the research in **Publications III and IV** considers an optimistic scenario that all major regions across the world will develop towards regional self-sustenance up to 2050. This entails all major regions having domestic manufacturing capabilities along with intraregional trade by 2050. The export-import shares of the different regions are derived from Rutovitz et al. (2015a), UNIDO (2013) and PwC (2017).

- **Local Fuel Production Factor** – represents the share of fuels produced locally in the different regions, which is applied only to fossil fuels (oil, gas and coal). As fossil fuels are exclusive to certain geographical locations, they are produced in some regions and consumed in other regions resulting in the global trade of fossil fuels. In order to capture the regional production and consumption in the structure of the nine major regions, local fuel production factors are applied. Furthermore, import shares and importing regions for all of the fossil fuels are applied across the nine major regions. The local production shares and relative import shares from corresponding import regions are presented for fossil methane, fossil oil and coal in **Publications III and IV**. This approach enables estimation of jobs related to fossil fuel exports, which is quite predominant in certain regions.

As indicated in Figure 11, EFs for manufacturing as well as construction and installation were applied to newly installed capacities during each year for the corresponding 5-year interval during the transition from 2020 to 2050. While operation and maintenance EFs were applied to cumulative installed capacities for every 5-year interval between 2020 and 2050. The fuel EFs are applied to annual electricity and heat generation form the various power and heat generation technologies that utilise fuel sources along with energy demand for transport. The decommissioning EFs are applied to the annual decommissioned capacities of power and heat generation, fuel production and storage technologies during each 5-year interval for the entire transition (2020-2050). The transmission and distribution EFs are applied to the total electricity generated in the different regions during the transition period. The installed capacities, electricity and heat generation, fuel production and supply and decommissioned capacities for the various power and heat generation, fuel production and storage technologies are adopted from the results of the LUT Energy System Transition Model, as comprehensively documented in Bogdanov et al. (2021). A high electrification scenario drives the electricity demand from the heat and transport sectors, with heat generation, battery charging for EVs and production of e-fuels to cover other transport demand, which forms the basis for estimating job creation during the energy transition in nine major regions of the world.

Job creation across the 92 countries and regions is estimated from the energy specific jobs, which is jobs created for every unit of final energy estimated for each of the nine major regions. These energy specific jobs are applied to the final energy demand of the corresponding countries and regions to determine the total direct energy jobs in the respective country/region through the transition period from 2020 to 2050. The direct energy job creation in the 92 countries and regions is presented in the Supplementary Material of **Publication IV**.

4 Results

A summary of the main objectives, methods adopted and the key results from each publication that comprises this research thesis is presented.

4.1 Publication I: A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030

Aim

The key objectives of **Publication I** were to estimate the LCOE for different electricity generation and storage technologies for all the G20 member countries in 2015 and for the probable LCOE in 2030. It also inculcates the effects of externalities in the form of external costs from GHG emissions, health related costs among other societal costs and subsidies on the LCOE across G20 countries. Additionally, it also aimed to estimate LCOE (with and without external costs including GHG emissions costs) of the most relevant electricity generation and storage technologies for all the G20 member countries from a future perspective (2030). Furthermore, providing a comparative analysis of the costs of renewable electricity generation combined with storage, and the costs of electricity from fossil fuels and nuclear. With the growing relevance and significance of the G20 forum, the purpose of the research in **Publication I** was to inform global energy policy discourse with comprehensive, rigorous and impartial cost analyses of the existing as well as emerging energy technologies.

Methods

Estimating annualised costs of electricity for different electricity generation and storage technologies on an equal and comparative footing are employed in **Publication I**. In general, LCOE calculations include all the costs associated with the building and operating of power plants in relation to electricity generated over the technical lifetimes. Costs of transmitting and distributing are usually not considered for plant level LCOE estimations. Invariably, socioeconomic and ecological externalities are also often excluded from LCOE estimations beyond the market price of CO_2 emissions. However, the analyses in **Publication I** attempted to include the full costs of electricity generation by internalising them as justifiably as possible. In this context, a wider range of costs both upstream and downstream from power plants are included to deduce a more accurate representation of the full costs of electricity generation. Such costs include those related to effects on human health, the environment, climate change and global warming, long-term waste disposal and management, plant decommissioning, financing, investments and budget overruns.

Results

LCOE estimations for all the G20 countries in 2015 and 2030 across different electricity generation technologies and battery storage are presented in **Publication I** with detailed analyses. However, in general onshore wind energy results in the lowest overall LCOE, especially in regions at higher latitudes (either in the north or the south). Exceptions exist for some regions in Asia where wind resources are less favourable in comparison to solar resources, which are more favourably distributed. In 2030, solar PV utility power plants yield the lowest LCOE of all technologies across all the G20 countries apart from Northern European countries which happen to be part of the European Union, where onshore wind continues to deliver the lowest LCOE. Across all the G20 countries, rooftop solar PV emerges more cost competitive than conventional electricity generation (fossil fuels and nuclear) in 2030, especially when a more comprehensive range of costs are internalised for all technologies. Decline in costs projected for battery storage by 2030 also increase the competitiveness of PV-battery systems (rooftop and utility) across all the G20 countries. Electricity from conventional fuel sources becomes significantly less competitive by 2030 when the costs of CO_{2eq} and other externalities are internalised. Gas-based technologies, crucial for flexibility to global energy systems, have the potential to reduce overall LCOE through switching fuel from natural gas to more sustainable bio-based or e-methane. Carbon capture and storage offers opportunities to reduce costs associated with emissions from fossil fuel combustion but remains significantly higher in costs than renewable electricity generation, even with the anticipated cost reductions due to development of CCS technology. Nuclear power has already lost its cost competitiveness to electricity from wind and solar PV in 2015 across most of the G20 countries and further worsens its relative competitiveness with renewable electricity by 2030 when the high levels of social, environmental and economic risks are internalised in LCOE estimations.

4.2 Publication II: Cost optimal self-consumption of PV Prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050

Aim

Combining solar PV, heat pumps, battery storage, thermal energy storage and a couple of battery electric vehicles within a residential energy system is emerging as a likely future prospect to meet the overall energy demand of households. In this context, the research presented in **Publication II** explored various settings with four different scenarios constituting the basis for a cost optimised self-consuming prosumer household. However, just a combination of system components is not sufficient to optimise the household energy system. Therefore, the research presented in **Publication II** focussed on creating a PV prosumer model for optimising solar PV electricity usage and minimising annual total cost of energy for average residential households spread worldwide. Additionally, performing a comprehensive investigation of the impacts from the different system components and development of annual total cost of energy, self-consumption ratio, demand cover ratio and heat cover ratio over the period from 2015 to 2050. It also includes, finding the least cost PV capacities and corresponding cost optimal battery sizes. It is the first study to perform a global analysis of solar PV prosumers with a range of complementary solutions to cover household energy demands in the most cost optimal manner.

Methods

The PV prosumer model follows the fundamentals of the LUT Energy System Transition Model, which conducts energy system analyses on an hourly resolution (Bogdanov and Breyer, 2016; Breyer et al., 2018; Ram et al., 2017a). In order to determine cost optimised (least annual total cost of energy) solar PV and stationary battery capacities, simulations were conducted on an iterative basis for PV capacities (1 – 30 kW_p) and stationary battery capacities (1 – 50 kWh_{cap}) with intervals of 1 kW_p for PV and 1 kWh_{cap} for stationary battery. Furthermore, the simulations were performed on a global scale consisting of 145 regions (Breyer et al., 2018; Ram et al., 2017a), in 5-year intervals from 2015 until 2050. In addition, four different scenarios with distinctive prosumer component combinations for the residential household were explored. A list of all the regions and the corresponding technical and financial assumptions with all details can be found in the Supplementary Material of **Publication II**.

Results

In cost optimised PV prosumer household scenarios, the ATCE reduced from about 900 – 6000 €/a with 100% grid supply to approximately 550 – 5500 €/a, for minimised cost development across eight representative regions of the world. Development of the ATCE for household PV systems decreases linearly, with decreasing investment costs of system components until 2050. Stagnating or marginally decreasing energy costs from 100% grid electricity supply in some regions results from the decline of HP and TES costs, which compensate for the increasing retail electricity prices from the grid network. SCR optimised residential PV systems are already profitable for prosumer households in many regions with high retail grid electricity prices in 2015. Whereas for prosumer households in regions with lower retail grid electricity prices, it is yet to be profitable to optimise self-consumption. This is mainly due to higher capital investment costs for stationary batteries in riskier market conditions.

The level of development across the regions, expressed in terms of GDP per capita, has negligible impact on the level of profitability for prosumer households. Higher energy consumption of households in developed countries make SCR optimisation more cost effective. Compared to complete grid electricity supply, SCR optimised PV systems can reduce ATCE up to 80% within 2025. Until 2050, it is possible to cut energy expenditures across all the scenarios by up to 90%. SCR optimisation can be achieved partially, with the substantial decline of PV system costs, large feed-in quantities are deemed economically attractive. SCR levels between 30% - 60% until 2050 for all scenarios across households from most regions of the world can be achieved. High levels of SCR are prevalent in the initial periods of the transition with most regions yet to achieve grid parity. Whereas in the later periods of the transition, lower SCR is observed as most regions achieve grid parity. Optimisation of capacities of stationary batteries has varying effects based on the variation between regions with excellent to moderate solar resource conditions.

In all the scenarios, development of least ATCE systems seems to have a cost effectiveness limit determined by the battery to PV capacity ratio of about 2 kWh_{cap}/kW_{p}. With few exceptions, most of the prosumer household systems are below this battery-PV capacity ratio limit. It is observed that very high battery capacities do not occur in residential PV systems for households in most regions in all the scenarios. With the absence of V2H, small and mid-sized battery capacities emerge as the most cost optimal storage option. With BEVs and V2H, only smaller battery capacities are necessary for cost optimal usage of solar PV electricity. Solar PV capacities vary depending on solar resource conditions as well as demand for electricity and heat, which varies significantly across households in the various regions and different years through the transition. Detailed analyses are presented in **Publication II**.

4.3 Publication III: Job creation during the global energy transition towards 100% renewable power system by 2050

Aim

Publication III aimed to evaluate the hypothesis of sound socioeconomic impacts of transitioning to a sustainable economy by determining net employment effects of achieving global 100% renewable power supply by 2050. With the world structured into nine major regions from 145 regional energy system analyses. The transition of power sectors across these regions are showcased in Breyer et al. (2018) and Bogdanov et al. (2019), serving as the basis for estimating jobs created and net employment effects during the transition from 2015 to 2050. In addition, job creation potential on a technology-wise basis and on a category-wise basis during the global power transition is estimated. Thereby, providing better insights on the types of jobs that will be created in the long-term. Moreover, the research in **Publication III** is the first to estimate potential job creation from various storage technologies and in particular batteries during a global power sector transition. This is enabled by the unique aspects of the LUT Energy System Transition modelling tool (Bogdanov et al., 2019b; Breyer et al., 2018) which analyses power systems across the world on an hourly basis with detailed assessments of storage requirements.

Methods

Jobs created during the global power transition from 2015 to 2050 are estimated with the EF approach, adopted from Rutovitz et al. (2015). The EF method was adopted amongst the other methods (Breitschopf et al., 2011), due to its simplicity and effectiveness as highlighted in **Publication III**. The EF approach enables estimating direct employment associated with energy generation, fuel production, storage and transmission. One of the key features of the EF approach is that it can be modified for specific cases, as well as applied over a range of different energy scenarios. The detailed methods are presented in **Publication III**.

Results

Rapid growth in the renewable electricity sector results in an increase of around 70% in direct power sector jobs by 2030. Moreover, the overall jobs created in 2050 compared to 2015 are 1.5 times higher. Jobs created continue to rise and reach about 34 million direct energy jobs by 2030. Beyond this, they decline to around 30 million and then steadily increase to nearly 35 million direct energy jobs by 2050.

Solar PV with 22.2 million direct energy jobs by 2050 leads, followed by batteries with 4.5 million direct energy jobs in 2050 and wind energy with 1.4 million direct energy jobs in 2050 constitute the major job creating technologies during the power sector transition from 2015 to 2050. With respect to wind power generation, around 7.3 million jobs are created in the period from 2020 to 2030, beyond that, as solar PV becomes more cost effective, they drive most of the installations until 2050 and jobs in the wind sector are stabilised. While hydropower (1.9 million jobs by 2050) and bioenergy (2.3 million jobs by 2050) create a stable share of jobs through the transition period.

Fuel jobs decline dramatically from 44% of the total direct energy jobs in 2015 to just around 2% of the total jobs by 2050, as fossil fuels and nuclear power capacities as well as the operational hours decline. On the contrary, operation and maintenance jobs have the most significant rise in the share of the total direct energy jobs created from 15% in 2015 to 50% by 2050. This indicates that the transition towards a 100% renewable power system enables the creation of more stable direct energy jobs, thereby contributing to stable economic growth of countries particularly in the developing regions of the world.

4.4 Publication IV: Job creation during a climate compliant global energy transition towards 100% renewable energy across the power, heat, transport and desalination sectors by 2050

Aim

Publication IV focuses on quantifying direct energy jobs and analysing the net employment impacts for an accelerated uptake of renewable energy driven by electrification that envisages countries and regions around the world deriving 100% energy from renewable sources by 2050. The research presented in **Publication IV** further advanced and expanded the methods of **Publication III**, from the power sector to other energy sectors and conducted more comprehensive analyses of net direct energy jobs created during a regional-global energy transition, which included a wide range of energy technologies. It is the first research to estimate jobs created by complementary heat storage and power-to-X technologies (including the production of green hydrogen and e-fuels) across the energy sector comprising power, heat, transport, and desalination demands. Moreover, the research also included estimates of decommissioning jobs across the various energy technologies and estimated jobs linked to transmission and distribution of electricity created during the energy transition in the coming three decades (2020 to 2050). The estimates for 92 countries, nine major regions and globally were based on comprehensive data collation of actual jobs. Estimates of direct energy jobs involved in the production and trade of fossil fuels across different major regions of the world have been estimate and presented in **Publication IV**.

Methods

A comprehensive literature review is conducted to determine the most ideal EFs for all technologies in the energy system and are presented in **Publication IV**. The components of the energy system and potential job creating technologies are classified into power generation technologies, heat generation technologies, combined heat and power technologies, storage technologies (electricity and heat) and fuel production technologies (fossil and synthetic) along with transmission and distribution. The EFs are correspondingly categorised as manufacturing (imports and exports), construction and installation, operation and maintenance, fuel supply (imports and exports) and decommissioning to capture the entire value chain in energy conversion and supply. Transmission and distribution grid jobs are linked to electricity generation, which are linearly extrapolated to determine jobs with the corresponding electricity generation in the future across the different regions and countries of the world. The global direct energy jobs created through the transition are an aggregate of jobs created across the nine major regions constituting the world. Moreover, the global direct energy jobs estimate also include exports and imports of fossil fuels and manufactured technologies that were traded across the nine major regions. The methods, EFs and assumptions are presented briefly in the methods and materials section and further in the Supplementary Material of **Publication IV**.

Results

The trends highlighted in Bogdanov et al. (2021) lead to a rapid ramp-up in installed capacities of renewable electricity generation technologies, compensating for the phasing out of fossil fuels and nuclear based energy capacities around the world. This forms the fundamental basis for the overall direct energy sector jobs, which as indicated in **Publication IV** increase significantly from about 57 million in 2020 to around 134 million by 2050. Driven by strong growth in the renewable energy sector, coupled with direct and indirect electrification the direct power generation jobs are more than tripled in 2050 with 69 million, as compared to 20 million jobs in 2020. While in the heat sector, jobs created decline in the initial periods with high levels of electrification and increase later in the transition to about 28 million jobs with more jobs in the e-fuel supply chain including green hydrogen. Similarly, jobs associated with fuels mainly for the transport sector decline initially with the decline in utilisation of fossil fuels due to phasing in of BEVs as well as the production of e-fuels. On the contrary, storage jobs take off in the 2030s and reaching about 10 million jobs by 2050. The high levels of electrification also drive the transmission and distribution grid jobs through the transition reaching about 22 million jobs in 2050.

From a value chain perspective, manufacturing of energy technologies leads to significant increase in manufacturing jobs from around 6 million in 2020 to over 23 million in 2050, which includes some shares of export quantities for certain regions. However, as highlighted in **Publication IV** major regions of the world are expected to be domestically self-reliant in terms of manufacturing energy technologies by 2050. Thereby, ensuring increased domestic job creation. Jobs associated with the operation and maintenance of energy technologies create the highest number of jobs by 2050, with around 42 million jobs worldwide. Similarly, construction and installation of energy technologies leads to over 40 million jobs by 2050. Jobs associated with the production and supply of fossil fuels, both domestic and exports are set to decline from around 32% of the total energy jobs in 2020 to just around 3% of the jobs by 2050, with mainly jobs for decommissioning of fossil fuels and nuclear power capacities. Global export volumes of fossil fuels accounted for around 8% of total energy jobs in 2020, which are eliminated by 2050 with no exports of fossil fuels, as countries transition to adopting locally produced e-fuels and some bioenergy. Furthermore, the development of the final energy demand specific jobs increases through the transition period, from 563 jobs/TWh in 2020 to 1000 jobs/TWh in 2050. This indicates that an energy system based on renewables creates nearly twice as many jobs for every unit of final energy demand covered, as compared to the current fossil fuels dominated energy system. The detailed job creation with technological, sectoral and regional distribution is presented in **Publication IV**.

4.5 Publication V: Pathway towards achieving 100% renewable electricity by 2050 for South Africa

Aim

The aim of **Publication V** was to simulate and evaluate dynamic decarbonisation pathways for the South African power sector up to 2050. Moreover, a cost optimal and climate compliant pathway was explored for transitioning from a coal dominated power system to one that is built on renewables complemented by storage and flexible technologies to enable South Africa's carbon mitigation strategy. Some of the socioeconomic aspects were evaluated, particularly water consumption issues associated with the operation of thermal power plants, in the context of South Africa that is prone to severe water scarcity. Thus, energy-based water demand was examined by assessing the water footprint during energy transition pathways in **Publication V**. In addition, to address growing unemployment in South Africa, direct energy jobs were quantified, and net employment impacts analysed for the different energy transition scenarios.

Methods

The techno-economic analysis of the transition pathways was carried out with the LUT Energy System Transition Model (Bogdanov et al., 2019b). The modelling is performed in 5-year intervals from 2015 up to 2050, in an hourly temporal resolution, which guarantees a more comprehensive assessment of the power generation mix. Additionally, the water footprint of thermal power plants was estimated using water withdrawal and consumption factors for various thermal power plants provided by Macknick et al. (2012) and using the methods of Lohrmann et al. (2019). While direct energy jobs created during the transition pathways were estimated based on the methods of **Publication III**, using the employment factor approach. Detailed financial and technical assumptions, employment generation factors and key power capacities during the transition are available in the Supplementary Material of **Publication V**.

Results

The South African power sector transition is technically feasible and economically viable, with a power system on 100% renewables in the Best Policy Scenario (BPS), which is low-cost, zero GHG emission, ensuring water adequacy and creating more jobs. Solar PV and wind energy evolve as the primary sources of electricity for an entirely renewable power system in South Africa. Solar PV with around 75–79% dominates shares of total generation capacities, followed by wind energy with around 11–16% in 2050. Solar PV emerges as the most versatile and low-cost source of power generation, contributing around 71–73% of the total electricity generation in 2050, followed by wind energy with 22–28%. On the contrary, in the Current Policy Scenario (CPS), fossil fuels based power generation still plays a role in 2050.

The LCOE just increases slightly from around 49 €/MWh in 2015 to about 51 €/MWh by 2050 in the BPS, while it significantly increases reaching nearly 105 €/MWh in the CPS. In addition, without GHG emission costs, LCOE increases from around 44 €/MWh in 2015 to about 47 €/MWh by 2050 in the BPS, and further increases to nearly 63 €/MWh in the CPS. Without GHG emission costs, LCOE is about 25% lower in the BPS than in the CPS, and further decreases by around 50% with GHG emission costs.

A renewable-led power mix as demonstrated in the BPS will not only deliver a power system that is low-cost and sustainable, but also consumes considerably less water than the CPS. Water demand for energy purposes in the BPS reduces by 87% in 2030, and by 99% in 2050, compared to 2015. Whereas energy-based water use in the CPS decreases only by 38% in 2050. The results indicate that transitioning to a renewable energy dominated power system, as observed in the BPS will dramatically influence the jobs market. Jobs increase significantly from about 210 thousand in 2015 to nearly 408 thousand by 2035, due to increasing electricity generation capacities stimulated by high growth rates. However, jobs created gradually reduces to over 278 thousand by 2050, as growth rates stabilise and labour productivity increases. On the other hand, jobs created in the CPS remain rather stable with a slight decline to about 184 thousand by 2050.

4.6 Publication VI: Transition towards decarbonised power systems and its socioeconomic impacts in West Africa

Aim

Publication VI aimed to explore the integration of large shares of renewables into a regional power system, for the West African power sector. Regional energy transitions are investigated to understand the underlying characteristics of energy systems that cover large geographic areas. There is a lack of sustainable energy transition studies for West Africa on high levels of geo-spatial and temporal resolutions. The research further examines the effects of large shares of renewables in meeting the rising demand in the region, including the roles and benefits of flexible electricity generation, power transmission and flexible storage solutions. The transition towards a fully decarbonised power system is envisioned for the 15 member states of the Economic Community of West African States (ECOWAS), from 2015 until 2050. In addition, the study seeks to determine the least-cost and most-job enriching power system for West Africa.

Methods

The West African power system was analysed with the LUT Energy System Transition Model (Bogdanov et al., 2019b). The job creation during the transition was analysed based on the methods of **Publication III**. The region was structured into 20 defined sub-regions based on existing cooperation. The main input parameters in determining a cost optimal transition pathway are described in the **Publication VI** and data are presented in the Supplementary Material. Employment factors used for jobs estimation can be found in the Supplementary Material of the **Publication VI**. Six different scenarios are analysed to understand the effects of various policy constraints such as regional electricity trade and GHG emissions costs.

Results

Results of the BPSs demonstrate that high shares of solar PV across West Africa can be supported by battery storage and other flexibility measures, such as extended grid interconnections, dispatchable renewables, curtailment and balancing gas turbines with e-fuels.

Transitioning to a fully RE-based power system, as illustrated in the BPS will not only deliver the lowest cost electricity but also emits less GHG and creates more jobs in West Africa and is compatible with the Paris Agreement and SDGs of the United Nations. This study presents a critical aspect of the transition for West Africa, which pertains to cost-competitiveness of RE technologies as observed in the BPSs in comparison to the CPSs.

Increasing costs of fossil fuel technologies in the CPS render the power system as economically unviable and violate sustainability constraints that form the core of resilient power systems. Furthermore, even without GHG emission costs, the least-cost solution leads to nearly 100% renewables in the BPSs with interconnections across the West African countries.

In the BPS, around 440 thousand direct energy jobs were created with solar PV emerging as the prime job creating technology with 68% of the total jobs in 2050. Whereas fossil methane based power generation created the most jobs in the CPS, with 45% of the jobs in 2050. In the BPS, batteries emerge as the key storage technology and hence drive jobs created from 2025 onwards, which increases to 44 thousand in 2030 and further increases to 76 thousand in 2050. Direct energy jobs created in the BPS grew massively from around 20 thousand in 2015 to about 440 thousand in 2050. On the contrary, jobs created in the CPS increased from around 20 thousand in 2015 to just about 183 thousand in 2050. Climate compliant and cost optimal energy system is the cornerstone for a vibrant and job-intensive energy policy option for entire West Africa as highlighted by the findings of **Publication VI**.

5 Discussion

5.1 General discussion of the presented results

Driving energy transitions and steering them towards high levels of sustainability will be one of humanity's greatest challenges in the 21st century. Whatever form they take, energy transitions will evidently be complex social, economic, ecological and technological transformations that require major changes for many communities around the world, as demonstrated in this research thesis and in **Publications I to VI**. Energy models explore and assess the feasibility and viability of this transformation and outline transition pathways. These have mostly been in the context to explore the current energy system transitioning towards renewable energy based systems. Additionally, to explore the full potential of renewables, energy efficiency and energy flexibility more comprehensive modelling of the energy system is required, which are often untapped in most models, in particular IAMs due to simplifications they adopt in the treatment of energy systems and outdated or sometimes biased input assumptions (Creutzig et al., 2017; Garcia-Casals et al., 2019). It is rather clear that energy scenarios have been underestimating the role of renewables in future energy systems due to the dynamic cost development of these technologies. Specifically, solar PV has been the most rapidly evolving energy technology in the last decade and is expected to be the prime source of energy in the 21st century (Haegel et al., 2019), despite which, IPCC scenarios have consistently underestimated the potential and corresponding costs of solar PV (Jaxa-Rozen and Trutnevyte, 2021), as a prominent climate mitigation solution (Victoria et al., 2021). Energy transition modelling and analyses have to evolve towards people centric concepts and inculcate social aspects into broader energy systems (Krumm et al., 2022), further energy transitions must address issues of gender equality and social inclusion for them to be truly just (Walk et al., 2021).

The comprehensive and often bottom-up energy system model formulation approach has allowed exploring the feasibility and viability, mainly indicating techno-economic implications of transitioning towards renewables based energy systems (Prina et al., 2020). Global analyses for high shares of renewable energy transition scenarios have been evolving since its first conceptualisation in 1975 and are increasingly getting complex and comprehensive as documented by Hansen et al. (2019) and Breyer et al. (2021). In addition, more recent comprehensive global energy system transitions towards 100% renewables have been proposed (Bogdanov et al., 2021; Jacobson et al., 2017; Pursiheimo et al., 2019; Teske, 2019) and many more 100% renewable energy analyses have been listed and analysed (CAT, 2018). However, there is overwhelming consensus globally that low carbon energy transitions must simultaneously achieve multiple goals: create a circular and green economy, ramp-up renewable energy capacities as well as increase access, reduce energy poverty, ensure positive employment effects with decent jobs along with gender equity and social inclusion, while safeguarding the environment and most importantly, mitigating climate change (Siciliano et al., 2021; Walk et al., 2021). Various energy transition scenarios also include links to and insights from socioeconomic and environmental systems. In most cases these are post modelling evaluations expressed in terms of system costs, jobs, pollution, GHG emissions, but not necessarily dynamic systemic couplings. Contextually, this research thesis has presented some of the key socioeconomic impacts (with externalities of GHG emissions and air pollution in **Publication I** and net employment impacts in **Publications III to VI**) emanating from the technoeconomic assessments of energy transitions (Bogdanov et al., 2019; 2021). Also highlighted the importance of externalities in determining energy costs in **Publication I** and the role of solar PV prosumers for increased citizen participation in **Publication II**, which can be internalised in energy transition analyses as indicated in recent research (Bogdanov et al., 2019; 2021). The social and environmental costs of energy generation are accounted through a price on CO_2 equivalent emissions (Bogdanov et al., 2019; 2021), which increases through the transition and can be enabled by a CO_2 equivalent emissions pricing either in the form of a tax or a cap and trade mechanism as suggested in **Publication I**. Solar PV prosumers are modelled initially and in conjunction with energy system analyses (Bogdanov et al., 2019; 2021), with the shares of prosumers determined by annual energy costs and local retail electricity prices as highlighted in **Publication II**.

It is evident from the results of **Publications I to VI** that energy transitions towards high shares of renewables will result in a multitude of benefits: declining levelised cost of energy, declining air pollution with induced health impacts and associated costs, declining GHG emissions contributing to climate mitigation and rising jobs with rising shares of solar PV prosumers. Despite these apparent benefits, energy transitions around the world face techno-economic challenges as well as socioeconomic dilemmas.

Energy costs with externalities as a key determinant of transition pathways

From the LCOE results presented in **Publication I**, it is unmistakeable that renewable electricity generation in all of the G20 countries have further reduced in costs than conventional alternatives. Lead by countries such as the USA, Argentina, Brazil, the EU, Turkey, China, India and Australia. This is already the case when external and CO_{2eq} costs are not considered. However, with clear socioeconomic and environmental impacts of electricity generation along with increasing adverse health impacts of fossil fuels and nuclear power generation being evident (Grausz, 2011; Kemfert et al., 2017; Löffler, 2021; Wealer et al., 2021), the need to represent the real costs of electricity generation is incontrovertible. When external and CO_{2eq} costs of the various electricity generation technologies are considered, LCOE of renewables and storage are much lesser than the LCOE of fossil fuels and nuclear across all the G20 countries. This suggests that there are clear socioeconomic benefits in making the right energy choices for governments of the G20 countries as well as rest of the world. At the same time, as indicated earlier it is expected that all G20 countries will demonstrate full cost competitiveness of renewable sources much before 2030 on a simple LCOE basis, which arguably is already the case in 2021 with record low costs of solar PV, wind energy and battery storage.

Fossil fuels based energy generation currently appears relatively low in cost due to the absence of or low costs of GHG emissions imposed by many markets around the world, which does not represent the real impacts of those emissions. Coal-based generation appears to be the lowest cost of fossil fuels due to its baseload nature of power plant operation when compared to methane based technologies. However, the coal industry has been in steady decline in the last decade plagued with rising risk profile and diminishing prospects of raising capital, stringent operational and environmental regulations are further jeopardising profitability (Carbon Tracker, 2020; 2021). The recent COVID-19 pandemic has only aggravated the coal industry further with countries worldwide prioritising green recovery plans (Oei et al., 2020). It should be noted, however, that methane based technologies are more flexible and play important roles in grid stabilisation and balancing, with the prospects of switching over to sustainable e-fuels in the future. Therefore, lower full load hours of methane turbine power plants are a major contributor to higher LCOE. CCS technologies appear very high in costs now and do not represent an economically competitive option in the near term (IEA, 2020c). Nuclear power appears relatively lower in costs in China and the Republic of Korea (likely due to high domestic subsidies and untransparent costs of nuclear reactors) but has significantly higher costs in other parts of the world, when the costs of financing, budget overruns, waste management, decommissioning and associated risks are included. After ten years of the Fukushima Daiichi disaster the nuclear industry remains in perils with scarce new constructions and the existing reactors in operational decline (Schneider and Froggatt, 2021). New entrants and emerging economies that plan to build new nuclear power plants should take heed of the fact that decommissioning of existing and end of life nuclear power plants across Europe and North America is increasingly complex and expensive, let alone the numerous waste management issues (Schneider and Froggatt, 2021). It is evident from research that nuclear power is not a viable climate solution (Kemfert et al., 2017; Larsen, 2020), and the costs of even the new age reactors are significantly prohibitive (Wealer et al., 2021).

Trends around the world are indicating to the unsound economics and substantial risks to investments in new fossil fuels and nuclear energy infrastructure. However, the sheer scale of subsidies makes them an important pillar of the energy industry (Coady et al., 2016; Duić, 2015). A recent study (IISD, 2020) found that production subsidies from the G20 countries averaged 290 billion USD annually during 2017-2019. Of this amount, almost 95% went towards oil and gas, with a relatively small amount earmarked for coal. Similarly, in 2019, global consumption subsidies stood at around 320 billion USD (Urpelainen and George, 2021). Once more, oil subsidies were the largest component, followed by electricity, natural gas, and then coal. While these subsidies have declined over the past several years, consumption subsidies were over 500 billion USD in 2013 (IEA, 2020e), which is still far higher than they should be in the context of global efforts to mitigate climate change. The plunge in fossil fuel prices and consumption induced by the Covid-19 pandemic is set to bring down global fossil fuel consumption subsidies to 180 billion USD in 2020 (IEA, 2020e), which would be the lowest annual figure in the last decade. This clearly points to the fact that governments around the world are yet to realise the substantial socioeconomic costs that will be induced from the continued support to fossil fuels and nuclear (Kemfert et al., 2020; Oei et al., 2020). The results of **Publication I** could help inform energy planners, investors and other key stakeholders on the unsound economics as well as the social and environmental costs induced by fossil fuels and nuclear sources of energy.

Solar PV prosumers as enablers of the energy transition

The emergence of decentralised electricity generation systems and demand side technologies including energy storage options and smart energy management systems are continually changing the way in which electricity is produced, sourced and consumed. The modularity of solar PV has propelled it to emerge as one of the most disruptive energy technologies in the 21st century. In this context, the research in **Publication II** highlights that value addition of PV prosumers and how they can reach beyond just the power sector and integrate heating as well as mobility aspects of residential households. Furthermore, the research in **Publication II** explores synergies of various complementary technologies such as Li-ion batteries, BEVs, HPs and TES that will most likely play significant roles in future energy systems. There is a growing synergy between energy and communication technology transitions, which also entails societal changes as further explored by Ruotsalainen et al. (2017). These technologies enable consumers to optimise their energy use, match it with their needs, and when applicable, with their energy generation and storage, increase cost effectiveness or energy efficiency (Parag and Sovacool, 2016). Peer-to-peer (P2P) energy sharing is an emerging disruptive phenomenon that has the potential to reshape power systems across the world and bring various benefits for both prosumers as well as power systems (Zhou et al., 2018). Furthermore, the role of prosumers in co-creating flexibility is a promising area to be further explored, offering greater potential for optimising energy utilisation as well as minimising overall costs of energy across a substantial number of prosumers (Kubli et al., 2018). These aspects of the rapidly evolving prosumer segment need to be integrated in future research.

PV prosumer systems with various components and the effects of residential retail electricity prices on their design and sizing are vital (Schwarz et al., 2018). It is evident that optimising system design and size is crucial to maximise benefits for PV prosumers, as showcased in the results of **Publication II**. Moreover, demand patterns for both electricity and heat vary significantly across the various regions worldwide and sometimes within regions themselves. Therefore, localising PV prosumer models is extremely vital to determine the most cost optimal solution in an accurate manner. The major benefit of this model is its ability to be modified according to different regional conditions and generate results with higher local relevance, as showcased for the case of Germany (Keiner et al., 2019), India (Ram et al., 2017) and in combination with the LUT Energy System Transition Model for Finland (Child et al., 2020). A recent energy transition scenario for Europe (Child et al., 2019) indicates that solar PV prosumers have a significant role with the costs approaching and even bettering retail electricity price parity across Europe and many parts of the world. This entails that solar PV prosumers will be an integral part of future energy systems and must be considered in energy system analyses worldwide.

Solar PV prosumers need to be embedded in global energy system transition analyses, which nearly no energy model current practices. However, recent studies for the global power sector transition and energy sector transition towards zero emissions in 2050 analyse solar PV prosumer shares in total electricity generation. About 18.8% of global electricity is met by PV prosumers in the power sector transition, while 10.4% of electricity is attributed to solar PV prosumers in the energy sector transition in 2050 (see Figure 12). However, these shares could be even higher with increased participation across residential, commercial and industrial premises.

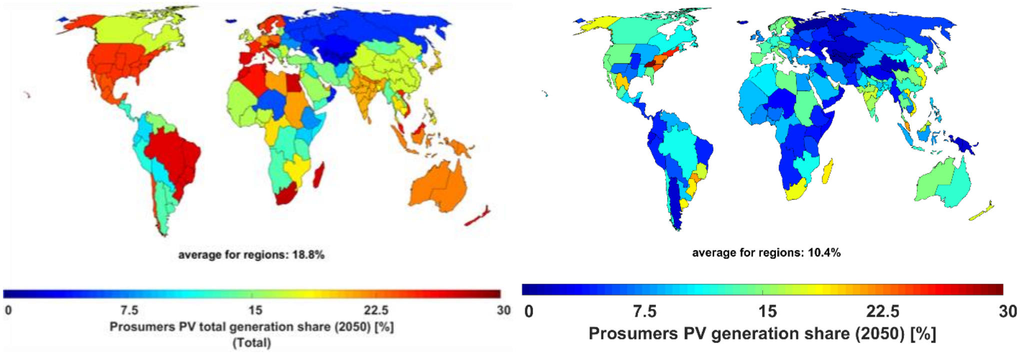

Figure 12: Electricity generation shares of PV prosumers in 100% renewables based power sector (left) and energy sector (right) across the different regions of the world in 2050 (Bogdanov et al., 2019; 2021). The energy sector comprises of energy demand from power, heat, transport and desalination.

The solar PV prosumer movement is gaining traction driven by declining costs and increasing electricity prices, with over 184,000 systems in Germany installed last year (BSW, 2021) and over 362,000 rooftop solar PV installations across Australia in 2020 (CSIRO, 2021). To complement this, there were over 11 million EVs on the world's roads at the end of 2020, following a decade of rapid growth. The near-term outlook for EV sales is rapidly gaining. In the first-quarter of 2021, global electric car sales rose by around 140% compared to the same period in 2020, driven by sales in China of around 500,000 vehicles and in Europe of around 450,000 (IEA, 2021a). Integrating BEVs into residential PV systems is beneficial for ensuring optimal energy usage as well as minimal ATCE, as indicated by **Publication II**.

Net employment effects of energy transitions as a vital socioeconomic parameter

The issue of jobs has always been a contentious topic, in the context of energy transitions. Most opinions are rather swayed by political commentary on the adverse employment effects of energy transitions and tend to focus on possible job losses in a particular locality, state, region, or country (Brown and Ahmadi, 2019). Over the recent past, there is growing evidence that the employment impacts of energy transitions across the world have positive correlation. A study (Lund and Hvelplund, 1998) conducted as early as 1998 concludes that the net employment effects will be positive from energy transitions towards renewable energy technologies. Several studies have demonstrated that the exploitation of renewable energy sources for electricity production creates a greater number of jobs than that supplied by conventional power generation and is analysed by Cameron and Van Der Zwaan (2015). It is found that for the installation of every megawatt of power generation capacity, renewable energy sources create between 1.7 to

14.7 times more jobs than natural gas based power generation and up to 4 times more jobs than those supplied by coal fired power generation (Cameron and Van Der Zwaan, 2015).

The job creation results of **Publication III** for the global power sector and **Publication IV** for the global energy system seem to follow different patterns, but both suggest significantly higher jobs through the transition. Direct energy jobs in the case of the energy system are primarily driven by the fundamental change in the energy system with increasing levels of electrification by 2050. This leads to significant jobs through the transition period and the specific jobs (jobs per unit of final energy demand) rise through the transition driven by efficiency gains from high levels of electrification (see Figure 13). On the contrary, specific jobs (jobs per unit of electricity) in the power sector follow a more conventional pattern with the ramp up of capacities and further steady decline with increasing productivity across the world (see Figure 13). Solar PV is expected to emerge as the primary jobs creator in both the power sector as well as energy sector, with the wind and battery industries creating substantial jobs too.

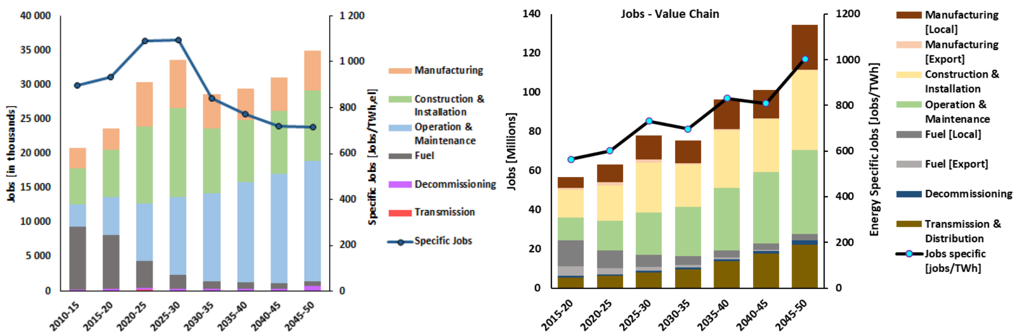

Figure 13: Job creation in 100% renewables based power sector (left) and energy system (right) across the different regions of the world in 2050 (**Publications III and IV**). The energy system comprises of energy demand from power, heat, transport and desalination.

The collective consensus indicates that higher shares of renewables and complementary sustainable technologies do have net positive impacts on employment and jobs. **Publication IV** estimated and presented the net employment effects during a global energy transition across the power, heat, transport, and desalination sectors with around 134 million direct energy jobs by 2050. There are a few recent studies, Jacobson et al. (2019), Dominish et al. (2019), Pai et al., (2021), IRENA (2020a) and IEA (2021b) that have estimated employment impacts from global energy transitions. Jacobson et al. (2019) estimated nearly 55 million total energy jobs in 2050 (net of 29 million after considering jobs lost) form wind energy, water and solar energy (WWS) generators with transmission for the entire energy system (power, heat and transport). Dominish et al.

(2019), quantitatively estimated that in 2050, there were about 29.6 million energy sector jobs in the 5.0 °C scenario, 50.4 million energy jobs in the 2.0 °C scenario, and 47.8 million energy jobs in the 1.5 °C scenario. Pai et al. (2021) find that, by 2050, jobs in the energy sector would grow from today's 18 million to 21 million in the reference scenario and even more, to 26 million, under the well-below 2°C scenario. While fossil fuel extraction jobs rapidly decline, these losses are compensated by gains in solar and wind jobs, particularly in the manufacturing of solar and wind technologies (Pai et al., 2021; 2020). In IEA's net zero emissions 2050 (NZE2050) scenario, clean energy employment increased by 14 million to 2030, while employment in oil, gas and coal fuel supply and power plants declined by around 5 million, leading to a net increase of nearly 9 million jobs resulting in a total of 49 million energy jobs in 2030 (IEA, 2021b). IRENA (2020a) estimated 100 million jobs in the energy system by 2050, however, the energy transition pathway results in just 65% renewable energy in the total primary energy supply in 2050.

The wide range of estimates of net jobs created across the different studies is attributed primarily to the different approaches adopted and the varying energy scenarios that are a fundamental determinant. Moreover, most of the studies are limited to renewable electricity generation technologies that do not consider storage, power-to-X, e-fuels including green hydrogen production in the corresponding job estimates. Comprehensive analyses of energy system transitions will enable estimates of net employment effects in not only renewable electricity generation, but also in complementary and auxiliary technologies throughout their value chains.

Jobs created and net employment effects from the increasing adoption of flexible energy technologies (storage and Power-to-X) must be considered for more comprehensive analyses. However, in terms of assessing broader socioeconomic aspects, IRENA has evaluated impacts to GDP, employment and welfare (IRENA, 2020b, 2018b). The assessments show that even a less ambitious energy transition scenario with around 90% emissions reduction creates substantial welfare benefits, while lesser benefits in terms of employment and GDP (Garcia-Casals et al., 2019). **Publications III and IV** indicate that a greater number of jobs are created in 2050, with lower electricity costs and stable energy costs implying the current fossil fuels dominated energy system is less labour intensive and drives the concentration of wealth in fossil fuels extraction industries. On the contrary, renewables are more labour intensive and enable distribution of wealth across the value chain, with financial benefits for the end use consumers too, through prosumer models. In addition, regional and decentralised value chains with local manufacturing could enable creation of jobs around the world as highlighted in **Publications III and IV**. COVID-19 has induced disruptions (Panwar et al., 2022) in global supply chains of many industries including renewable energy and storage technologies, which has necessitated various stakeholders to emphasise sustainable and resilient supply chains (Sarkis, 2020) for enabling the energy transition in countries around the world. This could further boost the creation of local and regional industries within supply chains to enable energy transitions and green recovery of economies worldwide (Tian et al., 2022).Labour markets across the world face stagnating economic activity plagued with high and rising unemployment rates, that have been exacerbated by the recent COVID-19 pandemic. To make matters worse, risk of social instability, unrest or discontent are increasing worldwide. The ILO’s social unrest index, which seeks to represent the expressed discontent with the socioeconomic situation in countries, indicates that average global social unrest has increased (ILO, 2017; Kollewe, 2010). Therefore, the creation of employment opportunities around the world is a major policy and recovery priority, either as a long-term issue or as an immediate consequence of the COVID-19 pandemic. The research through **Publications III and IV** substantiates the case for ensuring an economic recovery with energy transition investments, creating ample jobs and investing in a more sustainable future. Diversifying supply chains with emphasis on local and regional manufacturing can further boost employment prospects, particularly for emerging and developing economies. Similarly, **Publications V and VI** imply job creation through energy transitions in South Africa and West Africa, regions that suffer from widespread unemployment (ILO, 2021).

Air pollution and greenhouse gas emissions reductions as co-benefits of climate compliant energy transitions

Besides being a health problem, ambient air pollution contributes to less-liveable conditions across the cities worldwide and hinders economic growth, especially in developing countries. Synonymously, GHG emissions have exacerbated the fragile ecosystem of the planet and brought society to a juncture of eminent collapse with runaway climate change. Economically disadvantaged people are more likely to live in polluted environments and suffer adverse impacts induced by air pollution and GHG emissions induced climate impacts. In addition, people who are sick because of exposure to air pollution are more likely to take days off work and suffer from reduced productivity, which in turn undermines their contributions to economic development. Air pollution could also hinder the ability of cities to attract talented workforce, thereby reducing attractiveness. Furthermore, air pollution imposes heavy economic burdens on countries around the world due to premature deaths, illness, lost earnings, and increased health care expenditures. Ironically, it is those that have the least means to address health damages from air pollution that often disproportionately carry the economic burdens. However, various research studies (Galimova et al., 2022; Garcia-Casals et al., 2019; Jacobson, 2017; Ram et al., 2022) show that with a progressive energy transition towards higher shares of renewables, developing countries can reduce air pollution impacts rapidly and leapfrog into a sustainable future. There is growing evidence that air pollution, GHG emissions, climate impacts and health are interlinked (Carlson et al., 2021; Reis et al., 2022; Uitto, 2021) and have to be tackled in a wholistic manner by both developed and developing nations.

Global health crises further highlight the need for continued action in addressing global and cross-cutting challenges such as air pollution and GHG emissions induced climate change. The current global COVID-19 pandemic, caused by the novel coronavirus SARS-CoV-2, underscores the importance of reducing air pollution through preventive and mitigation measures. People who contract COVID-19 and have underlying medical issues such as heart disease, lung disease, and cancer are at a higher risk of developing serious life threatening illnesses that could lead to deaths (Urrutia-Pereira et al., 2020). It is noteworthy that air pollution is already a cause for many diseases (Cohen et al., 2017). Ongoing research (Bourdrel et al., 2021) is finding relationships between air pollution and the incidence of illness and death due to COVID-19. Such research suggests that $PM_{2.5}$ air pollution plays an important role in increased COVID-19 incidence and death rates. One such study (Andree, 2020) reported that $PM_{2.5}$ is a highly significant predictor of the number of confirmed cases of COVID-19 and related hospital admissions. This implies more impetus to mitigation actions.

Fixing air pollution implies eliminating its sources. As energy use in the power, heat, and transport sectors represent almost the entire energy and fuels used, it is crucial for countries around the world to finally phase out fossil fuels and combustion of bioresources for heating and cooking that emit both GHG and air pollutants by substituting them with sustainable energy sources. As Hansell et al. (2016) conclude the most recent exposure to pollutants has the largest effects, which means that despite the current population already being exposed to pollution, it is still in the best interest of nations to cut harmful emissions as fast as possible to limit the impacts (Uitto, 2021). Air pollution and GHG emissions induced climate change are closely interlinked, as both share common emission sources, which mainly arise from fuels combustion and industrial processes. Climate mitigation actions bring co-benefits on air quality and human health.

5.2 Policy implications

Large-scale energy transitions are the most momentous decisions that societies ever make. It will most likely define much of the local, national, regional and global politics of the next three decades and beyond. It is critical, therefore, that societies grapple with the full ramifications of these transitions and approach them as complex social, economic, ecological and technological systems transformations that they actually are. This research thesis has explored some of these aspects in a more comprehensive manner.

The issue of real energy costs and corresponding subsidies, mainly for fossil fuels and nuclear industries have been discussed in global forums for quite a few years now (Coady et al., 2016; Duić, 2015; Grausz, 2011; Parry et al., 2014). However, very little translates into actions as fossil fuels subsidies continue to be handed out. Subsidies further encourage the uncompetitive, inefficient and potentially wasteful production and use of fossil fuels and can mean emission-intensive assets are funded today, thereby locking in their emissions for decades or rendering them stranded assessts in the near future (Baron and Fischer, 2015; Caldecott et al., 2016). Therefore, an absolute ban on fossil fuels and nuclear subsidies should be encouraged by the global community. On the contrary, cross subsidisation from penalising fossil fuel consumption to boosting adoption of renewable and sustainable technologies must be pursued.

Solar PV prosumers are already disrupting energy systems and markets. Policies to promote greater adoption of solar PV across the residential, commercial and industrial premises should be adopted and encouraged (Kihlström and Elbe, 2021; Parag and Sovacool, 2016; Zapata Riveros et al., 2019). Financing of these systems will lead to greater adoption. Solar PV has huge potential in ensuring universal access to energy, small scale systems and micro grids are already a viable option to extension of centralised grids (Laursen, 2017). Therefore, solar PV prosumer concepts could be adopted to rural electrification and to provide energy access.

Job creation should be a great motivator to governments around the world. Most importantly in developing and emerging countries that have higher shares of youth in the population will need to create more jobs to ensure sustained growth (ILO, 2018; 2020). It is evident that countries that ramp up manufacturing capabilities for renewable energy and sustainable technologies will stand to gain from export opportunities and a vibrant domestic industry. Sun Belt countries could emerge as the hubs for low cost solar energy opening avenues for low-cost production of green hydrogen and e-fuels (Vartiainen et al., 2021). Thereby creating plenty of jobs and building robust economies on solar energy. There could very well be ‘solar economies’ that replace the legacy ‘oil economies’ as the hubs for energy in the future.

Air pollution policies have traditionally aimed at reducing exposures to air pollution, which has yielded important benefits for many cities and countries around the world (Quarmby et al., 2019). However, with growing air pollution from developing and emerging economies it has come to the forefront as a global problem (Mujtaba and Shahzad, 2021). Therefore, cutting emissions at the source is the most powerful tool for protecting people's health over the long term. The transport sector contributes substantially to air pollution particularly in cities with high density traffic (Anenberg et al., 2019). Diesel exhausts from movement of goods, specifically trucks, trains and marine sources are growing and of particular concern. The WHO (IARC and WHO, 2012) and other research (Silverman, 2018) have classified diesel engine exhaust as carcinogenic to humans. Promoting the uptake of BEVs aggressively is required all over the world, as reducing tailpipe emissions also reduces GHG emissions that contribute to climate change. Reduction in air pollution and corresponding mortality and damage costs are more than just co-benefits of the energy transition, in most cases air pollution induces more economic costs than the cost of transitioning to renewables (Pereira et al., 2021). Therefore, designing economically integrated policies that simultaneously generate cleaner air and less global warming increases global wellbeing, and facilitates the political economy of a sustainable energy transformation in key emitting regions (Reis et al., 2022).

The findings of **Publications I to VI** serve as clear evidence that policies and fiscal incentives must be oriented towards enabling a rapid energy transition worldwide. The socioeconomic benefits are immense and cannot be ignored by planners and policy makers around the world. These benefits could soon turn into high opportunity costs if progress in energy transition is delayed.

5.3 Limitation of the current research and future research prospects

Socioeconomic benefits mostly tend to have local relevance. Thereby, contextualising the benefits from a local perspective is vital. Evaluating socioeconomic benefits for global energy transition scenarios could be limited with certain global assumptions and simplifications that ignore the regional variation. This research thesis is focused on the LCOE with externalities, solar PV prosumers, direct energy jobs and net employment effects, and air pollution levels with corresponding health and economic impacts. However, other socioeconomic dimensions such as water and food availability through energy transitions and corresponding impacts could enrich this research thesis to deduct more comprehensive analyses. Furthermore, some fundamental assumptions in determining cost optimal energy transition scenarios could be enhanced, particularly the interest rates of capital or lending rates for energy projects around the world. Simple WACC assumptions do not capture or justify the complexity of investment decisions around the world and capital costs of energy technologies including renewables vary drastically across the world. Enhanced cost assumptions and comprehensive analyses on interest rates could benefit energy system transition analyses form researchers around the world (Bogdanov et al., 2019a).

Some of the more specific limitations are:

- Levelised cost of energy estimations are extremely contentious, and the issue of externalities make it even more complex. Access to real data pertaining to cost of different technologies is rather limited and are dynamic to regional markets. Some of the cost assumptions could be rendered conservative in **Publication I**, however this does not impact the key findings and rather substantiates them. As the costs of renewable and storage technologies have beaten the best estimates and keep declining even further. Some of the assumptions are discussed in further detail in the response article by Ram et al. (2020a). The issues around capital costs of different energy technologies and corresponding WACC are highlighted in **Publication I** and further explained in Ram et al. (2020a).

- Solar PV prosumers are significantly influenced by local conditions and household characteristics. It is acknowledged that global analyses of solar PV prosumers induce a few limitations on capturing local conditions. Household characteristics vary drastically across the different countries and within the countries of the world. However, the findings of **Publication II** could provide crucial insights for further regional and national research on solar PV prosumers.

- Likewise, jobs are defined by local characteristics and vary across the different regions of the world. However, global influences in terms of trade flows and exports-imports are prominent. Global assessments of job creation do have limitations, as some of the assumptions are captured on a larger regional level, in particular labour productivity. Capturing the flux in employment origination is a challenge, as manufacturing and production jobs shift to low-wage markets. There are further uncertainties such as impacts of technological trends of automation and digitisation on workforce requirements. All these factors do amplify the limitations of global assessments of employment trends. However, the current trends do follow earlier assessments, especially with the growing number of jobs in the renewable and sustainable technology space.

- Air pollution assessments have similar limitations with availability of localised data, local regulations influencing adoption of different fuels and technology standards around the world. In addition, significant limitations in assessing mortality and health impacts, assigning costs to human lives and lost productivity are prone to uncertainties.

More comprehensive socioeconomic analyses are required to assess the magnitude of change induced by energy transitions. Capturing the effects of renewable energy and sustainable technologies on economic growth and contributions to welfare across the different countries of the world. Further analyses on real costs of energy with considerations of risks and capital availability. Comprehensive analyses of solar PV prosumers with different regional contextualisation. Employment analyses in greater detail with well-defined methods and upgrading to latest technogies that have the potential to enable energy transitions. Comprehensive analyses of air pollution with greater regional perspective enables well informed research insights. Moreover, other socioeconomic dimensions of water and food in correlation to the energy transition could be explored in greater detail.

6 Conclusions

Renewables are the harbinger for the new energy age set to dawn upon us. Society is now decoupling from an era of constructing large-scale centralised energy systems, which have turned out to be highly inefficient, inequitable and unsustainable to now re-constructing diverse, flexible, intelligent and sustainable energy systems. It is evident from this research thesis and through **Publications I to VI** that energy systems are not in isolation but are intrinsically linked to the wider economy and society. The energy choices made by society will have ramifications in some of the most essential systems such as water, food and the natural environment. The 6th Assessment Report from the IPCC has warned that global warming of 2°C will be exceeded during this century resulting in dire consequences worldwide, unless rapid and deep reductions in GHG emissions occur in the coming decades to limit global temperature rise to 1.5°C. This implies a rapid energy transition towards renewables and other sustainable technologies, posing daunting challenges to engineers, policy-makers and societies around the world. However, there is growing scientific evidence that rapid energy transitions towards zero emissions are both technically feasible and economically viable as highlighted by **Publications I to VI**. Furthermore, it supports achieving global SDGs and enabling socioeconomic prospects, as substantiated in **Publications I to VI**. The new age energy system must be affordable with the reflection of true energy costs to society, ensure choices for increased active participation of consumers and prosumers, create equitable opportunities with decent jobs and foster a healthy and sustainable environment for future generations.

All energy production has social and environmental effects. But estimating these effects and pricing energy accordingly has and continues to be a rather contentious issue. Energy production is rife with externalities as highlighted in **Publication I**. Extraction of fossil fuels often causes water pollution, habitat destruction and other socioeconomic harms. Burning fossil fuels pollutes the air, sickening and killing millions of people, and introduces toxic mercury into aquatic food chains. Nuclear power plants require constant clean-up and maintenance of radioactive materials even years after decommissioning. Energy production in thermal power plants use water, sometimes at the expense of agriculture and domestic needs. Despite the challenges, economists are trying to put an appropriate price on some of these impacts as discussed in the earlier sections. As highlighted in **Publication I**, even with conservative external costs included in LCOE for energy production across different energy sources, renewables will have much lower LCOE than fossil fuels and nuclear. In terms of generation costs, solar PV is rapidly undercutting all energy technologies around the world, even without considering any external costs. This trend is only expected to drive costs lower, further aided by the rapidly declining costs of battery storage.

Solar PV complemented by battery storage is poised to become the prime source of energy in the 21st century. Solar PV prosumer homes, as highlighted in **Publication II** could soon become the norm, just as it is taken for granted in current times that modern homes come with assured electricity, folks in the 22nd century could look back and ponder how people lived in homes without solar, just as present day folks look back to the 20th century and wonder how people lived in homes without electricity or bulbs for that matter. Some may suggest that there are currently over 750 million people still without access to modern electricity according to the World Bank, however this could solely be attributed to the current inefficient fossil fuels reliant centralised energy system. On the contrary, the modularity and flexibility of solar PV has enabled access to the millions of unelectrified people along with solutions such as solar freezers enabling access to health care, solar water pumps helping farmers around the world and many more applications lifting millions out of poverty. Solar PV systems could be as ubiquitous as mobile phones around the world complemented by new age smart and digital technologies as highlighted in **Publication II**. Governments around the world should realise the potential of solar PV to disrupt legacy energy systems and invest their resources in building domestic capabilities to advance energy transitions, particularly in Sun Belt countries, which also happen to be mostly developing and emerging economies. Prioritising the development of local solar industries could be a means of leapfrogging into a sustainable future, thereby boosting domestic economies and creating much needed jobs.

Renewable energy and complementary sustainable technologies create jobs up and down the supply chains and can spur widespread social and economic development, as validated by **Publications III to VI**. Renewable energy technologies accounted for an estimated 11.5 million jobs worldwide in 2019 according to IRENA. Increasingly storage technologies are gaining ground, particularly battery storage propelled by the growing demand for EVs and despite the pandemic induced unemployment last year, over 400,000 jobs were added by storage and clean vehicles industries in the US according to latest employment figures from the US government. There is growing consensus and scientific evidence suggesting a rapid transition to 100% renewables powered energy systems will result in creation of more jobs than jobs lost in mainly extraction of fossil fuels, as highlighted in **Publications III to VI**. Nonetheless, just transition policies should be encouraged by governments around the world emphasising workforce reskilling. Creating substantial number of jobs implies ensuring a healthy workforce. However, high levels of GHG emissions and air pollution are taking a toll on people's health around the world.

Air pollution remains the leading environmental health risk factor contributing to growing numbers of premature deaths worldwide, as indicated in research (Galimova et al., 2022; Jacobson, 2017). In addition, growing health care costs and lost worker productivity are direct economic impacts of air pollution so large they can exceed the costs of many nations' annual budgets around the world. Both climate change and air pollution are deeply linked and influence each other, for example climate change induced forest fires in turn increase air pollution. Importantly, both originate from the same sources of anthropogenic emissions, predominantly burning fossil fuels. Research (Galimova et al., 2022; Garcia-Casals et al., 2019; Jacobson, 2017) highlights the steep socioeconomic impacts of air pollution from the current fossil fuels dominated energy system. However, a global energy transition towards zero emissions driven by rapid electrification of energy use indicates substantial socioeconomic benefits from reduced air pollution, as highlighted in various research studies (Galimova et al., 2022; Garcia-Casals et al., 2019; Jacobson, 2017). It must motivate governments around the world that air quality benefits could arrive much sooner than climate benefits, which are usually drawn out over decades. Nonetheless, energy transitions to high shares of renewables induce multiple co-benefits and the impacts of climate change as well as air pollution are mitigated.

This research thesis has attempted to comprehensively evaluate the socioeconomic aspects of energy technologies and corresponding transitions. It has consistently found positive impacts of renewable energy technologies and particularly solar PV. The findings of **Publications I to VI** further substantiate the fact that renewables are not only cost competitive but are undercutting conventional energy sources, despite the continual flow of massive subsidies into fossil fuels and nuclear energy. Moreover, renewables led by solar PV are reorganising the energy system towards higher decentralisation and enabling participation of consumers. In the process of the transition, it is evident that renewables and corresponding technologies will create substantial numbers of jobs across the value chain, thereby neutralising the effects of job losses in fossil fuels. Most importantly, the transition to renewables can enable rapid decline in GHG emissions as well as air pollution, both having extremely detrimental impacts.

Mitigating climate change does not mean losing out on current socioeconomic comforts or lifestyles, but rather moving towards a future with greater socioeconomic benefits and most likely more equitable and sustainable lifestyles.

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Publication I

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A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030

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A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030

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A B S T R A C T

Despite the positive momentum achieved by the renewable energy sector in recent years, there are substantial challenges that need the attention of the global community, and one of the more pressing issues is dealing with the deleterious external costs of power generation. One of the parameters to compare costs of energy across various technologies is levelised cost of energy (LCOE), but it has been conventional practice to neglect the external costs in estimating the LCOE of power generation technologies. Furthermore, as LCOE is a critical indicator for policy and decision makers, there is a need to juxtapose actual costs of renewable and conventional power generation technologies. This research paper attempts to internalise some of these external and GHG emission costs across various power generation and storage technologies in all the G20 countries, as they account for 85% of global power consumption. As future investment decisions are largely influenced by costs, estimates in this research prove renewables and storage to be far cheaper than fossil and nuclear sources by 2030, even without considering external costs. The myth that renewables are 'way too expensive' has been debunked repeatedly, and the cost decline of wind and solar photovoltaic (PV) technologies have outpaced most industry expectations. The results of this research not only substantiate this trend, but also statistically display that all the G20 countries have the opportunity to decrease their energy costs significantly, between now and 2030. Renewable energy technologies offer the lowest LCOE ranges across G20 countries in 2030. Utility-scale solar PV generally shows the lowest values ranging from 16 to 117 €/MWh_{el} and onshore wind LCOE range is from 16 to 90 €/MWh_{el}. Rooftop solar PV generally offers the next lowest LCOE ranging from 31 to 126 €/MWh_{el}, followed by LCOE of offshore wind power ranging from 64 to 135 €/MWh_{el}. Solar PV and battery systems are highly competitive on an LCOE basis at utility-scale ranging from 21 to 165 €/MWh_{el} and at residential scale from 40 to 204 €/MWh_{el}. The G20, as well as other countries, can continue to develop their economies in a sustainable manner, along with substantial co-benefits in adjacent policy fields such as higher national welfare, better health of citizens, lower respective health costs and improved energy security.

1. Introduction

The United Nations adopted two historically significant agreements in 2015: the Paris Agreement (UNFCCC, 2015) and the 2030 Agenda for Sustainable Development (United Nations, 2015). Governments agreed to a long-term target of limiting the increase in global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit temperature increase to 1.5 °C (UNFCCC, 2015; Roehrkasten et al., 2016). The agreement calls for global greenhouse gas (GHG) emissions to peak as soon as possible, recognizing that this will take longer for developing countries, and for rapid emission reductions thereafter. Moreover, the United Nations has for the first time included energy in its new Sustainable Development Goals (SDG 7 - Ensure access to affordable, reliable, sustainable and modern energy for all), calling

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Abbreviations

BECCS	Bioenergy Carbon Capture and Storage
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
CAES	Compressed Air Energy Storage
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
CCGT	Combined Cycle Gas Turbine
COP	Conference of the Parties
CSP	Concentrated Solar Thermal Power
DACCS	Direct Air Carbon Capture and Storage
EU	European Union
FLH	Full Load Hours
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GW	Gigawatts
G20	Group of Twenty
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
MW	Megawatt
OCGT	Open Cycle Gas Turbine
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydroelectric Storage
PtL	Power-to-Liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy, partly used in the sense of Renewable Electricity
SDGs	Sustainable Development Goals
SNG	Synthetic Natural Gas
TPED	Total Primary Energy Demand
TW	Terawatt
USD	Unites States Dollar
WEO	World Energy Outlook (flagship report of the IEA)

for an increased acceleration of renewable energy (RE) deployment. Two-thirds of global GHG emissions stem from energy production and consumption, which puts the energy sector at the core of efforts to combat climate change and the successful outcome of these international agreements will depend on a rapid transition of the global energy system (IPCC, 2014; Halsnæs and Garg, 2011).

Economies around the world face the complex challenge of tackling climate change whilst ensuring the social and economic progress of their populations. In this context, the Group of Twenty (G20), which is a critical forum for global economic governance, has the prerogative to set the agenda for a global energy transition. It includes twenty of the world's largest economies: Argentina, Australia, Brazil, Canada, China, the European Union (EU), France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, Republic of Korea, Turkey, the United Kingdom (UK) and the United States of America (USA)(G20 Research Group, 2018). Member countries account for 86% of the global gross domestic product (GDP), more than three quarters of global energy demand and 84% of global GHG emissions from the energy sector as indicated in Fig. 1. Given the sheer weight in the global energy system of the G20 countries with nearly 85% of the global power consumption, it is not surprising that 87% of global renewable power capacity addition happened in the G20 nations as indicated in Fig. 1. Hence, any collective move by the group will have substantial effects on global energy markets.

A rapid transition of power systems in the G20 countries is taking shape, and in this context, costs will play an important role in determining the required investment levels across the entire power system. The fall in costs of wind turbines, solar photovoltaics (PV) and batteries, mainly due to their increasing deployment, is well documented and demonstrated by overall investments in renewable sources remaining quite flat between 2011 and 2015 despite annual capacity additions rising by 40% (Ram et al., 2017; Frankfurt School-UNEP Centre/BNEF, 2017). An International Renewable Energy Agency (IRENA) analysis shows that between the end of 2009 and 2016, solar PV module costs have fallen by around 80% and those of wind turbines by 30–40% (IRENA, 2016). In many regions of the world, biomass for power, hydropower, geothermal and onshore wind can all now provide electricity competitively compared to fossil fuel-fired electricity generation (Ram et al., 2017). The levelised cost of energy (LCOE) of solar PV has fallen by more than 60% between 2010 and 2016 based on preliminary data; moreover, solar PV achieved highly competitive levels at the utility-scale across the world (IEA-PVPS, 2017).

The G20's energy agenda has been evolving in recent years. The task of the G20 through successive summits has been to seize the momentum of the Paris Agreement and the SDGs to foster collective action towards a sustainable, decarbonised and affordable global energy system (Roehrkasten et al., 2016). Investments in efficiency and renewable energy are expected to become the norm, as investments in fossil-based power generation will be an exception with clearly defined timelines for an exit. One of the main agendas for the global community is to move away from fossil fuel subsidies both in developed and in developing countries that are beginning to show adverse economic impacts (Mills, 2017). A shift in investments towards sustainable energy sources is already underway, as governments and financial institutions want to avoid lock-in effects. This will be a challenging undertaking, as the G20 members are highly diverse, often with very divergent interests in the energy spectrum. Fig. 2 highlights the diverse energy mix of the G20 countries and their corresponding shares of installed capacities. If the G20 members agree on joint action, this will have important international signalling effects and considerable influence on international policymaking. This could make the G20 an ideal forum to steer an energy transition by complementing existing institutions and bringing greater coherence to the global energy architecture.

Technology and finance are strong determinants of future societal paths. While society's current systems of allocating and distributing resources while prioritising efforts towards investments and innovations are in many ways robust and dynamic, there are some fundamental tensions with the underlying objectives of global sustainable development. Technological innovations and financial systems are highly responsive to short-term motivations, and are sensitive to broader social and environmental costs and benefits only, to an often limited extent that these costs and benefits are internalised by regulation, taxation, laws and social norms (IPCC, 2014). In this context, as costs are a vital indicator for planning and decision making of government's around the world, this research paper analyses the costs of power generation in the G20 countries in the present context and from a future perspective for 2030. It involves estimating the LCOE for different power generation and storage technologies for each of the G20 member countries in 2015 and for the possible situation in 2030. It also

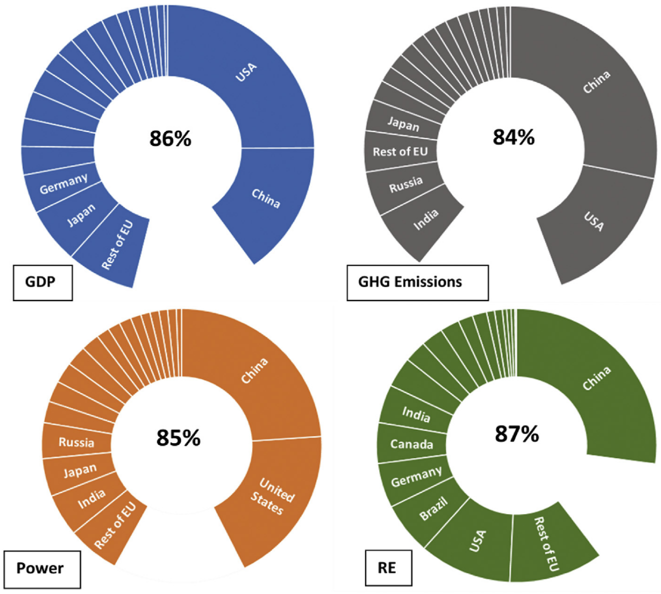

Fig. 1. G20 share of global GDP, Greenhouse Gas (GHG) emissions, power consumption and share of renewable energy (RE) installed capacity (IEA, 2016; IMF, 2017; IRENA, 2017b).

considers the effects of externalities such as, additional costs of GHG emissions, health related costs amongst other societal costs and subsidies on the levelised costs of power generation in the G20 countries. Additionally, this is a first of its kind study aimed at estimating LCOE (with and without external as well as GHG emission costs) of the most relevant power generation and storage technologies for each of the G20 member countries from a future perspective. Furthermore, providing a comparative analysis of the costs of renewable power generation combined with storage, and the costs of fossil fuels and nuclear. These results will assist policy makers across the G20 and other countries to make informed decisions in carving out their future energy pathways, and inform all the stakeholders as well as civil society in general. This paper includes a literature review of most relevant cost of energy estimations across the different parts of the world presented in section 2. The detailed methodology along with the relevant assumptions and parameters adopted for estimating LCOE are presented in section 3. Followed by section 4, which highlights the results for all G20 countries in 2015 and 2030, and section 5 presents the analyses of LCOE for renewables and storage in comparison to conventional fossil fuel and nuclear power generation. Finally, section 6 draws conclusions and raises a few policy implications of the results.

2. Literature review

In general terms, LCOE is the estimated amount of money that is incurred for a particular electricity generation plant to produce a standard amout of electricity (either kWh or MWh) over its expected lifetime. Despite some critiques of LCOE as a tool for comparing costs across power generation technologies such as Hirth et al. (2015), Schmalensee (2016) and Synapse Energy Economics (2016) amongst others. LCOE remains a robust tool, as it offers several advantages as a cost metric, such as its ability to normalise costs into a consistent format across decades and technology types. Additionally, it provides ample flexibility to incorporate many factors and parameters to provide comprehensive cost perspectives. Consequently, it has become the de-facto standard for cost comparisons amongst the many stakeholders such as policymakers, analysts, and advocacy groups (Rhodes et al., 2017). There are many organisations that estimate LCOE values on an annual basis, a few of them are BNEF (Frankfurt School-UNEP Centre/BNEF, 2018, 2017) that analyse LCOE for the different power generation technologies and Lazard (2016; 2017) that determine the LCOE of all technologies in the power sector of the USA. Whereas, IRENA estimates the renewable power generation costs across the world on a periodic basis (IRENA, 2018, 2015). Similarly, the IEA with it's annual flagship report world energy outlook (WEO) (IEA, 2017, 2016) have long term projections of LCOE upto 2050 for the different power generation technologies. Furthermore, various government organisations have developed LCOE models customised for their respective countries, such as US LCOE model by the Department of Energy (DOE) (USDOE and NREL, 2018), UK Government's electricity costs model developed by Department of Energy and Climate Change (DECC) (DECC, 2013) and Australia Energy Technology Assessment (AETA) model by Bureau of Resources and Energy Economics (BREE) (Arif Syed (BREE), 2013), amongst many others. But, there is a huge variance in the consideration of externalities and other parameters, as shown in the comparitive analysis amongst these along with a few other LCOE models in Foster et al. (2014).

Although LCOE is a well developed and standard technique in evaluating energy sector economics, authors approach model formulation in various ways, so as to ensure the model matches research objectives and data availability (Foster et al., 2014). There

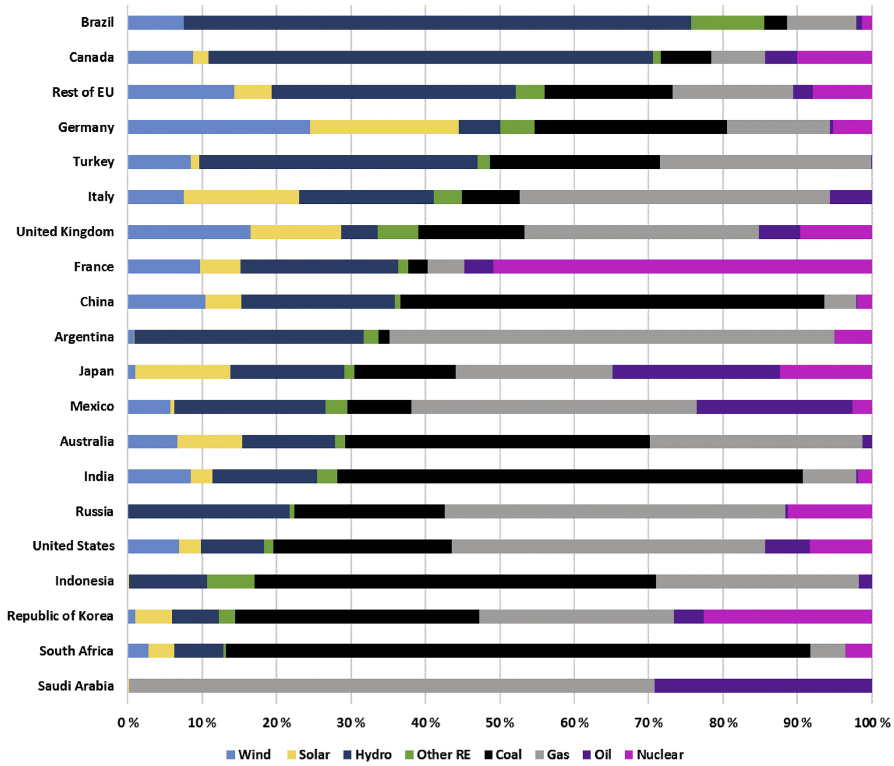

Fig. 2. Shares of different power generation capacities across the G20, with Brazil at the top having the highest share of renewables and Saudi Arabia at the bottom with the lowest share (IRENA, 2017b; Coal Tracker, 2017; Knoema, 2016; Schneider and Froggatt, 2016).

have been previous efforts to comprehensively integrate social and environmental costs of power generation as part of LCOE estimations, some of the interesting approaches are (Rhodes et al., 2017), which applied a geographically-resolved method to calculate the LCOE of new power plants on a county-by-county basis while including estimates of some environmental externalities across the USA. Küchler and Meyer (2012) estimate the full cost of power generation and systematically compare state subsidies for nuclear, hard coal, and lignite with those for renewables across Germany. Also, Siemens Wind Power (2014) showcases LCOE including societal and economic benefits for the different power generation technologies across UK and Germany.

While these studies have comprehensively addressed the aspects of externalities of power generation costs from national perspectives, there is still a need to expand this to a broader global context to inform public policy discourse. In this regard, the research paper is an effort to highlight LCOE of key power generation technologies across the G20 countries with and without consideration of external and GHG emission costs. Moreover, most LCOE estimations lack in providing a long term purview of cost developments that can aid in developing future plans and agendas. Therefore, this research estimates LCOE in 2015 to represent the current trends and LCOE in 2030 to represent the likely development prospects of the various technologies across the G20 countries. Besides, almost none of the studies include storage (mainly batteries) as part of power source options. In recent years, apart from the increasing share of battery storage adoption among prosumers (REN21, 2017), there have been a growing number of utility-scale battery storage installations across countries such as USA, UK, Germany and Australia (Clover, 2018; Cook, 2017; Mcconnell, 2018; Walton, 2018). The trend for solar PV with large-scale battery storage intsllations is becoming more widespread as costs of batteries are declining rapidly (Kenning, 2018). Considering these developments, this research paper is the first of its kind to estimate levelised costs of batteries along with solar PV (both utility-scale and rooftop) across the G20 countries for 2015 and 2030. Unlike most LCOE estimates, this research juxtaposes the estimated levelised costs of renewable power and storage with those of fossil fuel and nuclear power, considering external as well as GHG emission costs, in 2015 and 2030, across all the G20 countries. With the growing relevance and significance of the G20 forum, the purpose of this research is to inform global energy policy discourse with comprehensive, rigorous and impartial cost analysis of the existing as well as emerging power technologies.

3. Materials and methods

In order to represent the comparative annualised costs of electricity generation for different technologies on an equal footing, a LCOE calculation is often employed (Short et al., 1995). In general, LCOE calculations include all the costs of building and operating a power plant in relation to the energy generation over its lifetime. Costs of transmitting and distributing this energy are not usually included in such plant level LCOE calculations. Importantly, socio-ecological externalities are also often excluded from LCOE calculations beyond the market cost of CO_2 emissions. However, this analysis will attempt to include the full costs of energy generation by internalising them as fairly as possible. To this end, a wider range of costs both upstream and downstream from power plants are included in order to give a more accurate representation of the full costs of energy generation. Such costs will include those related to effects on human health, the environment, global warming, long-term waste management, plant decommissioning, financing and budget overruns.

Too often, LCOE calculations merely represent so-called overnight costs of power plants, which do not fully represent the fact that the true costs may differ significantly from originally budgeted costs. As financing of construction may be done over many years and there may be significant time and budget overruns. For some technologies, these are exceptional. However, for others, they appear to be rather normal due to inherent complexity and changing public expectations (Sovacool et al., 2014a,b). For example, a solar PV rooftop system on an individual home can be ordered from a service provider who can deliver a turnkey product within weeks. In addition, as such projects can be paid for by homeowners, financing costs are rather minimal. In contrast, a nuclear power plant will take many years to go through the long process of availing permissions and construction. Moreover, a recent trend has been observed in time and cost overruns that dramatically inflate the originally projected overnight cost. A case in point is the Olkiluoto 3 reactor in Finland. The first application for the project was made in 2000 to the Finnish cabinet, and construction began in 2005. The project was originally estimated to be completed by 2010 for a cost of approximately 2.8 b€. However, the reactor has not yet been commissioned by end of 2017, and recent cost estimates exceed 8.5 b€ (Koistinen, 2012; World Nuclear Association, 2017b).

It is generally agreed that many values representing these components vary greatly on a global level. Hence, low, median and high values of LCOE for each technology have been calculated for each of the G20 countries in 2015 and 2030. Accurate background data were available for all technologies and collected using respected international and local sources. These include the following:

- International Energy Agency (IEA, 2016)
- International Energy Agency – Photovoltaic Power Systems Programme (IEA-PVPS, 2016)
- European Commission Joint Research Centre, 2014 (EC, 2014)
- Danish Energy Agency, 2016 (Danish Energy Agency, 2016)
- International Renewable Energy Agency, 2015 (IRENA, 2015)
- European Technology & Innovation Platform – Photovoltaic (ETIP-PV) 2017 (ETIP-PV, 2017)
- Bongers, 2015 (Bongers, 2015)
- Lazard, 2016 (Lazard, 2016)
- Grausz, 2011 (Grausz, 2011)
- Ahmad and Ramana, 2014 (Ahmad and Ramana, 2014)
- World Nuclear Association, 2017 (World Nuclear Association, 2017c)
- Rafaj and Kypreos, 2007 (Rafaj and Kypreos, 2007)
- International Energy Agency and Nuclear Energy Agency, 2015 (IEA & NEA, 2015)
- Mann et al., 2014 (Mann et al., 2014)
- Schlissel, 2016 (Schlissel, 2016)
- Government of India Ministry of New & Renewable Energy, 2017 (MNRE, 2017)
- Central Electricity Regulatory Commission of India, 2015 (CERC, 2015)
- UBS, 2017 (UBS, 2017)
- Pöller et al., 2015 (Pöller et al., 2015)
- World Nuclear Association, 2017 (World Nuclear Association, 2017a)
- Schneider and Froggatt, 2016 (Schneider and Froggatt, 2016)

The current situation is represented by values from 2015, which are at this time the latest available on a global scale. LCOE is also estimated for 2030 using recognised projections of cost components. In many cases, when reliable data was unavailable for a particular G20 country, a value was substituted from a source found from a regionally neighbouring country. Primarily, these assumptions were made based on the similar economic and geographic conditions prevailing in some of the G20 countries. Such regional groupings were most often related to geographic closeness, but could also represent political closeness in the case of EU member states. Regional groupings were most often made for Argentina and Brazil; Australia, Indonesia, India, Japan and the Republic of Korea; Canada, the USA and Mexico; the Kingdom of Saudi Arabia and South Africa; the United Kingdom and the countries of the EU. These can be further examined in the supplementary material.

The components of the LCOE calculations employed in this analysis includes real capital expenditures (capex) instead of overnight costs. In addition, this analysis includes plant decommissioning costs, fixed operational and maintenance expenditures (opex fixed), variable operational and maintenance expenditures (opex variable), storage costs, fuel costs, GHG emission costs, waste disposal costs, and a full range of additional socio-economic costs. Other important components of the LCOE calculations are plant lifetimes and full load hours (FLH) of annual operation.

The calculation of LCOE (expressed as €/MWh_{el}), representing a discounted cash flow approach for the case of constant annual cash flows (Short et al., 1995), in this report is characterised by the following equation (1):

$$LCOE = \frac{(Capex_{Real} * crf) + Opex_{fixed} + \frac{Decommissioning\ costs}{N}}{FLH} + Opex_{variable} + LCOS + Fuel\ costs + Waste\ disposal\ costs + External\ costs + GHG\ costs \quad (1)$$

where,

$Capex_{Real}$ is annual capital expenditures (€/MW_{el}), which include a low and high estimate for investments and budget overruns; $Opex_{fixed}$ are fixed operation and maintenance costs (percentage of capex/year); *Decommissioning costs* are expressed as a percentage of capex for all technologies except nuclear power plants, for which they are expressed as a value in €/MW_{el}; *N* is the operational lifetime of the technology (years); $Opex_{variable}$ is the annual variable operation and maintenance costs (€/MWh_{el}); *LCOS* is the levelised cost of storage in €/MWh_{el} (see below); *Fuel costs* are expressed in €/MWh_{el}; *Waste disposal costs* are expressed in €/MWh_{el}; *External costs* (annual) include a range of socio-economic costs related to energy generation (€/MWh_{el}); *GHG costs* (annual) include the full socio-economic costs of GHG emissions (€/MWh_{el}). Importantly, there has been no discounting of decommissioning costs, i.e. a social discounting rate of 0% has been applied for supporting real societal costs. Instead, they are applied to the time of energy generation.

The capital recovery factor (*crf*) is calculated according to the following equation (2):

$$crf = \frac{WACC*(1+WACC)^N}{(1+WACC)^N - 1} \tag{2}$$

where,

WACC is the weighted average cost of capital; *N* is the operational lifetime of the technology (years).

WACC is set at 7% per year for all technologies with the exception of coal and nuclear power, which are set at 10%. In general, the WACC represents the weighted cost of both debt and equity based capital. WACC is also a representation of the relative risk that various investors perceive in the development of a project. For this reason, a higher WACC was used for coal and nuclear power. This is due to the fact that we are currently seeing divestment from such assets and a higher risk of stranded investments (Baron and Fischer, 2015). This risk is a result of accelerated phasing out of coal plants in many parts of the world due to climate change mitigation, and shut downs of nuclear plants in a post-Fukushima world. In addition, budget overruns in recent years of nuclear power projects have left investors sceptical (Koplow, 2011; Moody's Investors Service, 2008; Pearce, 2017; Schneider and Froggatt, 2016), making it more difficult to raise capital.

The levelised cost of storage (LCOS) is calculated for the case of both rooftop and utility solar PV according to the following equation (3):

$$LCOS = \frac{Storage\ capacity*\left[(Capex_{Real}*crf) + Opex_{fixed}\right]}{System\ output} + \frac{Costs\ of\ battery\ losses}{System\ output} \tag{3}$$

Major components of LCOE are further described in turn below. Afterwards, a brief explanation of how low, median and high values of LCOE were calculated.

3.1. Capex

Overnight capital expenditures were derived from a range of internationally recognised sources for each of the G20 countries. In most cases, these sources supplied low and high ranges for many technologies. When data was not available for a particular country, values from a neighbouring country were substituted in the manner described above. For utility-scale solar PV, the most economical option is sometimes a fixed, optimally tilted system. Such is the case for countries such as Canada, France, Germany, Japan, Russia and the UK. However, at other times it is more advantageous to operate a single-axis tracking system, since the higher yield of the system outweighs the additional capex. Therefore, for all other countries an additional cost of 10% was added to capex values (Bolinger et al., 2017) to reflect the additional costs of the tracking systems.

In all cases but three, a value for this overnight capex was the starting point of all calculations. The exceptions will be discussed below in the section on $Capex_{Real}$.

3.2. Investment and overruns

For solar PV and wind energy generation technologies, a low value of 1.5% of capex and high value of 3.5% of capex were added (IEA & NEA, 2015). These values reflect the fact that solar and wind installations typically have very short construction times (1–2 years), but that some delays may occur due to complex procedures related to permitting. Battery technologies did not have an investment and overrun addition. It was assumed that coal and gas-based thermal power plants have low and high investment and overrun additions of 5% and 15%, respectively. These capex additions are consistent with estimates made by the IEA (IEA & NEA, 2015; IEA, 2016). For nuclear power, a low investment and overrun addition of 20% was assumed due to the longer construction times of nuclear power plants. This was also consistent with high IEA estimates. However, another source was used to estimate the high investment and overrun addition of 40% (Koomey and Hultman, 2007). This source was deemed to better account the reality of the international trend towards longer construction times and budget overruns. It also showed that such overruns have gotten progressively larger over time. Currently, nuclear power plants in Finland and France are seven years beyond their scheduled construction time of 5 years, and cost overruns are approximately 300% (Koistinen, 2012; Le Monde, 2012). The applied range of 20%–40% of cost overruns is rather conservative, given the scientific analysis for 180 nuclear reactors which had a cost overrun of 117% on average and no single reactor within the planned budget had been found (Sovacool et al., 2014a,b).

3.3. $Capex_{Real}$

A high and low value for $Capex_{Real}$ was calculated by adding the high and low investment and overrun additions to the high and low values of capex. In some cases, only a single value for capex was available, and so the variance in $Capex_{Real}$ represents only the variance in the investment and overruns addition.

In three cases, values for $Capex_{Real}$ were not the result of calculations, but were taken straight from the literature. Thereby, the value of overnight capex could be derived in reverse for the high values of Argentinian, Chinese and South Korean nuclear power plants. The high $Capex_{Real}$ value for nuclear power in Argentina was based on a known cost of 5.8 bUSD for the 800 MW Atucha 3 reactor (Schneider and Froggatt, 2016; World Nuclear Association, 2017a). Interestingly, the technology provider for the Atucha 3 reactor is Chinese (CANDU), and the cost of similar projects in China are generally reported at much lower costs. This indicates a high level of domestic subsidy possibly incorporated in the reported overnight costs that are commonly used in international publications. The same phenomenon is suspected for Korean technology providers. Therefore, high $Capex_{Real}$ values for China and the Republic of Korea are derived from known costs for the same technologies in other countries. The high $Capex_{Real}$ value for nuclear power in China was based on a known cost of 9.6 bUSD for the 2028 MW Karachi 1&2 reactors in Pakistan built by the Chinese National Nuclear Corporation (Schneider and Froggatt, 2016; World Nuclear Association, 2017a). Likewise, the high $Capex_{Real}$ value for nuclear power in South Korea is based on an estimated cost of 32 bUSD for the 5380 MW Barakah 1-4 reactors in the United Arab Emirates, which are built by the Korean Electric Power Corp. (Schneider and Froggatt, 2016).

3.4. Decommissioning

A decommissioning cost of 5% of capex was applied to solar PV, wind, coal and gas technologies. No decommissioning costs were applied to batteries. For nuclear power plants, a decommissioning cost of 1100 €/kW was applied. However, the difficulty in accounting decommissioning costs accurately merits further discussion. Globally, there is very little actual experience and information related to fully decommissioned nuclear power plants. For this reason, estimates of future costs range from values as low as 200 €/kW for reactors in Finland (219 mUSD for 2*440 MW VVER) to 1500 €/kW for reactors in Slovakia (1.3 b€ for 2*440 MW VVER) (EC, 2016; IAEA, 2002). In this research, it is assumed that decommissioning costs globally will be 1100 €/kW in 2015 and 2030. The effect of varying this value by ± 50% has an effect on LCOE of ±1 €/MWh_{el}.

3.5. Opex

This category is divided into fixed and variable operational and maintenance expenditures. $Opex_{fixed}$ is commonly expressed as a percentage of capex per year, and represents costs unrelated to how many hours per year the plant operates. Such costs include material, personnel, administration and insurance costs, but do not include fuel or emissions costs. $Opex_{variable}$ represents costs that are directly related to the frequency and duration of plant operations. Some operations and maintenance costs, such as those related to pumps, fans and lubricating fluids, are incurred only when the plant operates. In the case of batteries, a similar value to $Opex_{variable}$ is calculated based on the costs related to storage losses. These losses are a function of the energy throughput and battery efficiency.

3.6. Lifetime

Assumptions made related to plant lifetimes are consistent with those made by the International Energy Agency and other international agencies. Wind energy plants are assumed to have a lifetime of 25 years. Solar PV rooftop units and power plants are assumed to have a lifetime of 30 years (ETIP-PV, 2017). This value was chosen even though some facilities may have physical lifetimes of up to 35 years. Increasing PV lifetime by 10 years would mean that LCOE could be reduced by about 5 €/MWh_{el}. The real lifetime of solar PV modules and wind turbines installed today are, obviously, unknown. More relevant to LCOE calculations, however, is the perceived economic lifetime by the international community, including investors. Another unknown is the lifetime of batteries, which has been set at 10 years for 2015 and 15 years for 2030. The extended lifetime for 2030 is based on projected lifetimes of electric vehicle Li-ion batteries (UBS, 2017). Complicating this matter is that batteries have both calendric and cycle lifetimes, meaning batteries that are charged and discharged more frequently and deeply will have reduced lifetimes. The lifetimes of coal and gas power plants is assumed to be 40 years. Nuclear power plant economic lifetime is set at 50 years. It should be noted, however, that nuclear power plants are typically given operating permits for 30–40 year periods, after which refurbishment or renovation is needed to extend the physical lifetime to 60 years or beyond. And again, perceived economic lifetimes for investors are typically shorter, making a 40 year economic lifetime perhaps more relevant for the purposes of LCOE calculations. The same was done by Lazard (Lazard (2016). The competition of low cost solar PV and wind plants already led to earlier than possible shut down decisions (Nikolewski, 2016). However, the high risk profile of nuclear power plants may lead to much shorter lifetimes, due to detracted societal willingness to accept the risk, which seems to be also well covered by liberal western constituencies, as confirmed by the Federal Constitutional Court of Germany in 2016 (The Federal Constitutional Court of Germany (Bundesverfassungsgericht), 2016).

3.7. Full load hours

For nuclear plants, baseload operation is assumed. Therefore, FLH values reflect capacity factors of 80% at a low end to 90% at the high end. For coal power plants, some of which have not witnessed such high FLH in recent years due to competition with renewable energy and decarbonisation targets, capacity factors range between 50% and 90%. Median values for coal and nuclear power plants are the average between the lower and upper estimates. For open cycle gas turbines, low, median and high capacity factors are assumed to be 10%, 45% and 80%, respectively, due to the more peak following profile of generation. Similarly, these values are set at 40%, 60% and 80%, respectively, for combined cycle gas turbines. These values are consistent with international agencies.

For solar PV and wind energy generation, FLH for each country in the G20 were calculated individually, based on real weather data over the period of 1994–2005. The procedure for estimating FLH was complex, but took into account both geographic and temporal variation of the resources. Data was derived from (Stackhouse, 2016; Stetter, 2012), which gave irradiation and wind speed data on an hourly resolution for the years indicated. The geographic resolution of the data is a 0.45° latitude by 0.45° longitude node (approximately 50 km by 50 km at the equator). These nodes were ranked in terms of the quality of the resource as percentiles, with the 100th percentile being the node with the highest average annual irradiation or wind speed. Maximum FLH for solar PV and wind energy were determined as the highest value for the 100th percentile node over the time period (1994-2005). Minimum FLH were determined as the lowest value for the 51st percentile node over the same time period. To determine the median FLH value, a weighted average of nodes was used. It was assumed that not all capacity of solar PV and wind could be located in only the best sites, and that most of the worst sites could be rejected as being infeasible. So, 10% of capacity would be located in the areas ranked from the 51st to 60th percentile, 10% of capacity would be located in the areas ranked 61st to 70th, 20% of capacity would be located in areas ranked 71st to 80th, 30% of capacity would be located in areas ranked 81st to 90th, and the remaining 30% of capacity would be located in areas ranked 91st to 100th. The weighted average value for FLH was calculated for each country and each year, and the median was calculated as the average over the time period.

Exceptions to the above were made for several countries that have less than ideal wind conditions: Brazil, Indonesia, India, Mexico, Kingdom of Saudi Arabia, and Turkey. It was assumed that there would be limited locations of sufficient wind quality in some onshore and offshore locations, so the range of acceptable nodes were limited between the 81st and 100th percentiles. For Italy, Mexico, Kingdom of Saudi Arabia and Turkey, this limitation was applied only to offshore wind energy generation.

For single-axis tracking PV systems, FLH data was only available for a single year (2005). However, this data was compared to the values for fixed optimally tilted systems for the same year, and values for other years were extrapolated based on this comparison.

For LCOE calculations for solar PV + Batteries, FLH were assumed to be the same for solar PV rooftop. However, the ratio of storage capacity to generation capacity was varied, with a ratio of 1 assigned for low and median LCOE calculations, and a ratio of 2 assigned for high LCOE calculations. This takes into account that larger battery capacity that would lead to higher LCOE. At the same time, this raises an important point. The LCOE for the solar PV + Battery systems may not, therefore, be immediately comparable to the LCOE of the other generation technologies, but should be compared to consumer's costs of electricity in order to determine if it is low or high.

Table 1
Fuel cost assumptions for coal (upper) and gas (lower) in €/MWh_{th}.

	2015	2030	2015	2030
	€/t		€/MWh_{th}	
Coal Europe	45.86	64.66	5.63	7.94
Coal China	71.43	68.42	8.77	8.40
Coal India	30.08	63.91	3.69	7.85
average			6.03	8.06
	€/MMBtu		€/MWh_{th}	
Gas Europe	5.26	9.77	17.96	33.35
Gas Japan	6.02	10.53	20.52	35.92
Gas China	9.77	9.77	33.35	33.35
Gas USA	2.26	8.27	7.70	28.22
average			19.88	32.71

3.8. Fuel

Fuel costs were taken from projections found in Bloomberg New Energy Finance's New Energy Outlook 2015 (BNEF, 2015) and are summarised in Table 1.

A cost of 5.26 €/MWh_{el} for nuclear fuel (IEA, 2016) was assumed for all countries for both 2015 and 2030 due to large stockpiles of nuclear fuel. This corresponds to an approximate cost of 7 USD/MWh_{el}, and may vary by ±1 €/MWh_{el} globally.

3.9. Waste disposal

Waste disposal costs were considered only for nuclear power plants and were derived directly from the IEA (IEA & NEA, 2015). This source reported values for each country in 2015 which included both fuel and waste disposal costs. The waste disposal costs were determined after subtracting the above fuel costs. Values reflect the economic difficulty that some countries have in safely disposing off nuclear waste (Japan, the USA and the UK).

3.10. External costs

A comprehensive review by Climate Advisers (Grausz, 2011) of the total social cost of different forms of electricity generation determined that the work of Rafaj and Kypreos (2007) provided the most comprehensive estimates of the external costs of electricity generation. Similarly, these same costs have been used as the basis for LCOE calculations in this present study, and are summarised in Table 2 below. Note that values do not include external costs related to CO_2 emissions, which will be explained in the next section.

Table 2
External costs of electricity generation excluding CO_2 costs used for LCOE calculations. From (Rafaj and Kypreos, 2007). All values are in €$_{2015}$/MWh of electricity produced and based on long-term conversion of 1.33 EUR/USD and 57% inflation of the USD between June 1995 and June 2015. ASIA includes all Asian countries. OECD includes Australia and all other countries not specified. NAME includes all North American countries. EEFSU includes all Eastern European and Former Soviet Union countries. LAFM includes countries of Latin America, Africa and the Middle East.In the Table, PP is Power Plants, CCS is Carbon Capture and Storage and CCGT is Combined Cycle Gas Turbine.

	ASIA	OECD	NAME	EEFSU	LAFM
	€/MWh_{el}	€/MWh_{el}	€/MWh_{el}	€/MWh_{el}	€/MWh_{el}
Coal PP	18.9	18.9	13.3	13.3	13.3
Coal PP + CCS	22.7	22.7	15.9	15.9	15.9
Gas PP - CCGT	19.0	5.7	14.8	13.5	13.5
Gas PP - CCGT + CCS	22.7	6.5	7.4	15.2	15.2
Nuclear PP	7.7	7.7	7.7	7.7	7.7
Solar PV	1.5	1.5	1.5	1.5	1.5
Wind turbine	1.5	1.5	1.5	1.5	1.5

3.11. GHG emission costs

For CO_2 emissions, a range of costs exist that represent the cost of a metric ton of emissions. Some of these are market based, while others are politically determined. Carbon markets are percieved to be imperfect mechanisms that often transfer and consolidate power and wealth, as concluded in (Sovacool, 2011) in which the author reviewed more than 300 articles discussing the merits and drawbacks of global and regional carbon markets over the past decade. In this research, a value of 7 €/ton of CO_{2eq} was assumed based on the market value of carbon in the EU for the year 2015. For 2030, a value of 74 €/ton of CO_{2eq} was assumed based on estimates of the social cost of carbon by the Stern Review (Stern, 2007). The recent report of the High-Level Commission on carbon price confirms CO_{2eq} emission costs of up to 74 €/ton of CO_{2eq} for the year 2030 (Carbon Pricing Leadership Coalition, 2017). However, it should be noted that there are a range of estimates related to the actual costs of carbon from 30 to 165 €/ton of CO_{2eq} (Moore and Diaz, 2015). Some others (Jakob et al., 2016) argue that emissions pricing could be utilised to promote sustainable socio-economic development by providing public goods that are essential for human well-being through public financing.

Determining a single, universally acceptable value for GHG emissions is an impossible task, which often leads to confusion or objection. In truth, measuring the full socio-economic impacts of GHG emissions is inherently inaccurate and thus open to debate. The range of impacts included or excluded play a major role. The Stern Review (Stern, 2007) was amongst the first influential publications to place a social cost on GHG emissions. This was set at 85 USD_{2007} per ton (74 €$_{2015}$/ton of CO_{2eq}) for the case of a business as usual scenario with global concentration exceeding 550 ppm in the atmosphere. However, the Stern Review acknowledged that this cost could be up to a third lower if global concentration was around 450 ppm. This shows that the cost of GHG emissions, even the social cost, is not static. Instead, we must accept that the costs will be higher as global atmospheric concentrations increase. What is more, a recent study (Moore and Diaz, 2015) suggests that higher concentrations of GHG emissions in the atmosphere will have a so far inadequately accounted, negative effect on economic growth, which may lead to much higher impact on a full socio-economic level. The article argues that to this point the focus has been on the environmental impacts of GHG emissions on people. The authors remind that there will also be significant economic impacts on people. If effects on global economic growth are also taken into account, the full cost of GHG emissions could be much higher, up to 220 USD/ton (165 €/ton of CO_{2eq}) (Moore and Diaz, 2015).

3.12. Other technical assumptions

The technology-wise assumptions are as listed below,

1. Wind onshore: Full Load Hours (FLH) are based on the power curve of a 3 MW onshore wind turbine (Enercon E101with a hub height of 150 m).
2. Wind offshore: Full Load Hours (FLH) are based on the power curve of a 3.6 MW offshore wind turbine (Siemens SWT-3.6-120 with a hub height of 100 m).
3. PV rooftop: Performance characteristics are based on the scale of a 5 kW_p system.
4. PV utility: Performance characteristics are based on the scale of a 50 MW_p system.

5. Li-ion batteries: Charactersitics based on power capacity of 1–3 MW and storage capacity of 0.5–1.2 MWh for utility-scale.
6. Coal PP: Characteristics based on supercritical, pulverised coal condensing power plant burning black coal; plant efficiency based on lower heating value.
7. CCGT PP: Characteristics based on combined cycle gas turbine of up to 580 MW (net); plant efficiency based on lower heating value of fuel.
8. OCGT PP: Characteristics based on advanced open cycle gas turbine of up to 250 MW (net); plant efficiency based on lower heating value of fuel.
9. CCS: Characteristics based on post-combustion carbon capture; plant efficiency based on lower heating value of fuel.
10. Nuclear PP: Characteristics based on advanced light water reactor technologies in the range of 1000–3300 MW; plant efficiency based on lower heating value of fuel.

3.13. Summary of calculations

Calculations for low, median and high LCOE were made to account for national differences in LCOE components and variance in energy generation from different technologies, and these are available along with all the Supplementaty Material. The variance may be due to geographic factors in the case of solar PV and wind energy generation, but also due to how technologies are used in the energy system (peaking vs. baseload plants). The main factors for the variance in LCOE are capex, investment and overruns, and FLH. At the same time, fuel costs and assumptions about technology lifetimes could slightly increase the variance as discussed above. Low LCOE values are calculated from a combination of low capex estimates, low values for investment and overruns, and high FLH. Median LCOE values are calculated from a combination of low capex estimates, low values for investment and overruns, and median FLH. High LCOE values are derived from a combination of high capex estimates, high values for investment and overruns, and low FLH. Importantly, high values for gas turbines should not immediately be seen as entirely negative. Such high values are primarily the result of low FLH of peak-following gas turbines, which have an important regulatory function in many energy systems.

While a full range of values were calculated for LCOE, only values below 250 €/MWh$_{el}$ are shown in figures in the results section. Above this level, investments are highly unlikely to be profitable in all but the most extreme, off-grid situations, or when technologies play an important regulatory function, such as frequency control of grids.

4. Results

Results of LCOE calculations for all the G20 countries are presented in Figs. 3–6, and all the applied assumptions and data are shown in detail in the supplementary material. The range of LCOE values for the years 2015 and 2030 are represented by bars that are coloured corresponding to the different technologies as shown in the legend. The range of LCOE values for conventional technologies (coal, gas and nuclear) also include CO_{2eq} and external costs. The median values for LCOE across the different technologies are represented by the red dots (which do not include the CO_{2eq} and external costs) and the white dots (which include the CO_{2eq} and external costs).

In general, onshore wind energy currently shows the lowest overall LCOE, especially in regions of high latitudes (either north or south). Notable exceptions exist for some regions in Asia where wind resources are less favourable as compared to the solar resource, which is more favourable. In 2030, solar PV utility power plants represent the lowest LCOE of all technologies across all the G20 countries with the exception of Northern European countries that are part of the European Union, where onshore wind continues to have the lowest LCOE. On a global level represented by all the G20 countries, rooftop solar PV becomes more competitive than conventional energy production (fossil fuels and nuclear) in 2030, especially when a more complete range of costs are internalised for all technologies. Cost reductions projected for battery storage in 2030 also increase the competitiveness of PV + Battery systems (rooftop and utility) across all the G20 countries. Conventional fuels become significantly less competitive in 2030 when the costs of CO_{2eq} and other externalities are fully considered. Gas-based technologies, important providers of flexibility to global energy systems, have the potential to reduce overall LCOE through switching from natural gas to more sustainable bio-based or synthetic methane. Carbon capture and storage offers an opportunity to reduce costs associated with fossil fuel combustion, but remains significantly higher in costs than renewable energy generation, even with the anticipated cost reductions due to development of CCS technology. It needs to be noted that net zero emissions are almost impossible with fossil-fuel based CCS, and still incur higher costs than renewable energy based energy systems. Nuclear power has already lost its competitiveness to wind and solar PV in 2015 in most of the G20 countries and further worsens its relative competitiveness with renewable energy in 2030 when high levels of social, environmental and economic risks are internalised in the LCOE calculations.

As shown in Fig. 3, the results for Argentina indicate that LCOE of wind onshore power (25 €/MWh$_{el}$) is already lower than fossil fuel based power generation (with coal having LCOE of 46 €/MWh$_{el}$) in 2015, and by 2030 LCOE of wind (22 €/MWh$_{el}$) along with utility-scale PV (22 €/MWh$_{el}$) will be much lower. In the case of Australia, wind onshore power has lower LCOE (35 €/MWh$_{el}$) as compared to fossil based power (with coal having LCOE of 55 €/MWh$_{el}$) in the present context, and by 2030 rooftop (36 €/MWh$_{el}$) and utility-scale PV (22 €/MWh$_{el}$) along with wind onshore (30 €/MWh$_{el}$) will be the cheapest sources of electricity. In Brazil, LCOE of wind onshore power (44 €/MWh$_{el}$) is competitive with respect to fossil fuel based power generation (with coal having LCOE of 46 €/MWh$_{el}$) in 2015 and remains competitive in 2030, whereas utility-scale PV (24 €/MWh$_{el}$) along with utility battery storage (32 €/MWh$_{el}$) will have the lowest LCOE in 2030. In Canada, fossil fuel based power generation (with coal and CCGT having LCOE of 52 €/MWh$_{el}$) has lower LCOE in the present context, whereas wind onshore (40 €/MWh$_{el}$) and utility-scale PV (35 €/MWh$_{el}$) will have lower LCOE by 2030. In China, wind onshore power has the lowest LCOE (29 €/MWh$_{el}$) in 2015, and by 2030 wind onshore (27 €/MWh$_{el}$) and utility-scale PV (23 €/MWh$_{el}$) will have lower LCOE than fossil and nuclear power (with coal having LCOE of 36 €/MWh$_{el}$).

As shown in Fig. 4, the results for France and Germany show that LCOE of wind onshore power (with 47 and 44 €/MWh$_{el}$) is presently competitive with fossil fuel based power (with coal having LCOE of 43 and 42 €/MWh$_{el}$), and by 2030 wind onshore (29 and 28 €/MWh$_{el}$) and utility-scale PV (32 and 40 €/MWh$_{el}$) have much lower LCOE. In India, fossil fuel sources (with coal having LCOE of 34 €/MWh$_{el}$) have lower LCOE in 2015, whereas utility-scale PV (25 €/MWh$_{el}$) has much lower LCOE in 2030. Similary in Indonesia, fossil fuel sources (with coal having LCOE of 39 €/MWh$_{el}$) have lower LCOE in 2015, whereas utility-scale PV (25 €/MWh$_{el}$) has much lower LCOE in 2030. In Italy, fossil fuel produces power (with coal having LCOE of 43 €/MWh$_{el}$) at a lower LCOE in 2015, whereas by 2030 wind onshore (29 €/MWh$_{el}$) and utility-scale PV (27

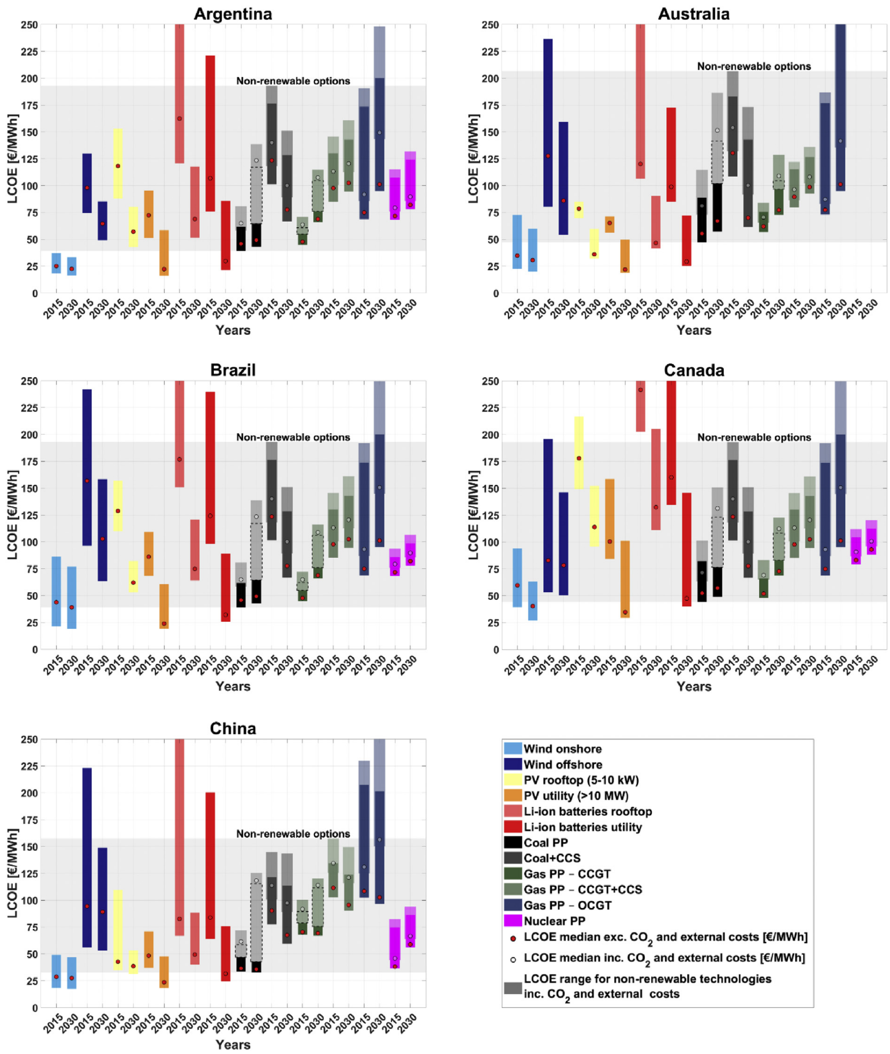

Fig. 3. Results of LCOE calculations for the G20 countries Argentina, Australia, Brazil, Canada and China in 2015 and 2030 (€/MWh$_{el}$).

€/MWh$_{el}$) will have much lower LCOE.

As shown in Fig. 5, the results for Japan indicate that fossil fuel based power (with coal and CCGT having LCOE of 57 and 55 €/MWh$_{el}$) have lower LCOE in 2015, whereas by 2030 utility-scale PV (31 €/MWh$_{el}$) and wind onshore (54 €/MWh$_{el}$) will have lower LCOE. In the case of Republic of Korea, fossil fuel and nuclear power (with coal and nuclear having LCOE of 37 and 40 €/MWh$_{el}$) have lower LCOE in 2015, whereas utility-scale PV (29 €/MWh$_{el}$) has much lower LCOE in 2030. In Mexico, utility-scale PV (60 €/MWh$_{el}$) is competitive with fossil fuel based power (with coal and CCGT having LCOE of 52 €/MWh$_{el}$) in 2015, and by 2030 utility-scale PV (21 €/MWh$_{el}$) and wind onshore (51 €/MWh$_{el}$) have much lower LCOE. Whereas, in Russia, wind onshore power (59 €/MWh$_{el}$) is competitive with fossil fuel based power (with coal and CCGT having LCOE of 52 and 51 €/MWh$_{el}$) in 2015, and by 2030 utility-scale solar PV (36 €/MWh$_{el}$) and wind onshore (52 €/MWh$_{el}$) have lower LCOE. In Saudi Arabia, fossil fuel sources (with coal and CCGT having LCOE of 47 and 49 €/MWh$_{el}$) has lower LCOE in 2015, whereas utility-scale PV (21 €/MWh$_{el}$) has much lower LCOE in 2030.

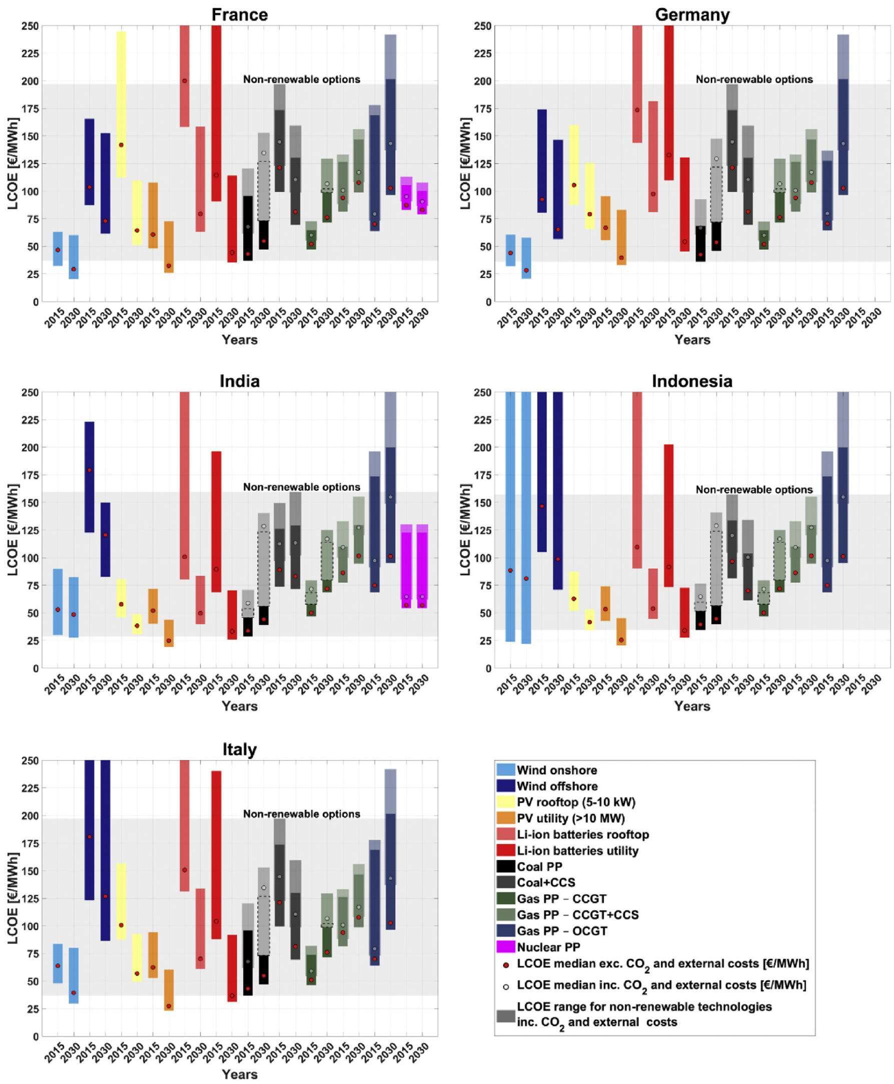

Fig. 4. Results of LCOE calculations for the G20 countries France, Germany, India, Indonesia and Italy in 2015 and 2030 (€/MWh_{el}).

As shown in Fig. 6, the results for South Africa indicate that fossil fuel produces power (with coal having LCOE of 47 €/MWh_{el}) at a lower LCOE in 2015, whereas by 2030 wind onshore (46 €/MWh_{el}) and utility-scale PV (21 €/MWh_{el}) will have lower LCOE. Similary, in Turkey, fossil fuel sources (with coal having LCOE of 43 €/MWh_{el}) have lower LCOE in 2015, whereas utility-scale PV (25 €/MWh_{el}) and wind onshore (40 €/MWh_{el}) have much lower LCOE in 2030. In the UK, wind onshore power (44 €/MWh_{el}) is competitive with fossil fuel based power (with coal having LCOE of 43 €/MWh_{el}) in 2015, and by 2030 wind onshore power has the lowest LCOE (23 €/MWh_{el}). In the USA, wind onshore power (31 €/MWh_{el}) has the lowest LCOE in 2015, and by 2030 wind onshore (30 €/MWh_{el}) and utility-scale PV (25 €/MWh_{el}) have much lower LCOE than fossil fuel based power (with coal having LCOE of 55 €/MWh_{el}). Lastly, in the EU, wind onshore power (40 €/MWh_{el}) has lower LCOE in comparision to fossil fuel based power (with coal and CCGT having

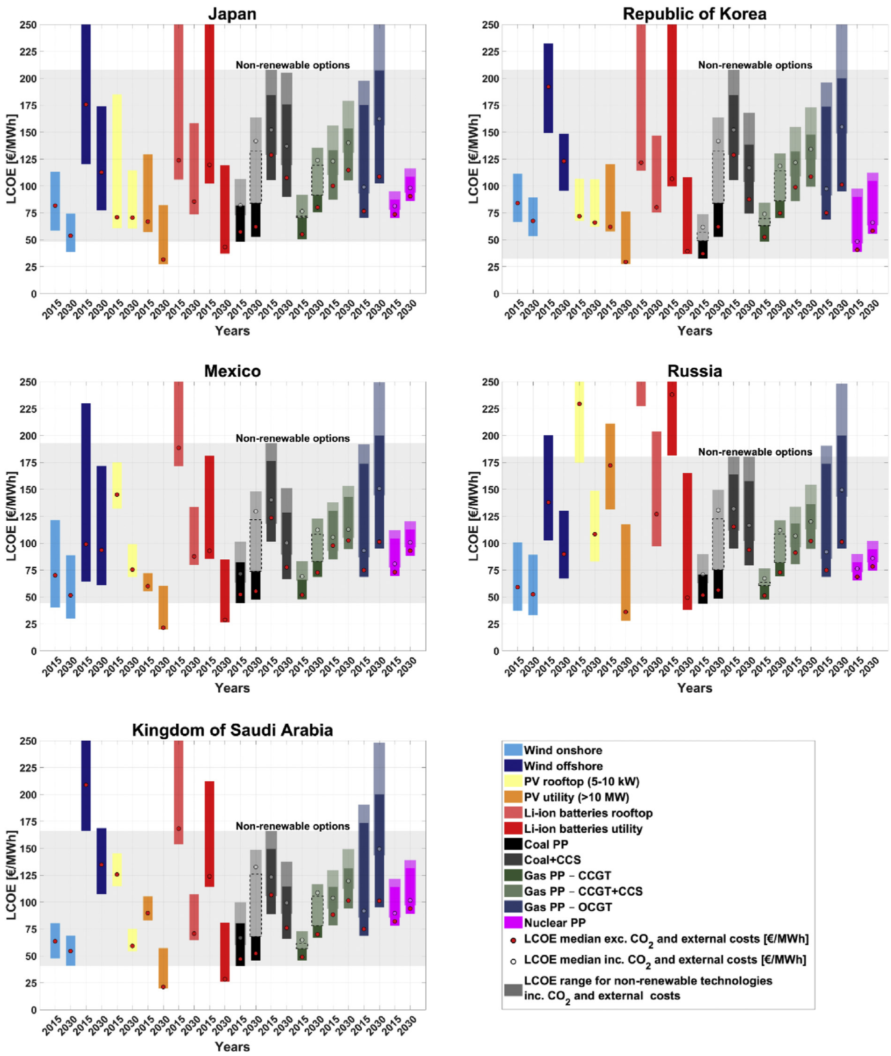

Fig. 5. Results of LCOE calculations for the G20 countries Japan, Republic of Korea, Mexico, Russia and Kingdom of Saudi Arabia in 2015 and 2030 (€/MWh$_{el}$).

LCOE of 43 and 51 €/MWh$_{el}$) and by 2030, wind onshore (30 €/MWh$_{el}$) and utility-scale PV (30 €/MWh$_{el}$) have lower LCOE.

5. Discussion

The LCOE of all technologies across the G20 countries are compiled into renewables and storage that includes wind onshore, wind offshore, PV rooftop, PV utility, Li-ion batteries rooftop and Li-ion batteries utility, and fossil fuels and nuclear that includes Coal PP, Coal with CCS, CCGT, CCGT with CCS, OCGT and Nuclear PP. Further, the LCOE of renewables and storage are evaluated against the LCOE of fossil fuels and nuclear, with and without the consideration of external and CO_{2eq} costs for 2015 as well as 2030. Fig. 7 presents the comparative results for LCOE of renewables and storage with LCOE of fossil fuels and nuclear in 2015, with and without external and CO_{2eq} costs. Countries are shaded in green when the LCOE of renewables and storage is lesser than the LCOE of fossil fuels and nuclear, shaded orange when the LCOE of renewables and

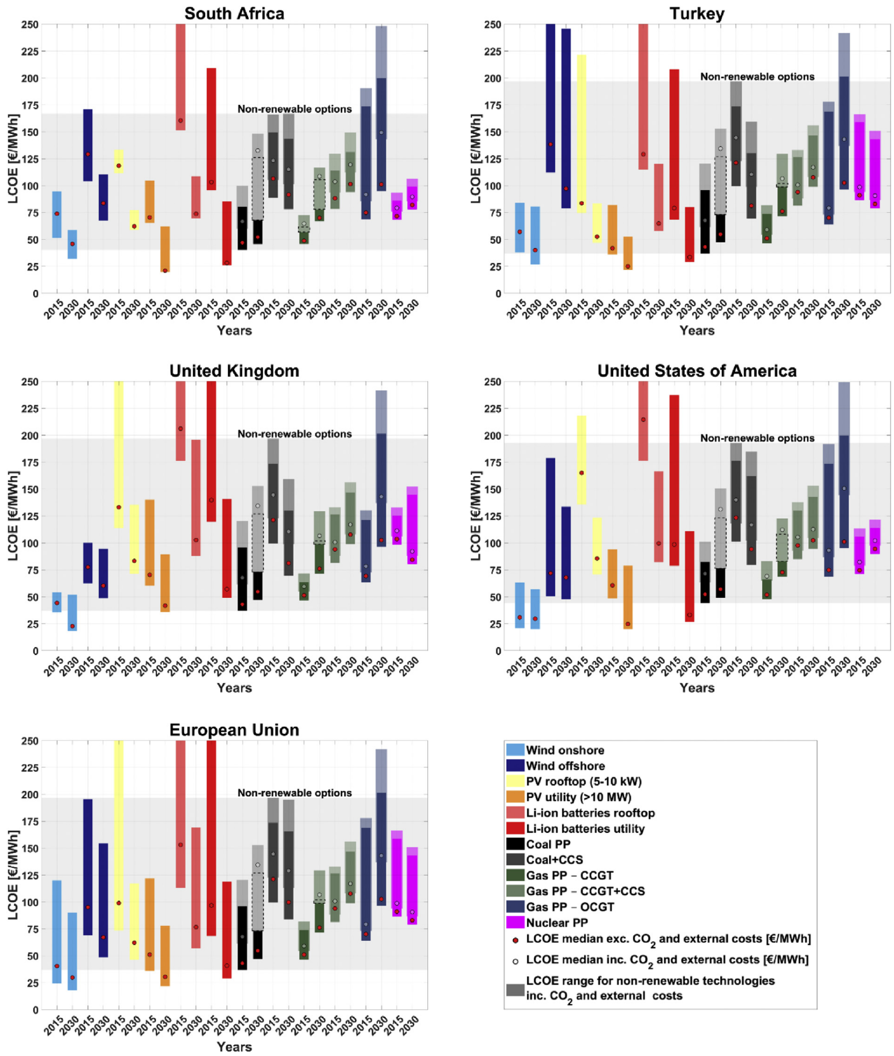

Fig. 6. Results of LCOE calculations for the G20 countries South Africa, Turkey, United Kingdom, United States of America and European Union in 2015 and 2030 (€/MWh$_{el}$).

storage are the same as the LCOE of fossil fuels and nuclear, and shaded red when the LCOE of fossil fuels and nuclear are lesser than the LCOE of renewables and storage.

On comparing the LCOE of all power generation technologies across the G20 countries in 2015, it can be concluded that the LCOE of renewable energy sources are already on par with fossil and nuclear sources in many of the G20 countries even without the inclusion of external and CO_{2eq} costs. Whereas, when external and CO_{2eq} costs are included in the LCOE estimations, the LCOE of renewables and storage are lesser than the LCOE of fossil fuels and nuclear in almost all the G20 countries. Apart from Republic of Korea, where the LCOE of fossil fuels and nuclear is still lesser than the LCOE of renewables and storage, and in Italy and South Africa, where the LCOE of renewables and storage are the same as the LCOE of fossil fuels and nuclear.

Onshore wind is currently the least cost source of electricity in many of the G20 countries, ranging from 18 to 121 €/MWh$_{el}$ (excluding Indonesia), and utility-scale PV, which is quite

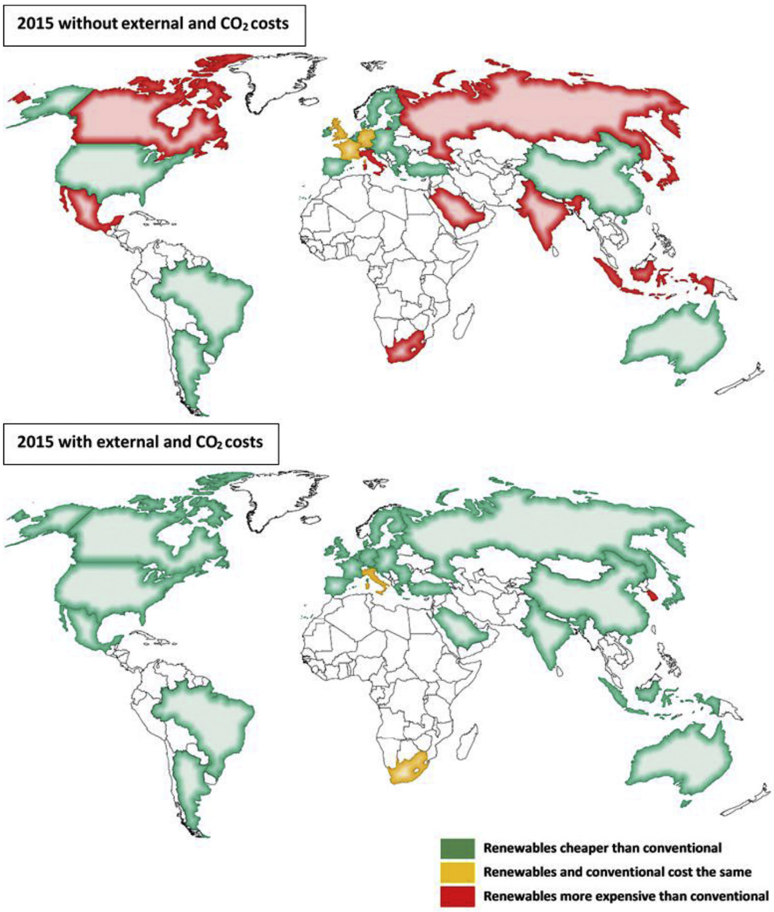

Fig. 7. Results of LCOE calculations for the G20 countries in 2015 without external and CO_{2eq} costs (top) and with external and CO_{2eq} costs (bottom).

competitive in many of these countries ranges from 36 to 140 €/MWh_{el} (excluding Russia). These values are comparable to present auction prices as shown in (Agora Energiewende, 2017). As indicated in Fig. 7, if external and CO_{2eq} costs are taken into account, wind and solar PV along with batteries will be cheaper in almost all the G20 countries in terms of LCOE.

Fossil fuel based energy generation currently appears relatively low in cost due to low costs of GHG emissions imposed by many global markets, which does not represent the real impacts of those emissions. Coal-based generation appears to be the lowest cost of the fossil fuels due to the baseload nature of plant operation when compared to gas based technologies. It should be noted, however, that gas based technologies play important roles in grid stabilisation and balancing. Therefore, lower full load hours of gas turbine plants are a major contributor to higher LCOE. CCS technologies appear very high in costs at the moment and do not represent an economically competitive option in the near term. Nuclear power appears relatively lower in costs in China and the Republic of Korea (likely due to high domestic subsidies), but has significantly higher costs in other parts of the world, when the costs of financing, budget overruns, waste management, decommissioning and associated risks are included.

Fig. 8 presents the comparitive results for LCOE of renewables and storage with LCOE of fossil fuels and nuclear in 2030 for all G20 countries without including external and CO_{2eq} costs. It is quite evident that renewables and storage prove to be much cheaper even without considering external and CO_{2eq} costs on a LCOE basis. This is primarily due to the rapid decline in costs expected for solar PV and battery systems, along with a steady decline in the costs of wind tubines up to 2030 (Breyer et al., 2017a,b).

Renewable energy technologies offer the lowest LCOE ranges across G20 countries in 2030. Utility-scale solar PV generally shows

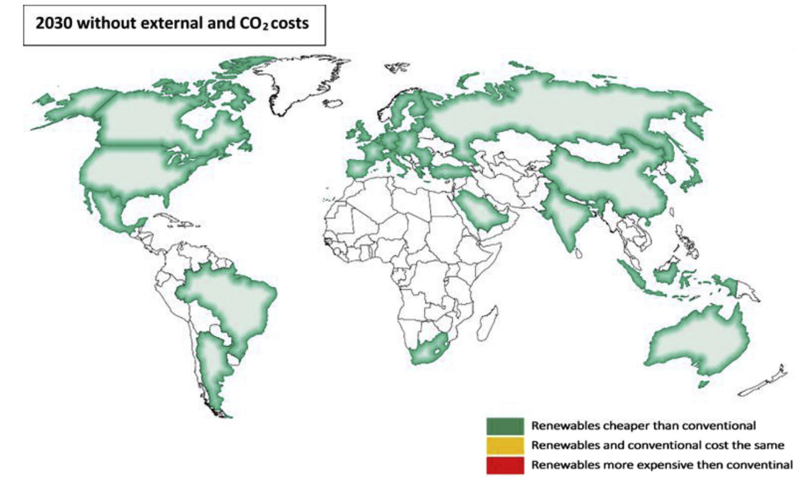

Fig. 8. Results of LCOE calculations for the G20 countries in 2030 without external and CO_{2eq} costs.

the lowest values ranging from 16 to 117 €/MWh$_{el}$, although there are notable exceptions for regions where the solar resource is more variable or the onshore wind resource is particularly good. The onshore wind LCOE range is from 16 to 90 €/MWh$_{el}$ (excluding Indonesia). This is the case for several countries at higher northern latitudes. Rooftop solar PV generally offers the next lowest LCOE ranging from 31 to 126 €/MWh$_{el}$, followed by LCOE of offshore wind power ranging from 64 to 135 €/MWh$_{el}$. However, similar exceptions exist for higher northern latitudes and in areas that typically have higher quality offshore wind resources (e.g. Canada, USA, UK). Solar PV and battery systems are highly competitive on an LCOE basis at utility-scale (21–165 €/MWh$_{el}$) with overall market costs of electricity depending on local costs, and at residential scale (40–204 €/MWh$_{el}$) depending on consumer costs of electricity including taxes, transmission costs, and distribution costs. As shown by Lazard (Lazard (2017) and IRENA (IRENA, 2018), these costs are attainable even before 2030 with the current market trends indicating substainal drops in the costs of renewable technologies. This is futher substantiated with the recent bids for solar PV in Chile and Mexico reaching 21.48 USD/MWh and 20.57 USD/MWh, respectively. Also, bids in Saudi Arabia for solar PV were below 20 USD/MWh (Bellini, 2017a, 2017b; Kenning, 2017). Interestingly, the lowest LCOE values seen for renewable energy technologies in the G20 are in Argentina, where both solar and wind resources are exceptional.

On the contrary, fossil fuel and nuclear power generation represents higher LCOE ranges across the G20 countries in 2030. Firstly, gas based energy generation represents the highest LCOE values with 107–124 €/MWh$_{el}$ for CCGT and 142 to 162 €/MWh$_{el}$ for OCGT. However, it must be reiterated that many of the higher range values are the result of operational conditions for gas turbines, especially OCGT. These operational conditions include the provision of essential control and stability for electricity grids, which may significantly limit the FLH of operation. In addition, gas-based technologies have the great potential to reduce costs associated with GHG emissions and external costs by switching to more sustainable fuels, such as biomethane and synthetic methane. Secondly, coal based power represents amongst the highest LCOE values ranging from 115 to 186 €/MWh$_{el}$ when CO_{2eq} and external costs are accounted. This trend is seen across the G20 countries. Thirdly, nuclear power shows a wide range of LCOE values from 62 to 152 €/MWh$_{el}$. Low values for 2030 are observed in China and the Republic of Korea as it is unclear if the reported overnight costs represent subsidised values. The technologies provided in these countries domestically differs significantly in cost to the same technologies installed internationally by the same technology providers. Conservative cost assumptions were used to specify the upper limit in relation to financing and overruns (40% of overnight capex). However, several projects worldwide have shown that such costs can exceed 300% of capex (Koistinen, 2012; Le Monde, 2012; Schneider and Froggatt, 2016) and the averaged cost overrun for 180 reactors has been found to be 117% (Sovacool et al., 2014a,b). Lastly, CCS offers little hope for positive business cases in the Americas through to at least 2030. The range of LCOE for coal CCS is 89–205 €/MWh$_{el}$, and the range for CCGT CCS is 102–179 €/MWh$_{el}$.

In comparision to other LCOE estimates, such as Lazard (Lazard (2017), IRENA (IRENA, 2017a, 2018) and Agora Energiewende (Agora Energiewende, 2017), these estimates seem rather on the conservative side with respect to LCOE values of renewable technologies, specifically utility-scale PV and onshore wind. Also, recent bids for large scale solar PV projects across Saudi Arabia, Chile and Mexico (around 20-22 USD/MWh) have demonstrated the rapid cost decline potential of solar PV power (Bellini, 2017a, 2017b; Kenning, 2017). Lazard's LCOE estimates show utility-scale solar PV ranging from 43 to 48 USD/MWh and wind onshore ranging from 30 to 60 USD/MWh, whereas coal ranges from 60 to 143 USD/MWh and nuclear ranges from 112 to 183 USD/MWh. Agora Energiewende estimates the average LCOE for onshore wind in the context of Germany to be in the range of 5–9.5 cents €/kWh. As the global energy transition increasingly shifts towards renewables and away from fossil and nuclear sources, the costs of energy are expected to decline futher (Breyer et al., 2017a,b). These estimates futher substantiate the results of this research in the context of 2030, as LCOE of renewables and storage are continuing to decline.

6. Conclusions

From the LCOE results presented in Figs. 7 and 8, it is clear that renewable electricity generation in several of the G20 countries is already lower in cost than conventional alternatives. These include the USA, Argentina, Brazil, the EU, Turkey, China and Australia. This is the case when external and CO_{2eq} costs are not considered, but with clear socio-economic and environmental impacts of power generation along with increasing adverse direct health impacts of fossil fuel and nuclear power generation being evident (Health Care Without Harm, 2015; Markandya and Wilkinson, 2007), the need to represent the real costs of power generation is incontrovertible. When the external and CO_{2eq} costs of the various power generation technologies are considered, LCOE of renewables and storage are seen to be much lesser than the LCOE of fossil fuels and nuclear across most of the G20 countries. This suggests that there are clear socio-economic benefits in making the right energy choices for governments of the G20 countries as well as rest of the world. At the same time, as indicated earlier it is expected that all G20 countries will demonstrate full cost competitiveness of renewable sources by 2030 on a LCOE basis. Even without the consideration of external and CO_{2eq} costs, renewables and storage make a fully viable economic case for all the G20 countries by 2030.

However, it should be stressed that all countries should begin to invest in renewable energy sources well ahead of 2030 in order to take full advantage of this opportunity and minimise adverse impacts. Firstly, waiting too long will mean that expanding intermittent renewable capacities may be unnecessarily disruptive to power systems if growth is too rapid. More gradual increases in capacities over the coming decade or so can mitigate such technical disruptions. Furthermore, existing industries and companies may need to adapt to the energy transition, and a steadier transition towards 2030 may help prepare them for the task ahead. Secondly, eliminating external costs as soon as possible will result in improved health and well-being, particularly in countries such as India and China (Jakob et al., 2016). As stated previously, these external costs are often felt disproportionately by the most vulnerable members of society. Therefore, each country must find its own unique transition towards greater sustainability based on their levels of population, affluence and technology (Shuai et al., 2017), and it would be unwise for any to lack an appropriate sense of urgency. Finally, renewable based power generation seems to be the reasonable option, as not only is it lower in costs and more efficient, but it also generates jobs and sustains economic growth as indicated in (Ram et al., 2017). Governments and institutions that most aggressively adopt the energy transition and create an enabling environment to facilitate faster flow of capital investments into their regions for renewable energy development will witness far more economic growth and benefit from it (Binz et al., 2017). It appears to be logical from an economic perspective, an environmental perspective, a health perspective and a moral perspective.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.07.159.

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Publication II

Keiner, D., Ram, M., Barbosa, L.S.N.S., Bogdanov, D., and 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

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Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050

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ABSTRACT

Globally, PV prosumers account for a significant share of the total installed solar PV capacity, which is a growing trend with ever-increasing retail electricity prices. Further propelled by performance improvements of solar PV and innovations that allow for greater consumer choice, with additional benefits such as cost reductions and availability of incentives. PV prosumers may be one of the most important enablers of the energy transition. PV prosumers are set to gain the most by maximising self-consumption, while avoiding large amounts of excess electricity being fed into the grid. Additionally, electricity and heat storage technologies, heat pumps and battery electric vehicles are complementary to achieve the highest possible self-consumption shares for residential PV prosumer systems, which can reach grid-parity within this decade in most regions of the world. This research finds the cost optimal mix of the various complementary technologies such as batteries, electric vehicles, heat pumps and thermal heat storage for PV prosumers across the world by exploring 4 different scenarios. Furthermore, the research presents the threshold for economical maximum battery capacity per installed PV capacity, along with self-consumption ratios, demand cover ratios and heat cover ratios for 145 different regions across the world. This is a first of its kind study to conduct a global analysis of PV prosumers with a range of options to meet their complete energy demand from a future perspective, up to 2050. Maximising self-consumption from solar PV generation to meet all energy needs will be the most economical option in the future, for households across most regions of the world.

1. Introduction

There is growing interest in solar photovoltaics (PV) all over the world, as costs for PV systems are steadily declining and by the end of 2020 are expected to achieve grid-parity in the remaining residential electricity markets (Gerlach et al., 2014; Breyer and Gerlach, 2013). Today, solar PV has become a major actor in the electricity sectors of several countries. Globally, close to 500 TWh of electricity has been produced in 2017 by PV systems (IEA-PVPS, 2018). This represents more than 2% of the global electricity demand, though some countries have rapidly reached significant percentages. Around 500 GW of PV has been installed around the world, which is more than 90 times higher than in 2006 (IEA-PVPS, 2019). Solar PV with options that allow consumers to generate electricity at the point of consumption, and send any excess into the grid, are emerging as an attractive option for households around the world, more so in countries where retail electricity prices are high. Prosumers are end-use consumers of electricity who also produce their own electricity at the point of consumption to meet their own electricity needs and feed excess electricity into "the grid" (the electricity system). In simple terms, prosumers are electricity

Abbreviations: ATCE, Annual Total Cost of Energy; ATGEC, Annual Total Grid Energy Cost; BEV, Battery Electric Vehicle; COP, Coefficient of Performance; DCR, Demand Cover Ratio; DHW, Domestic Hot Water; DoD, Depth of Discharge; DSC, Direct Self-Consumption; FIT, Feed-in-tariff; GDP, Gross Domestic Product; GSHP, Ground Source Heat Pump; HC, Heating Cartridge; HCR, Heat Cover Ratio; HP, Heat Pump; ICE, Internal Combustion Engine; LUT, Lappeenranta University of Technology; P2P, Peer-to-Peer; pph, people per household; PV, Photovoltaic; RE, Renewable Energy; SCR, Self-Consumption Ratio; SCOP, Seasonal Coefficient of Performance; SH, Space Heating; SoC, State of Charge; TES, Thermal Energy Storage; V2G, Vehicle-to-Grid; V2H, Vehicle-to-Home

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consumers interacting with the grid by generating some amount of electricity (Martin and Ryor, 2016). The increasing number of prosumers could transform the electricity system and the way in which electricity consumers interact with it. This is happening in a number of countries such as Australia, Germany and many of the EU countries, that are promoting policies for enhanced self-consumption through residential PV installations (IEA-PVPS and CREARA, 2016). While in California, it has become mandatory for new home owners to have solar PV systems that will offset part of their energy bills (Penn, 2018). In addition to the ability of prosumers to self-generate and connect with the grid, prosumers have the potential to help mitigate the growth of energy supply-demand gaps and electricity system losses. These potential benefits are particularly important at the city level, where almost two-thirds of the world's energy is consumed and is set to rise with rapid rates of urbanisation (IPCC, 2014).

The development of storage technologies, more precisely battery storage (Lithium-based batteries) have enabled prosumers to maximise self-consumption of solar PV generation and further reduce their Annual Total Cost of Energy (ATCE). Germany supports storage through financial incentives for prosumers, which has led to a significant share of new residential PV installations with storage units that reached 100,000 homes in mid-2018, with another 200,000 storage systems expected in the following years (Enkhardt, 2018). In Australia, 20,789 storage units were installed in 2017, mainly in the residential segment (IEA-PVPS, 2018). In countries with high retail electricity prices, rooftop PV-plus-storage systems are increasingly becoming the cost effective option and enabling consumers to turn into prosumers. Some markets have already reached grid-parity for PV systems with battery storage (Werner et al., 2012). Furthermore, driving the demand and contributing to the declining costs of batteries is the increasing adoption of battery electric vehicles (BEVs). The evolution of the global electric car stock reached nearly 2 million, within six years from 2010 to 2016 (IEA, 2017). The accelerated development of the EV market could be compared to the development of the PV market, with similar penetrations. With more than 1.2 million electric vehicles sold in 2017 (or 1.5% of the global car market), the penetration of this industry could reach the same levels as PV penetration in the power sector in the coming years and possibly evolve even faster (IEA-PVPS, 2018). Cumulative global EV sales has reached 4 million in 2018 and the intervals between each million EVs sold, is shortening (Willuhn, 2018).

Space heating and cooling combined with hot water supply corresponds to nearly half of the energy consumption in buildings (IRENA, 2013). In case of the European Union, there is a target of 20% renewable energy of the final energy consumption by 2020 and is estimated to include 4.9% of final energy from heat pumps as well as 2.9% from PV (IRENA, 2013). Heat pumps (HPs) for domestic heating and hot water supply are currently a niche technology in many EU countries, but they are increasingly expected to play an important role in a low carbon future. This is largely due to a future of rapidly decarbonised electricity supply, in which using electricity via heat pumps is one of the lowest polluting heating options (Fawcett, 2011). Several countries accept HPs as a renewable application sourcing surface geothermal energy and therefore support HP systems to enable a higher share in buildings, replacing conventional heating systems. The cost reduction of HPs is estimated to be about 30–40% for heat services by 2050 (IRENA, 2013). Furthermore, these can be coupled with thermal energy storage (TES) technologies, which are relatively inexpensive, reliable and do not require specific maintenance. In particular, residential applications require low temperature energy (i.e. in the range of 50–80 °C) and can thus utilise sensible thermal energy storage systems to provide the necessary heating (Facci et al., in press). Schwarz et al. (2018) and Facci et al. (in press) show that PV integration with TES units in combination with power-to-heat applications (such as HPs) are extremely beneficial. The benefits of PV and HP technologies can be best utilised by combining them in residential energy systems. Past surveys show that PV + HP systems combined with TES can economically challenge conventional solar collector systems (Tjaden et al., 2013).

Finally, a combination of PV, batteries, HPs, TES and BEVs in a residential energy system seems to be a future prospect in order to meet the overall energy demand of households. In this regard, the research explores various settings with 4 different scenarios as constituting the basis for an optimised self-consuming household. However, just the presence of system components are not sufficient to optimise the energy system. Therefore, the aim of this research is to create a PV prosumer model for optimising PV energy usage and the ATCE for average residential households across the different regions of the world. Additionally, the aim is to perform a more comprehensive investigation of the impact of the different system components and the development of the ATCE, self-consumption ratio (SCR), demand cover ratio (DCR) and heat cover ratio (HCR) over the time period from 2015 to 2050. This will also include, finding the least cost PV capacities and the corresponding battery sizes. This is the first study to conduct a global analysis of PV prosumers with a range of complementary solutions to meet their energy demands in the most cost effective manner. The next Section 2, presents a literature review of PV prosumer studies conducted nationally and regionally, followed by Section 3 with the methods and materials adopted in the research. Section 4, presents the results. Thereafter, the results are discussed in Section 5 and conclusions are drawn in the last Section 6.

2. Literature review

Until recently, across many regions of the world PV systems were mainly installed to feed the generated electricity into the electricity grid, which was remunerated with a feed-in tariff (FIT). However, with decreasing PV FIT and increasing retail prices of grid electricity, utilising the generated PV electricity on-site at the household level is becoming more attractive than feeding it into the grid across many regions of the world. In this context, the literature on PV self-consumption is quite diverse and encompasses a wide range of technologies and systems. The report by IEA-PVPS and CREARA (2016) reviews and analyses evolving PV-self consumption policies and business models across key countries and concludes that despite self-consumption being in an infant stage, most countries are probing regulations to frame its development. Furthermore, the report explores the most essential questions to be considered in order to ensure its smooth development and suggests that the most important one could be to identify whether the optimisation of self-consumption should be considered just locally or from a regional system perspective (IEA-PVPS and CREARA, 2016). Weniger et al. (2014) analyse residential PV battery systems by simulations in order to gain insights into their sizing, along with sensitivity analyses with varying sizes of PV battery systems to identify appropriate system configurations. Additionally, Weniger et al. (2016) explore sizing batter converters for residential PV storage systems. Finally, an economic assessment of residential PV battery systems is conducted to derive recommendations for cost optimal sizing (Weniger et al., 2014, 2016). Weniger et al. (2014, 2016), show that the self-consumption rate and the degree of self-sufficiency strongly depend on the PV system and battery size considered, however, the household load profiles were limited to north-east German lowlands. Similarly, Yu (2018) determines the economic attractiveness of the PV self-consumption model combined with lithium-ion batteries in the French residential PV sector in 2030. The study has shown that PV self-consumption with batteries could become profitable for individual investors in France before 2030 (Yu, 2018). However, these studies do not consider the integration of electricity and heat storages, which is an option to optimise self-consumption even further. In this regard, there are studies that have analysed the heating aspect of residential households, such as Brange et al. (2016) wherein, heat prosumers in Sweden were analysed and showed their potential to contribute significant amounts of heat to district heating grids. Furthermore, Delgado et al. (2018) conducts multi-objective optimisations for operational CO_2

emissions and lifecycle costs (LCC) of heat and electricity prosumers in the Netherlands and Finland. The study finds that as energy systems continue to develop, heat export to district grids has potential to become a common practice (Delgado et al., 2018). In addition, Shah et al. (2015) mention the potential of using off-grid residential hybrid energy systems (solar PV, battery, and combined heat and power) to address the energy transition and system integration for the United States of America. The study demonstrates the off-grid residential-scale hybrid energy systems incorporating solar photovoltaic, batteries and a co-generation unit are able to meet electrical load demands throughout the U.S. using reasonable sized components (Shah et al., 2015). Moreover, these studies are limited to just a region or a specific country and lack a broader global perspective.

Furthermore, there is a lack of holistic prosumer studies that integrated BEVs, heat storage technologies along with solar PV and battery storage. In this context, Bocklisch and Lindner (2016) conduct a technical and economic investigation of a decentralised, grid-connected PV, small wind turbine (SWT) – hybrid system with lead-acid battery, lithium-ion battery and heat-storage path. The study finds that configurations with battery storage can achieve even higher self-sufficiencies up to 85% with an economic profit and peak-shaving-/power2heat-concept reduce the maximum grid and battery powers reliably (Bocklisch and Lindner, 2016). Another option for enhancing self-consumption along with optimising PV and storage systems further is the integration of BEVs. In this regard, there are studies that have explored the integration of BEVs with prosumer households, such as Gudmunds, (2018), which investigates how the introduction of an EV to residential households, with small scale electricity generation from solar PV and both with and without stationary battery storage, can affect the electricity demand from the grid for these households. The study finds that there are benefits for integrating BEVs with household energy systems, but, it does not include any economic aspects such as investment costs for the components or considered retail electricity prices. Neither are sizes of the different systems in the model optimised. On the other hand, Erdinc et al. (2015) have considered bi-directional flows including the options for vehicle-to-home (V2H), vehicle-to-grid (V2G) and possibilities to use the stationary battery for selling back electricity to the grid. Moreover, different combinations of these options have been investigated together with consumer preferences for charging of the BEV, showing that the costs of electricity could be reduced by up to 65% (Erdinc et al., 2015). As these concepts are evolving and various options for optimising self-generation and consumption are still being explored across different regions of the world, there is a lack of research on prosumer models that combine all the aspects of electricity, heat and electric mobility integrated into a residential household. Exploring prosumer models across the different regions of the world as well as on a global scale is still lacking and is an issue for future research. In this context, this research explores a PV prosumer model with a combination of PV, batteries, HPs, TES and BEVs in a residential household energy system. Furthermore, it determines a cost optimal combination of the system components in order to minimise the ATCE for the prosumer households. In addition, this research is carried out across 145 regions of the world to provide an overview of prosumer potentials and possible benefits. However, to enable a global overview of prosumers certain broad assumptions and simplifications are inevitable and this is perceived as an acceptable limitation with such analyses. These are further discussed in detail in the following sections.

3. Methods and materials

The PV prosumer model follows the principles of the LUT Energy System Transition model, which is based on an hourly resolution (Bogdanov and Breyer, 2016; Breyer et al., 2018; Ram et al., 2017a). To determine the cost optimised (least ATCE) PV and stationary battery capacities, simulations were performed on an iterative basis over PV capacities, ranging from 1 to 30 kW_p and stationary battery capacities,

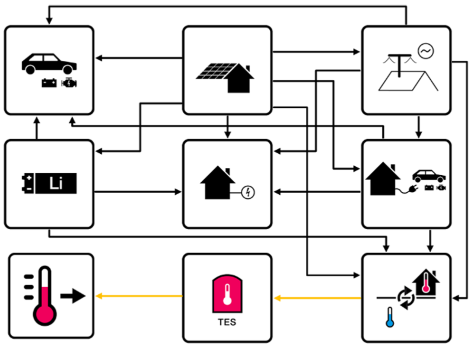

Fig. 1. Structure of the PV Prosumer model with all system components and the corresponding flow of electricity and heat.

ranging from 1 to 50 kWh_{cap}, with intervals of 1 kW_p and 1 kWh_{cap} each for PV and stationary battery capacities respectively. Furthermore, the simulations were carried out on a global scale comprising 145 regions (Breyer et al., 2018; Ram et al., 2017a), in 5-year intervals from 2015 until 2050. A list of all the regions with their abbreviations can be found in the Supplementary Material (Table S1). Simulation programme MATLAB was used in the process of formulating, estimating and visualising the research. Fig. 1 provides the schematic representation of the entire PV prosumer system, including all the components in the case of a standard household. Additionally, the black arrows represent electricity flows, while the orange arrows represent the flow of thermal energy in the form of hot water.

Components of the PV prosumer system from top left to bottom right are enlisted as follows,

a. Car 1: BEV with the primary function of daily commutes and occasionally available as tertiary electricity storage. It also plays a role in charge transfers with Car 2 and the stationary battery. External charging (work place charging) is not considered in this model.
b. Solar PV electricity generation system: Mostly rooftop PV that generates electricity to meet the energy demands of the entire household and feeds excess electricity into the distribution grid.
c. Grid integration: Allows for bidirectional flow of electricity with the local distribution grid and accounts for withdrawal of grid electricity as well as fed-in PV generation.
d. Electricity storage: Lithium ion batteries that store electricity for utilisation in the household as well as other components (BEVs and HP).
e. Household electricity demand: This represents all household appliances and equipment that consume electricity.
f. Car 2: BEV with Vehicle-to-Home (V2H) capability, low usage for commuting and available as secondary electricity storage.
g. Heating demand: provides the heating requirements of the household, mainly hot water demand and space heating during winters, applicable to the respective regions.
h. Thermal energy storage: stores thermal energy in the form of hot water in a hot water tank.
i. Heat Pump/Heating Cartridge: Heat exchange system with the primary function of converting electrical energy to thermal energy.

Sizing of the PV prosumer systems are based on average household energy demands from the different regions considered. Representative average households were considered, as there is substantial variation in household sizes and corresponding energy demands within the regions.

3.1. GDP and household size

Household data was adopted from the United Nations database (UNSD, 2017). Additionally, using the Gross Domestic Product (GDP) per capita, a relation between GDP per capita and people per household (pph) was established. The GDP projections were adopted from Toktarova et al. (2019). For the development of pph values until 2050, a linear increase of GDP per capita was assumed. Furthermore, it was assumed that the effect on pph is a quarter of the GDP per capita development, which means a 100% increase in GDP per capita will induce a 25% decrease in pph. This connection portrays a most appropriate development of the pph within the whole transition period and has been derived empirically. For regions with more than one country, the population-weighted average of the countries was considered. For countries that were split into more than one region, the same pph was assumed for all sub-regions. The development of pph through the transition period from 2015 to 2050 for all regions around the world can be found in the Supplementary Material (Fig. S1 and Table S2).

3.2. Solar data

PV electricity generation profiles were available for every region with full hourly resolution in kWh, according to Bogdanov and Breyer (2016) as shown in Fig. 2. These are adopted for the range of PV capacities used in the PV Prosumer model to generate the household PV generation profiles from 2015 until 2050.

3.3. Load profiles

Residential electricity load profiles are available for Brazil, Italy, Japan, Senegal, Thailand, Germany, New Zealand and the United States (Werner et al., 2012). The challenge is in creating load profiles for all regions of the world, which encompasses the local behaviours of residential households. To factor in the local aspects, regions with similar socioeconomic as well as geographical conditions were categorised into ten representative 'profile regions'. These are NA-US-SWMA (South Western and Middle USA), NA-CA-US-NE (North Eastern USA and Canada), SA (South America), Europe-Nordic-RU (Northern Europe and Russia), Europe-CE-East (Central and Eastern Europe), Europe-South-MENA (Southern Europe and MENA), SSA (Sub-Saharan Africa), Pacific (New Zealand and Australia), SEA (South East Asia) and NEA-Eurasia-CA (Central and Eastern Asia). By combining the load profiles of the various regions, an 'average human electricity consumption' load

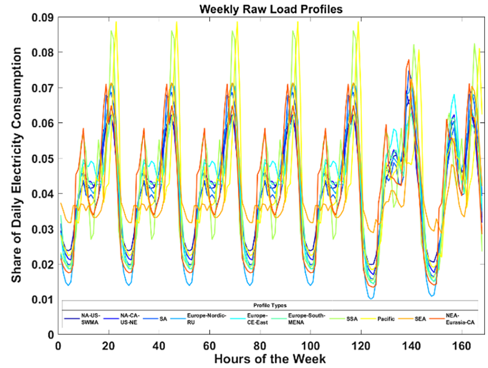

Fig. 3. Weekly load profiles as a share of energy consumption for the ten 'profile regions'.

profile was derived, to represent the activities of regular households across the world. Moreover, the variations in load profiles in relation to the average derived load profile helped in categorising the different regions with respect to their profile types. This resulted in regional load profiles containing area specific factors as well as average human behaviours with respect to electricity consumption (comprising the morning and evening peaks). The load profiles for the ten representative 'profile regions' are shown in Fig. 3. Wherein, it can be noticed that the profiles differ quite substantially during daytimes, which has an impact on Direct Self-Consumption (DSC) of households in those regions. This approach does lead to a more simplified load profile, which is ideal for the case of a representative average household. Whereas, aspects such as the urban and rural household differentiation that is higher in developing countries have not been considered. As it has been observed globally, prosumer proliferation generally begins in urban settings and then expands to the rural segments too.

Furthermore, the profiles factor in annual variations that occur predominantly due to seasonal changes. Country-wide and regional load profiles were adopted from Toktarova et al. (2019), which have factored in annual variations. These profiles were used to derive the annual mean loads. Further, by combining weekly load profiles with the

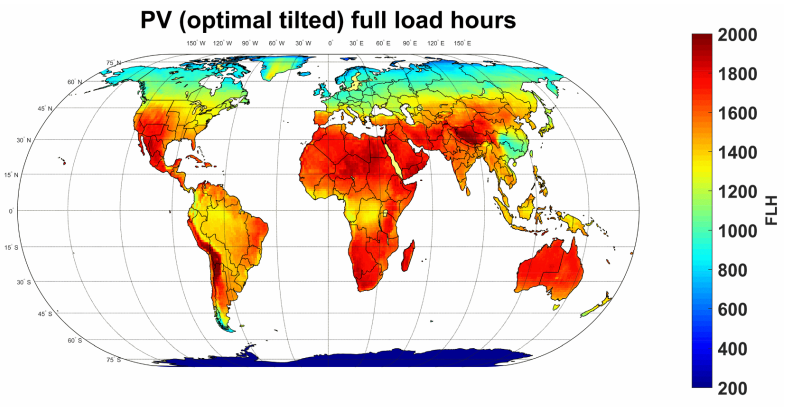

Fig. 2. Global full load hours of optimally tilted PV systems (Bogdanov and Breyer, 2016).

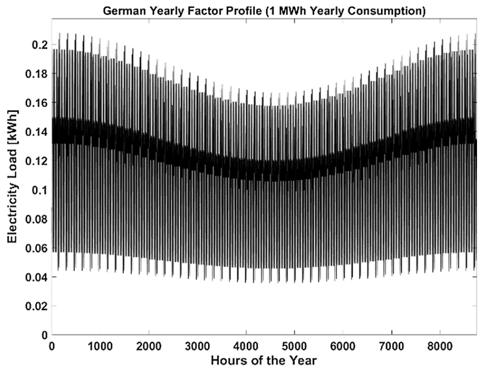

Fig. 4. German yearly factored load profile (normalised to an annual electricity consumption of 1 MWh).

specific weekly factors using Eq. (1) for every week of the year, the profiles for residential electricity loads across households in the different regions of the world were derived.

$$load_{factorised} = load_{raw} \cdot f_{week} \tag{1}$$

In Eq. (1), $load_{factorised}$ – real load profile; $load_{raw}$ – raw load profile; f_{week} – factor of the investigated week in comparison to the country-wide or regional annual mean load. This was applied for all weeks of the year and thereby deriving annual residential load profiles across households in the 145 regions. Fig. 4 shows the factorised yearly load profile for the case of Germany. These load profiles are normalised to annual electricity consumption of 1 MWh. Thereafter, the profiles were corrected by the annual electricity consumption per household across the different regions to represent the factorised electricity load profiles of households.

With the data for pph, total electricity consumption (IEA, 2017) and shares of residential electricity consumption across the different regions (Toktarova et al., 2019), the annual residential electricity consumption per representative average household was estimated for each of the regions. Also, it was assumed that the shares of residential electricity consumption will remain the same for all years until 2050. Indicating that the increase of residential energy consumption is according to the increase in total electricity consumption for each of the regions, respectively. This is a more simplified approach, which presumes the shares of residential electricity consumption to remain the same until 2050. This is based on the presumption that increased electrification across the different sectors will lead to a more stable share of residential electricity consumption.

Load profiles for Space Heating (SH) and Domestic Hot Water (DHW) demand were available on a region-wide scale for all the regions until 2050 (Barbosa and Breyer, 2017). Moreover, SH and DHW factorised load profiles were derived according to the pph and population per region. Electricity consumption, SH and DHW for households in all the regions across the different years can be found in the Supplementary Material (Tables S3–S5).

3.4. Battery electric vehicles

For a standard case of the PV Prosumer model, a residential household with 2 BEVs is envisioned. The capacity of batteries in the BEVs were set to specific values based on recent trends (UBS, 2017; ICCT, 2012), with Car 1 having 80 kWh_{cap} and Car 2 having 60 kWh_{cap}. UBS (2017) presents detailed analyses of the BEV market with insights into driving ranges and battery packs of upcoming BEVs. Currently, mass-market electric cars with over 350 km range such as the Tesla Model 3 and the Chevy Bolt, along with many more are expected to have similar battery capacities in the near future (Timofeeva, 2017). The Tesla Model 3 offers 50 kWh and 75 kWh packs for ranges of 350 km and 400 km, respectively (UBS, 2017). Whereas, the Chevy Bolt is offered with a 75 kWh pack that provides around 375 km range (Timofeeva, 2017). Nissan Leaf, the highest selling BEV has been upgraded to a 60 kWh battery pack to enable a better range (Lambert, 2018). According to ICCT (2012), the over-40-kWh pack segment increased from nearly zero in 2012 to 12% of overall electric vehicle sales in 2015, and the trend is set to continue toward larger battery packs. From a 2050 perspective, 80 kWh and 60 kWh were assumed as reasonable capacities for BEVs. Based on usability and driving patterns, availability of the BEVs for PV charging is assumed. As Car 1 is usually not at home during daytimes and weekdays, it should be possible to charge as much energy as possible during weekends and evening hours of weekdays. In some cases, Car 1 could satisfy its driving demand from the energy charged in the weekend, for the entire following week. This could be compared to a filled tank of a conventional internal combustion engine (ICE) vehicle. As Car 2 is mostly stationary, it is available for PV charging and can perform as a vehicle-to-home (V2H) device as well. This enables the possibility to charge as much PV electricity as possible for supplying household demands (electricity and HP). Furthermore, Car 2 is also assumed to provide electricity for charging Car 1. The Depth of Discharge (DoD) for batteries in BEVs is not considered, however, a safety buffer of 25% of the storage capacity was included for emergencies.

From an operational point of view, Car 1 is the primary usage vehicle for daily commuting as well as occasional weekend travels. Whereas, Car 2 is the sparingly used vehicle mainly for secondary activities such as shopping or other domestic purposes. Car 1 being a ‘usually away’ vehicle leaves the household in the morning hours and returns in the late afternoons, representing usual workplace journeys. Additionally, Car 1 is used for free time journeys on weekends. The occurring of the free time journeys was determined by a randomised function built into the simulation. This enables dynamic weekend journeys, independent of solar conditions on weekends. For Car 2, which is a ‘usually at home’ vehicle, the usage time was assumed to be three hours per day based on Marwitz (2012). The occurrence of these journeys were determined randomly, enabling journeys for Car 2 to be independent of solar conditions as well as load demands. Car 2 journeys occur mostly during late mornings. Data pertaining to the usage of Car 1 and Car 2, as well as their driving patterns were adopted from Marwitz (2012). In the case of poor solar conditions, the BEVs are charged by the grid electricity. The BEVs are charged by electricity from the grid during early morning hours, when household electricity demands are usually low (as in Fig. 3). In order to minimise grid charging, the State of Charge (SoC) of the BEVs has to be below the safety buffer plus the demand for one daily trip, in order to enable grid charging.

The daily trip demands were calculated using Eq. (2), as follows:

$$E_{Car,trip} = \frac{Yearly\ \ driving\ \ distance}{\sum\ \ journeys} \cdot E_{cons.} \tag{2}$$

Wherein, $E_{car,trip}$ – electricity demand per car trip and $E_{cons.}$ – specific electricity consumption of BEVs. The specific electricity consumption of the BEVs was set to 20 kWh/100 km (Marwitz, 2012), including energy losses and discharging efficiencies. The discharging efficiency of Car 2 to supply household demands and Car 1 charging was assumed at 96.8% (Luo et al., 2015), which represents the charging and discharging efficiency of Li-Ion batteries in the LUT Energy System Transition model (Breyer et al., 2018). Driving distances per year were assumed as 14,000 km and 10,000 km per year for Car 1 and Car 2 respectively, these were adopted from Khalili et al., (submitted for publication) that was based on a database from the ICCT (2012). Moreover, the global annual average of all cars were in the range of the average mileage of passenger car drivers in Germany at 12,800 km (Khalili et al., submitted for publication). In addition, the study Eurostat (2007) showed that the global daily driving distances are more or less in the range of European mean values, which are 30–40 km per day.

3.5. Stationary battery

A stationary battery is part of the standard PV prosumer household and the model based on various factors, in achieving the least ATCEoption, determines its capacity. A combination of installed capacities of PV and stationary batteries are determined by an iterative process to achieve the ATCE for the different prosumer households across the various regions of the world. As shown in Fig. 1, the stationary battery satisfies the electricity demand of the household and the HP, as well as charges Car 1 occasionally. The model prioritises charging of the stationary battery after DSC. Its primarily role is to deliver electricity to meet demands during evening and night hours, but also covering peak demands during daytimes when PV generation falls short, provided that the stationary battery is sufficiently charged. In order to minimise utilisation of grid electricity, charge transfers between the stationary battery and Car 1 are prioritised over charging Car 2 with grid electricity. This does not impact the household demand and provides for the possibility of maximising the utilisation of PV electricity within the system. A Li-ion battery is set as the standard for the PV Prosumer household, as they are increasingly common in residential applications. The DoD was assumed at 95%, while the charging and discharging efficiency was 96.8%, similar to BEVs (Luo et al., 2015). Along with charge transfers, the stationary battery is complemented by Car 2 that can cover demands during insufficiencies. Moreover, Car 2 has the provision to transfer excess charge to Car 1.

3.6. Heating system (heat pump, heating cartridge)

Currently, there is no technology to rival heat pumps for efficiently using electricity to deliver residential and commercial space heating (Fawcett et al., 2015). Ground source heat pumps (GSHP), which absorb energy from the ground using a dedicated borehole or network of buried pipes was chosen to be part of the standard PV prosumer household. As, the efficiencies compared to air source HPs are much better, the operational costs are lower and availability in comparison to water source HPs is higher. Another advantage of GSHPs is the stable Coefficient of Performance (COP) over the whole year caused by the stored solar energy in the ground, even during the winters with very low temperatures. The choice of GSHP as part of the representative prosumer household was based on the resulting lower annual costs as compared to other HPs, as the end objective of the research is to attain a cost optimal setting for PV prosumers. However, it could be the case that other HPs could be better in terms of performance for specific weather conditions. The HP specifications are based on a commercially available HP with the possibility of heating water up to 90 °C. Whereas, the rated power is 7 kW_{el}. The COP was set to a permanent value of 3.8 for operation at nominal value. For additional filling of the TES by PV generation, the COP is set at 3 and this is further discussed below along with the TES.

Heating requirements across the different regions of the world vary significantly, primarily due to climatic and geographic conditions. Therefore, for regions with a SH demand of less than 2 MWh_{th} per capita annually, application of HPs with TES of 800 L capacity is not the most appropriate solution. As investment costs for the system components are not reasonable for lower heat demands. For regions with a SH demand under the above-mentioned limit, heating cartridges were adopted with 7 kW_{th} output power. Fig. 5 maps the regions across the world according to the heating systems utilised. Only two regions change their system types during the energy transition period. Ecuador, which switches from a cartridge system to a HP system in 2045. Whereas, South Africa and Lesotho changes from a HP system to a cartridge system in 2050.

Another aspect to be considered is the minimum potable water temperature to be maintained. In this regard, the European standards DIN EN 806-2 (DIN, 2005) and DIN EN 1717 (DIN, 2000) recommend a temperature of minimum 60 °C for the avoidance of legionella development in potable water. Hence, operations at a nominal temperature of 65 °C was adopted to be well within the limits. This consideration seems as an optimal combination of the minimum temperature necessary for potable water quality as well as for the most efficient operation of HPs.

3.7. Thermal energy storage

The TES assumed is a tank-in-tank storage with a water capacity of 800 L for HP systems and 200 L for heating cartridge systems. This includes storage capacities for SH and DHW in one device, as they are usually used for solar thermal applications (Stadler and Sterner, 2017). A standby of 25% was set for the TES as shown in Fig. 6, which guarantees coverage of SH and DHW demands during refilling. Thereby ensuring, household occupants to carry our domestic activities such as taking a bath or shower, even when TES SOC is quite low without any refilling. Refilling is triggered when SOC of the TES falls below the 25% standby. The demand is covered either by DSC from PV generation or by the stationary battery depending on the time of day and availability of generation. Alternatively, the BEVs can also be utilised for satisfying the demand depending on the availability of charge in them and if none of the energy storage options are able to cover the demand, the refilling demand is covered by grid electricity. The TES gets filled by the HP with a COP of 3.8, as mentioned earlier. The maximum TES capacity is therefore 800 L at 65 °C. Eq. (3) describes the estimation of storable capacity of thermal energy in the TES.

$$E_{th,cap} = c_{p,water} \cdot V_{TES} \cdot \Delta T \tag{3}$$

Wherein, E_{th} – thermal energy; $c_{p,water}$ – specific heat capacity of water (0.0016 $kWh_{th}/(kg{\cdot}K)$, derived from 4.19 kJ/(kg·K)); V_{TES} – storage volume of the TES; ΔT – temperature difference (45 K for nominal operation, 70 K for PV additional filling).

Situations in which the stationary battery is fully charged, both BEVs are fully charged or not available and the TES is completely filled with 800 L at 65 °C, the generated PV electricity surplus is normally fed into the grid. But, this would hinder SCR optimisation, since capacity in the TES is still available. Generally, the TES as well as HPs are designed for 90 °C. Therefore, the system has the possibility to fill the TES up to 89.6 kWh_{th}, which means 800 L at 90 °C. Although COP of 3 for PV additional filling is lower than for nominal operation, the possibility of utilising more low cost energy compensates the lower efficiency. In order to maximise SCR optimisation, an added storage capacity of 32 $kWh_{th,cap}$ is factored into the PV Prosumer model. Fig. 6 visualises the TES filling conditions. PV additional filling is also considered for the heating cartridge systems with 200 L TES. In this case, efficiency for the heating cartridge remains the same. The nominal capacity for a 200 L TES is 14.4 kW_{th}, while the full thermal capacity is 22.4 kWh_{th}.

The losses of thermal energy storage systems are between 1.6 kWh_{th} and 2.5 kWh_{th} per day (24 h) according to Viessmann Werke GmbH (Viessmann, 2017). Considering the 800 L TES, thermal energy losses of about 0.15% per hour could be expected. This value was considered independently of the SOC and TES size. The efficiency assumptions for all relevant system components are listed in the Appendix (Table A.2).

3.8. Financial target function

The ATCE is estimated according to Eq. (4), which is minimised over the year.

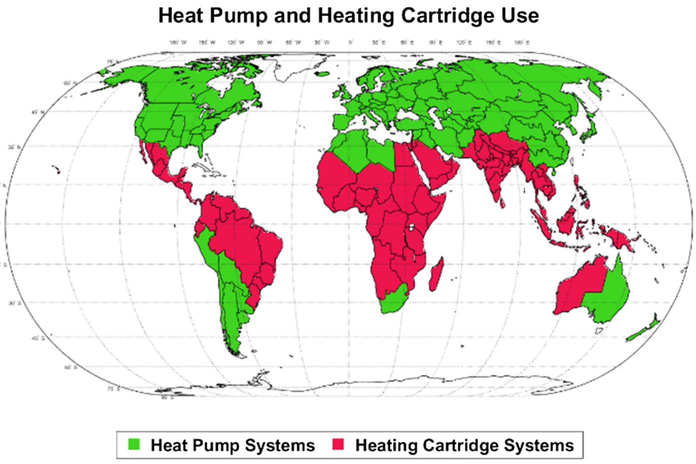

Fig. 5. A global map representing heating systems of the various regions.

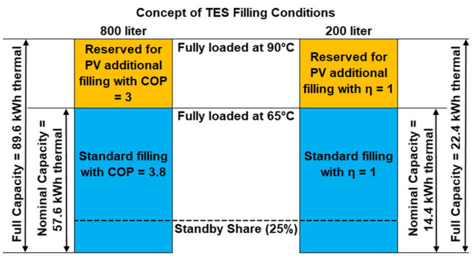

Fig. 6. Thermal capacities of TES filling for the operational modes of HP and Heating Cartridge.

$$ATCE = \sum_{i}^{technology} (Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + cost_{grid} - income_{feed-in} \tag{4}$$

Wherein *ATCE* – annual total cost of energy, *Capex* – investment cost for technology, *crf* – annuity factor, *opex*$_{fix}$ – fixed operational expenditures, *opex*$_{var}$ – variable operational expenditures, $E_{throughput}$ – energy handling of component (e.g. discharged energy of the battery), $cost_{grid}$ – cost of remaining electricity supplied by the grid, $income_{feedin}$ – income form PV electricity fed-in to the grid.

For comparing annual energy costs, Eq. (5) representing a 100% grid supply based energy system without PV and stationary battery is considered. This is minimised over an entire year. In the case of 100% grid supply, Car 2 is assumed as a normal BEV, as V2H application may not be beneficial. The HP operates nominally with grid supply, to minimise annual total grid energy cost (ATGEC) according to Eq. (5)

$$ATGEC = \sum_{i}^{HP,TES} (Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + \left(\frac{E_{th,DHW} + E_{th,SH}}{COP_{nom}} + E_{el,house} + E_{el,car1} + E_{el,car2}\right) \cdot price_{grid} \tag{5}$$

Wherein ATGEC – Annual Total Grid Energy Cost, $E_{th,DHW}$ – annual thermal energy for hot water demand; $E_{th,SH}$ – annual thermal energy for space heating; COP_{nom} – Coefficient of Performance of HP for operation at nominal value; $E_{el,house}$ – annual electricity consumption of household; $E_{el,car}$ – annual electricity demand for driving.

Financial assumptions for system components and grid electricity prices across the different regions are based on the LUT Energy System Transition model (Breyer et al., 2018; Ram et al., 2017a; ETIP-PV, 2017) and available in the Appendix (Table A.1) and Supplementary Material (Table S6) respectively. The costs of PV systems and battery storage systems vary quite significantly across the different regions (IRENA, 2018) and have been converging towards regional standards (Schachinger, 2018; ETIP-PV, 2017). Standard capex and opex costs are considered for all technologies across the different regions of the world, as costs of these technologies are assumed to converge towards a global standard from a long-term perspective. Moreover, the retail electricity tariffs (grid electricity prices) are from various sources that are collated in Gerlach et al. (2014) and in Breyer and Gerlach, (2013). The further regional categorisation of the retail electricity tariffs is based on averages across individual regions according to the electricity consumption of the respective regions. In the case of BEVs, no storage costs are considered as it is assumed batteries are paid for along with the car (whose primary function is commuting). For all regions of the world, a standard feed-in reimbursement of 0.02 €/kWh was assumed. Despite the presence of a significantly varying FIT across the different regions of the world, a low FIT is assumed from a 2050 perspective. Furthermore, the research is aimed at exploring options for residential households to optimise their self-consumption and minimise their energy costs without the aid of fiscal benefits in the form of taxes, subsidies, fees or others. Alternatively, the applied fixed reimbursement could be perceived as a form of revenue generation or a long-term agreement with electricity service providers on an average price for the excess electricity supplied by households. From a long-term perspective, FITs across the different regions of the world are expected to decline close to conventional grid costs, with rapidly declining PV and storage costs. Moreover, the feed-in reimbursement is assumed to be available only for up to 50% of generated electricity from the installed PV systems at households.

3.9. Operation and scenarios

Operation of the PV Prosumer model is considered to occur sequentially as represented by the flow diagrams in Fig. 7. Adopting this

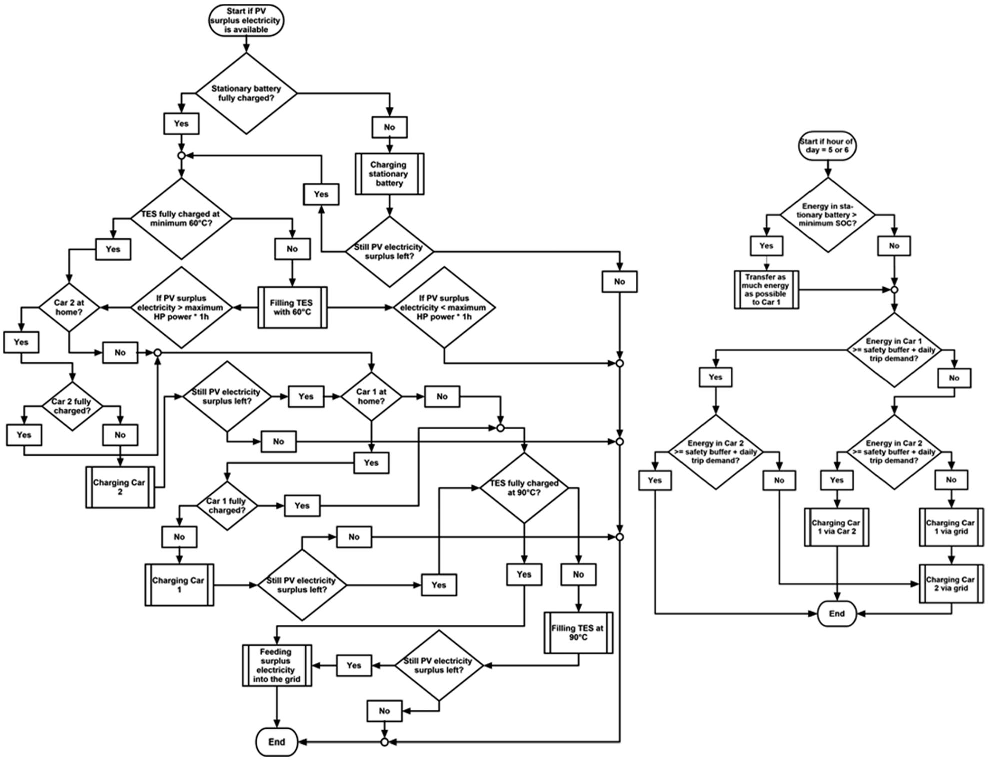

Fig. 7. Flow charts indicating the sequential operation of the components of a PV Prosumer household. PV electricity utilisation (left) and charge transfer between the BEVs (right).

process ensures maximising self-consumption and minimising the ATCE.

As shown in Fig. 7 (left), the stationary battery has first priority in the sequential order for utilisation of surplus PV electricity (available after meeting the household demand). Once the stationary battery is charged completely, TES at 60 °C is second in the sequential order. After TES is filled completely at 60 °C, Car 2 with V2H capability (if at the household) is considered in the sequential order. After Car 2 is charged completely, Car 1 (if at the household) is taken up in the sequential order for charging. Since, the primary role of Car 1 is daily commuting, the availaibility during PV generation hours is much lesser compared to Car 2. Charge transfers between the stationary battery, Car 2 and Car 1 ensures adequate levels of storage required for most efficient usage of generated PV electricity. In cases where Car 1 and Car 2 are unavailable at the household or are fully charged, TES is next in the sequential order. Additionally, TES is heated up to 90 °C (to store maximum heat). Finally, if there is still surplus PV electricity, it is fed into the grid for a FIT of 0.02 €/kWh as the final step in the sequential order. In addition, a further optimisation of the batteries (stationary and BEVs) occurs in the early morning hours, as shown in Fig. 7 (right), to ensure sufficient charge availibility in both BEVs as well as optimal utilisation of all 3 electricity storage options. At 5 am, charge transfer from the stationary battery to Car 1 occurs (if SOC of stationay battery is more than the minimum), alternatively charge transfer from Car 2 to Car 1 occurs (if SOC of stationay battery is below minimum as well as for Car 1). In case Car 2 as well as Car 1 along with the stationary battery have SOC below minimum, electricity from the grid is drawn to charge both Car 1 and Car 2 to meet their daily requirements (commuting demands). From a sequential point of view, Car 1 would be charged first as the utilisation is earlier as compared to Car 2, which is utilised later in the day and has the opportunity to be charged by PV generation during the late morning hours.

Furthermore, the PV Prosumer model is considered to operate in 4 different scenarios to better capture the wide range of household compositions across the various regions of the world. Table 1 shows the different scenarios, which are

- 'Two Cars' scenario: in this case, both the BEVs are in operation.
- 'Only Car 1' scenario: in this case, just the BEV that is primarily used for commuting is in operation.
- 'Only Car 2' scenario: in this case, just the BEV used primarily for

Table 1
Scenarios based on the usage of BEVs.

Scenarios	Car 1	Car 2 (V2H)
'Two Cars'	✓	✓
'Only Car 1'	✓	
'Only Car 2'		✓
'No Cars'		

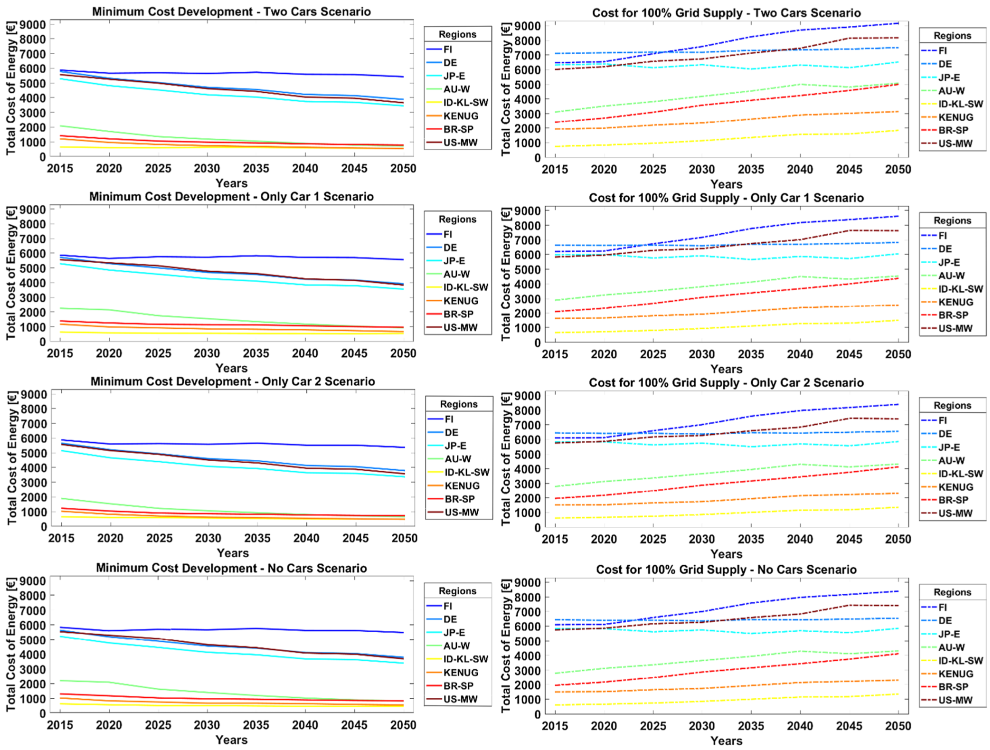

Fig. 8. ATCE for the least cost system (left) and full grid supply (right) in households across the 8 regions, for the 'Two Cars Scenario' (top), 'Only Car 1 Scenario' (center top), 'Only Car 2 Scenario' (center bottom) and 'No Cars Scenario' (bottom).

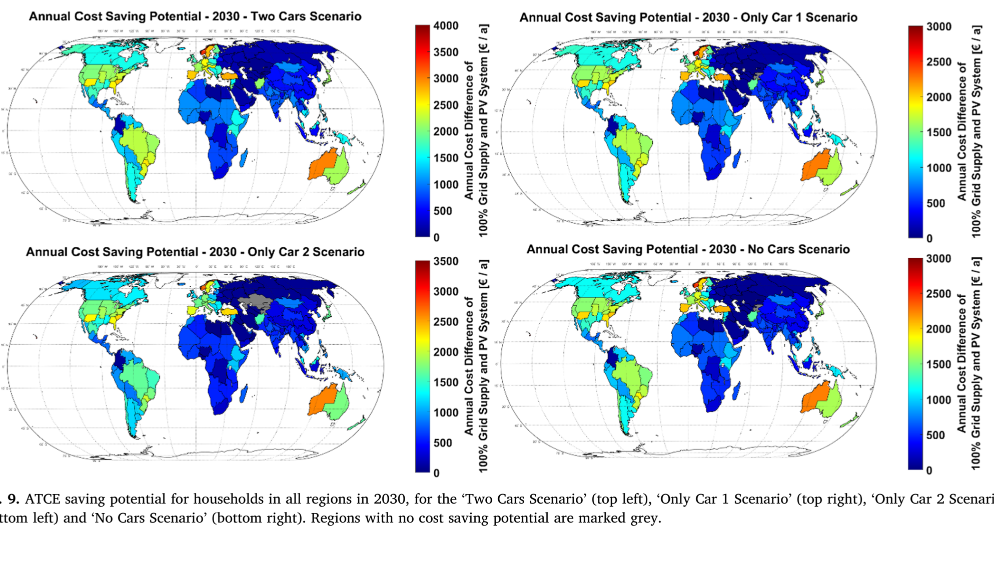

Fig. 9. ATCE saving potential for households in all regions in 2030, for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right). Regions with no cost saving potential are marked grey.

V2H as secondary storage is in operation.

– 'No Cars' scenario: in this case, both the BEVs are not in operation.

Results are presented according to the 4 different scenarios.

4. Results

Eight representative regions across the world were selected to display the results in a broader context. The regions are, FI (Finland), DE (Germany), JP-E (Japan East), AU-W (Australia West), ID-KL-SW (Indonesia East), KENUG (Kenya and Uganda), BR-SP (Brazil – Sao Paulo) and US-MW (United States – Midwest).

4.1. Total cost of energy and grid-parity

The resulting ATCE for all scenarios in households across the 8 regions are shown in Fig. 8. ATCE is reduced from about 900–6000 €/a in 100% grid supply scenarios to approximately 550–5500 €/a in minimum cost development scenarios for households across the 8 regions. Despite the fact that annual electricity demand is increased with the adoption of BEVs, the SCR can also be increased with BEV charging from low cost PV electricity. Hence, compensating for the expected additional costs of increased electricity consumption. The additional costs are observed in Fig. 8, highlighting 100% grid supply costs. The development of ATCE for PV systems decrease linearly, following the decreasing investment costs for the system components until 2050. Stagnating or slightly decreasing energy costs for 100% grid supply in some regions result from the decline of HP and TES costs, which compensate the increasing grid electricity prices. Fig. 9 shows the annual cost saving potential for households across all regions and scenarios in 2030, using a PV system as compared to 100% grid supply. Furthermore, results for 2050 are shown in the Supplementary Material (Fig. S2). Moreover, utilising SCR optimised residential PV systems is already profitable for households in many regions with high grid electricity prices in 2015. On the contrary, for households in regions with low grid electricity prices it is not yet profitable to optimise self-consumption, due to significantly high investment costs mainly for stationary batteries for these conditions.

In Fig. 10 the ATCEratios of PV to grid supply, or rather respective system profitability for all regions in relation to the GDP per capita, are plotted for 2030. The stage of development of the regions, expressed by GDP per capita, has a minor impact on the level of profitability. As, higher energy consumption of households in developed countries make a SCR optimisation more useful. Compared to full grid supply, SCR optimised PV systems are able to reduce ATCE up to 80% within the next decade. Until 2050, it is possible to save up to 90% of energy expenditures across all the scenarios. The use of BEVs has a marginal impact on the time required to achieve regional grid-parity. For the 'Two Cars Scenario', the last region (Tajikistan and Kyrgyzstan) attains grid-parity between 2025 and 2030. For the 'Only Car 1 Scenario' and 'No Cars Scenario', the last region (Tajikistan and Kyrgyzstan) will get beyond grid-parity between 2035 and 2040. Whereas, for the 'Only Car 2 Scenario', the last two regions (Tajikistan and Kyrgyzstan as well as Kazakhstan) attain grid-parity by 2035. However, the heating system (HP and TES) is not optimised for every region. As, the break-even point is very close to the grid-parity limit of the PV system cost to 100% grid supply cost ratio of 1. A marginally optimised TES capacity would be sufficient to shift the year for the last region to attain grid-parity across all scenarios by five years earlier, at a minimum. Nevertheless, some regions are able to reduce their ATCE up to 90%, as compared to 100% grid supply.

4.2. Self-consumption ratio

Optimisation of SCR can be achieved partially, as the substantial decline of PV system costs lead to an effect that makes large feed-in quantities economically attractive. The SCRs level off between 30% and 60% until 2050 for all scenarios, for households in most regions of the world as shown in Fig. 11. The difference between the scenarios is not very significant, but noticeable. By using both the BEVs (Car 1 and Car 2), the SCR can be improved by about 10 percentage points for households in some regions. The charging of Car 1 via the stationary battery results in a higher SCR than using only one V2H BEV (Car 2). There are several reasons for the difference between 'Only Car 1 Scenario' and 'Only Car 2 Scenario', for a higher SCR, the stationary battery transfers as much energy as possible to Car 1 in the morning hours. Therefore, SOC of the stationary battery is quite low when PV electricity is available again. This enables charging the stationary battery to a high level, almost on a daily basis. This effect is lacking in the 'Only Car 2 Scenario', as the stationary battery is deprioritised by Car 2 as a low cost storage option. The availability of Car 2 during daytimes and as a V2H option keeps recharging demand low, which leads to prevailing high SOC of Car 2. Furthermore, the lack of additional driving demand of Car 1 reduces the need for transfer of electricity from Car 2 to Car 1.

The regional variation of SCR as shown in Fig. 11, which is influenced by the corresponding regional grid electricity prices. Households in regions that have low grid electricity prices (such as Russia) tend to have a high SCR, as the installed capacities of PV and battery are much lower in comparison to households in other regions with higher grid electricity prices. The impact of the grid electricity prices varies through the transition period as the costs of PV and battery systems decline substantially, while grid electricity prices in most regions increase through the transition period until 2050. High levels of SCR are prevalent in the early periods of the transition as most regions still do not achieve grid parity. Whereas, in the later periods of the transition lower SCR is observed as most regions have achieved grid parity. This trend is highlighted in the Supplementary Material (Fig. S7).

Optimisation of the capacity of stationary battery has varying effects based on the difference between regions with excellent to moderate solar conditions. In case of the 'Two Cars Scenario', difference between households in Finland and Australia is quite low, at about $15\%_{abs}$. While, in the 'Only Car 1 Scenario' a spread of about $20\%_{abs}$ is expected between 2025 and 2045. In 2050, the SCRs will begin to match up. For the 'Only Car 2 Scenario' a difference of up to $15\%_{abs}$ until 2025 is noticed, with similar SCRs in 2050. The impact on SCR of using both cars or either of them, compared to the 'No Cars Scenario' across the various regions in 2050 can be seen in Fig. 11. Moreover, SCR is observed to be higher in the initial periods as compared to the later periods in most regions during the transition, across all the scenarios. The development of the SCR for the different scenarios across the 8 regions through the transition period from 2015 to 2050 can be seen in Fig. 12.

On comparing Figs. 13 and 14, it can be observed that SCR develops in contrast toATCE. Furthermore, results show that the SCR is mostly dependent on the installed PV capacity in the 'Two Cars Scenario' and the 'Only Car 2 Scenario'. While, for the 'Only Car 1 Scenario' and the 'No Cars Scenario', the SCR increases with higher battery capacities (for small to mid-sized batteries). This indicates that an optimal sizing of PV capacity and storage capacity (BEVs + stationary battery) is necessary for higher SCRs. For the case of households in Germany (Fig. 14), a halving of the installed PV capacity, causes additional energy costs of under 200 €/a, which results in a SCR increase of approximately 25% (refer Fig. 13, bottom left and Fig. 14).

4.3. Demand and heat cover ratios

DCR and HCR vary significantly across the different scenarios as shown in Fig. 15. Households in regions with excellent solar conditions are able to cover, theoretically up to 100% of their demands for electricity and heat in 2050 with self-produced PV electricity. While, households in regions with seasonal solar variation (good solar conditions during summers, but moderate conditions in winter), such as in

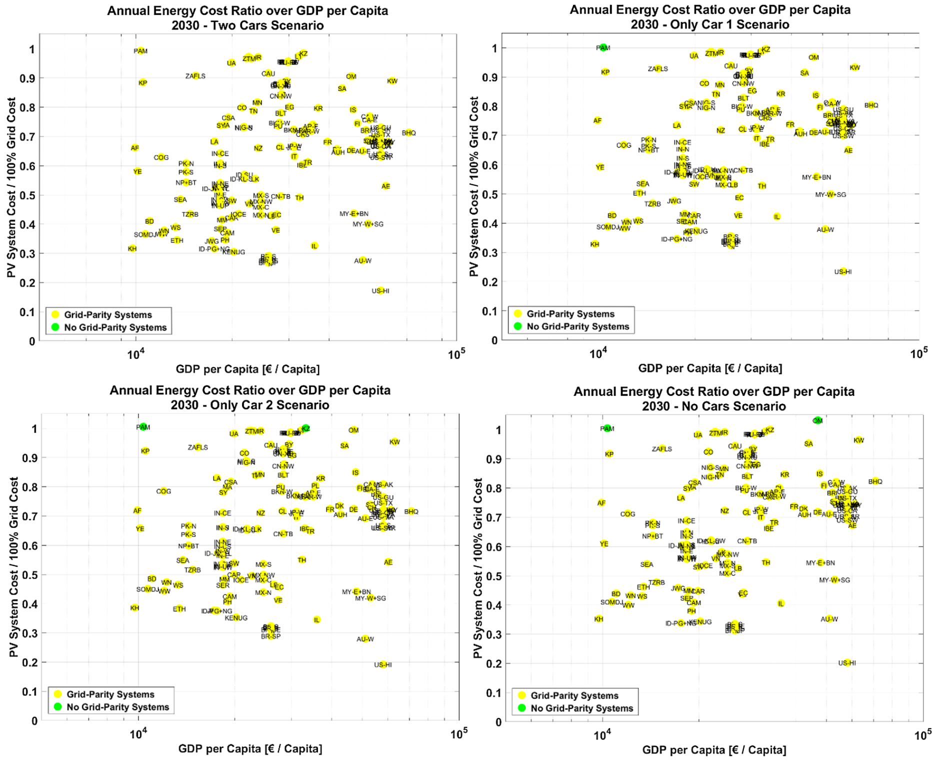

Fig. 10. System profitability (ratio of ATCE of PV to grid supply) over GDP per capita for the different regions of the world in 2030, for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right).

the United States or in Central Europe, are able to cover 90–95% of their electricity demand and 85–95% of their heat demand until 2050 on their own, across all scenarios. On the other hand, households in regions with relatively lower solar potential and higher heat demands, such as Canada or Northern Europe, can cover about 60–75% of their electricity demand and around 60–70% of their heat demand through self-generation. Higher DCR and HCR are achieved for the 'Two Cars Scenario', while they are much lower for the 'No Cars Scenario' as indicated by Fig. 15. Therefore, it can be concluded that widespread affordable electricity storage technologies are indispensable to effectively meet power and heat demands. The development of DCR and HCR through the years witness large changes in the early years and near stagnation from 2030 onwards for most regions across the world. As, the added value for DCR and HCR of cost optimised systems are not very significant beyond a certain point.

The extent for DCR can be noticed from scenarios without Car 2 at a range of smaller capacities of stationary battery. For a majority of the regions, increments in PV and stationary battery capacities have to coincide during the early years, resulting in significantly higher ATCE. Whereas for later years, as PV systems and batteries become more affordable and large PV capacities are part of the least cost system, larger battery capacities can make a significant difference. For the case of households in Australia in the 'No Cars Scenario', the DCR for PV capacities from 7 kW_p to 30 kW_p remains the same. However, as stationary battery capacities increase from 1 kWh_{cap} to 13 kWh_{cap} the DCR rises up to 40%$_{abs}$ by 2050. In the case of households in Indonesia, this impact is even more significant. An increase in battery capacity from 1 kWh_{cap} to 4 kWh_{cap} results in a DCR improvement of around 30%$_{abs}$. The development of HCR is contradictory to the development of SCR through the years. This implies that a low SCR results in a high HCR, as additional capacities of PV are required for filling the TES. Nevertheless, the amount of energy necessary to fill the TES is comparably smaller to the amount of energy generated.

The variation of DCR and HCR across households in the different regions and the impact of BEVs in 2025 are shown in Fig. 15. Using both the BEVs ('Two Cars Scenario'), the DCR is marginally higher for households in most of the regions, compared to the 'No Cars Scenario'. The variation in HCR of the 'Two Cars Scenario' and 'No Cars Scenario' is very evident for households in the African and Asian regions, which do not have significant heating demands. In addition, lack of chargeable BEVs allows for PV additional filling of the TES, which is attributed to stable solar conditions throughout the year. As observed from Fig. 15, retail grid electricity prices have an impact on the DCR and HCR, as households in countries and regions with low electricity prices (mainly due to subsidies) tend to have lower DCR and HCR. On the contrary, households in countries and regions with higher retail grid electricity prices have much higher DCR and HCR.

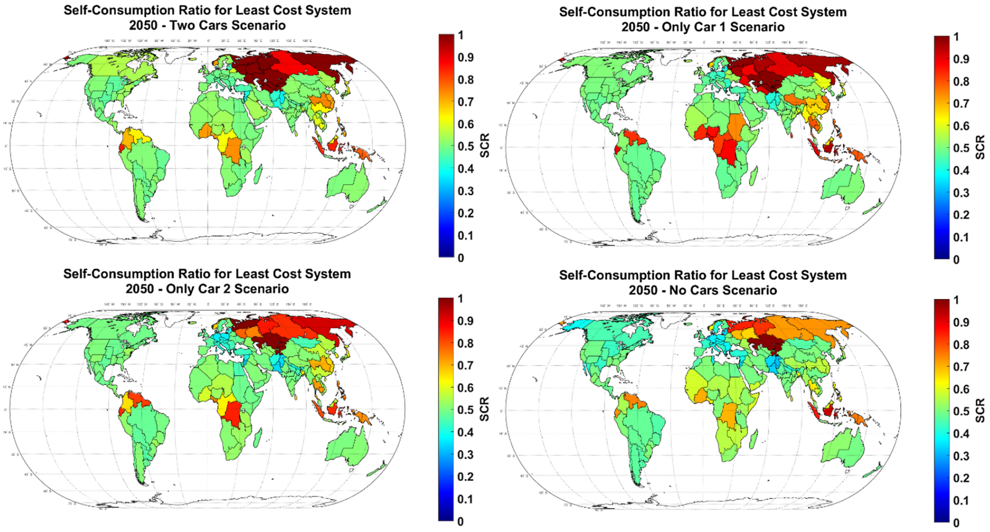

Fig. 11. Comparison of self-consumption ratio (SCR) for households in all regions in 2050, for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right).

4.4. Least ATCE system design

The range of least ATCE system designs vary significantly across the regions in the simulated scenarios. Fig. 16 shows the least ATCE system designs for the year 2030 with one or more regions that do not reach grid-parity. The impact of Car 2 on the capacity of the stationary battery can be observed here as well. In the 'Two Cars Scenario', some regions that already have large PV capacities also have battery capacities up to 15 kWh_{cap}, as part of their least cost system configuration. Majority of the regions have a resulting battery capacity of just 1 kWh_{cap}, due to the presence of Car 2. The relevance of stationary batteries is a lot higher for the 'Only Car 1 Scenario' and the 'No Cars Scenario'. Until 2050, majority of the regions will have stationary battery capacities greater than 1 kWh_{cap} for a least cost system design. For the two scenarios 'Only Car 1 Scenario' and 'No Cars Scenario', a dependence of battery capacities on PV capacities is quite evident. For high PV capacities, relatively high battery capacities are necessary. Furthermore, the use of Car 1 with energy supply via the stationary battery has an impact on the least ATCE system design, which increases corresponding system capacities. The least cost system designs for 2015, 2020, 2030 and 2050 for the different scenarios can be found in the Supplementary Material (Figs. S3–S6).

For all the scenarios, development of least ATCE systems seems to have a cost efficiency limit of battery/PV capacity ratio of 2 kWh_{cap}/kW_p (Fig. 16). With a few exceptions, most of the systems are below this limit. Across all the scenarios, it is observed that very high battery capacities do not occur in residential PV systems for households in most regions. In the absence of V2H, small and mid-sized battery capacities are the most optimal. Whereas, with BEVs and V2H, only smaller battery capacities are necessary. PV capacities will vary depending on solar conditions as well as energy demand for electricity and heat, across households in the various regions and years.

5. Discussion

The emergence of demand side technologies along with PV, energy storage options and energy management systems are continuing to change the way electricity is sourced and consumed. Despite a growing number of global energy scenario analyses, many of them lack comprehensive analyses of even energy storage systems as shown by Koskinen and Breyer (2016). Therefore, analyses on the role of PV prosumers in global energy systems is extremely scarce, Ram et al. (2017a) and Breyer et al. (2018) have analysed PV prosumers from a global power sector perspective. It is shown that residential PV prosumers can contribute up to 5.5% of the total power generation by 2050, with a global installed capacity of around 2 TW (Ram et al., 2017a; Breyer et al., 2018). Regional variation of the installed capacities as well as generation shares of residential PV prosumers is shown in Fig. 17. Furthermore, the global residential battery capacity in 2050 is around 4107 GWh_{cap}, as the prosumer aspect of the model is limited to just a combination of solar PV and Li-ion batteries (Ram et al., 2017a; Breyer et al., 2018). In regard, this research highlights that value addition of PV prosumers can reach beyond just the power sector and can integrate heating as well as mobility aspects of residential households. Furthermore, this research is an effort to better understand the synergies of various complementary technologies such as Li-ion batteries, BEVs, HPs and TES that will most likely play a role in future energy systems, in the context of residential PV prosumers. As many studies have already pointed out the benefits of integrating different components, such as absorption of surplus electricity by power-to-heat systems can offer flexibility to PV prosumers as well as the electricity system (Oluleye et al., 2018). Oluleye et al. (2018) also point out the benefits of coupling HPs with TES in a PV prosumer context. Additionally, Schwarz et al. (2018) analyse PV prosumer systems with various components and the effects of residential electricity tariffs on their design and sizing. It is quite evident that optimising the right system design and size is crucial to get maximum benefits for PV prosumers, as showcased in the results of this research. Moreover, demand patterns for both electricity and heat can vary significantly across the various regions of the world and sometimes within the regions themselves. Therefore localising PV prosumer models is extremely important to determine the most optimal solution in an accurate manner. On that note, the major benefit of this model is its ability to be modified according to different regional conditions and utilised to generate results

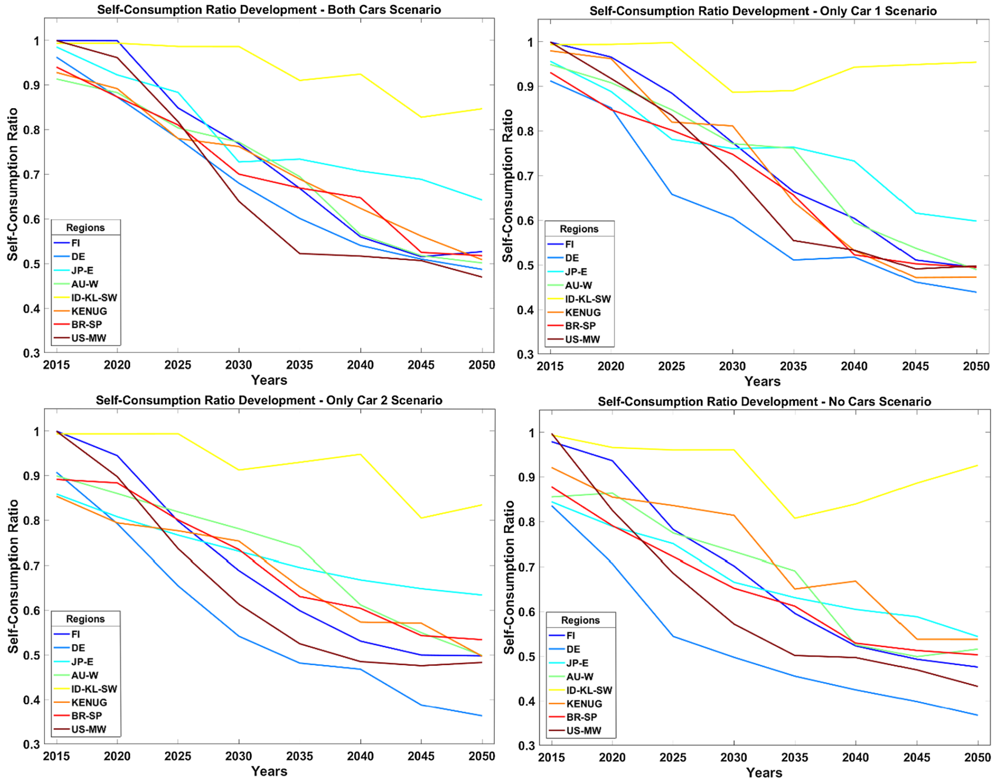

Fig. 12. Development of the Self-Consumption Ratio in households across the 8 regions, for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right).

with greater local significance, as showcased for the case of Germany (Keiner, 2018) and India (Ram et al., 2017b).

In general, from the results it is observed that PV prosumer systems are economically advantageous for residential households in all the different compositions of BEVs (the 4 scenarios). These results are realised without the consideration of substantial incentive mechanisms that are present in many countries, which can have a significant impact on the overall ATCE. High feed-in compensation rates could guarantee a secure financial return for the installation of the PV system and maximise generation fed into the grid. Furthermore, these can also influence the SCR coupled with HCR and DCR. Additionally, dynamic retail electricity pricing that is not considered in this research can influence the results, mostly in favour of PV prosumer systems. Another factor that was not considered in this research is the requirement of rooftop area (or other suitable area within the residential premises), which primarily varies with the size of the PV system. As the results indicate, the optimal size does not reach the maximum possible expansion of PV systems and corresponding roof areas, which should not be a major limiting aspect. Nevertheless, PV systems remain attractive in the residential household sector with the current compensation and electricity prices in many regions of the world. They become more attractive through the transition period as retail electricity prices increase coupled with increasing consumption. In order to optimise their ATCE, PV prosumers are expected to utilise maximum roof area (or other suitable areas within the residential premises). The option of not being a PV prosumer results in higher costs for electricity at the retail level on average and, hence, translates into a higher value of PV systems for residential households in the future. In this context, Weniger et al. (2014, 2016) identified that the optimal PV system size will shrink to small-scale systems with higher self-consumption rates, as the incomes from the feed-in payments will play a minor role in future. Additionally, Weniger et al. (2014, 2016) show that in the long-term a conjunction of PV systems with batteries will be not only profitable, but also the most economical solution. Results of this study show that the role of multi-objective optimisations have an important role in determining system configurations, which offer the best performance based on costs and other system parameters (Delgado et al., 2017). Delgado et al. (2017) conclude that GSHPs offer the best combinations of cost-optimality, operational equivalent CO_2 emissions, and exergy among the main heat supply systems investigated, and that they are generally best complemented with PV, which is similar to the findings of this study. Furthermore, Delgado et al. (2018) conclude that heat pumps represent the optimal main heat supply component in the Netherlands and Finland, and PV systems are the most attractive supplementary onsite generation components. Delgado et al. (2018) give valuable insights into the potential of prosumers in central and northern Europe, yet acknowledge that significant differences might arise in other geographical locations, indicating the need for separate case study assessments. This study has

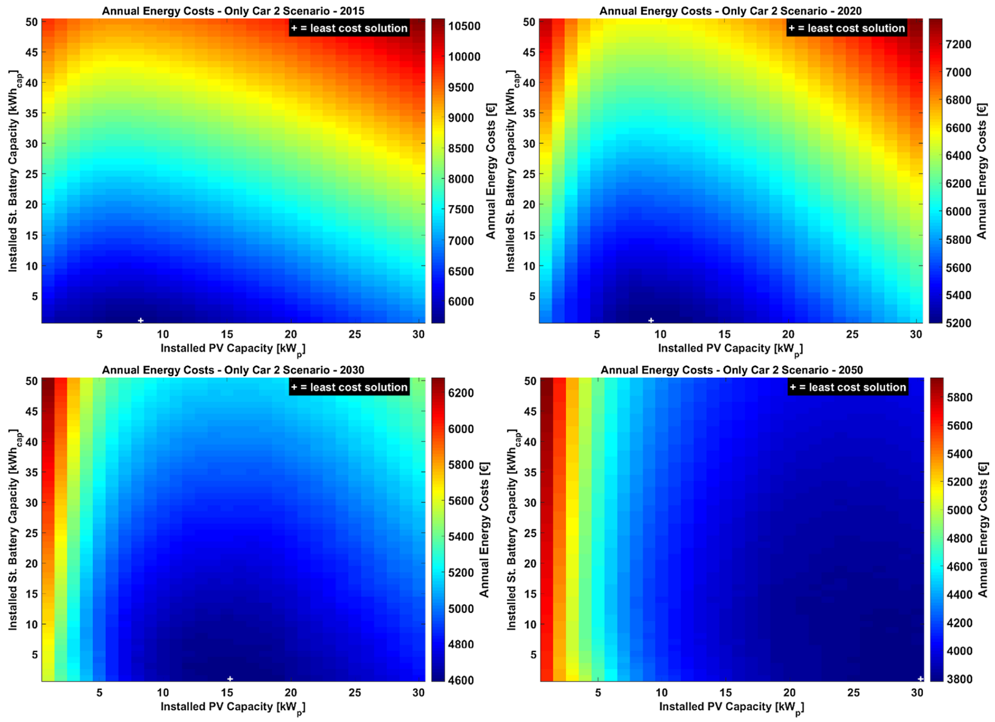

Fig. 13. ATCE for households in Germany for the 'Only Car 2 Scenario' in 2015 (top left), 2020 (top right), 2030 (bottom left) and 2050 (bottom right).

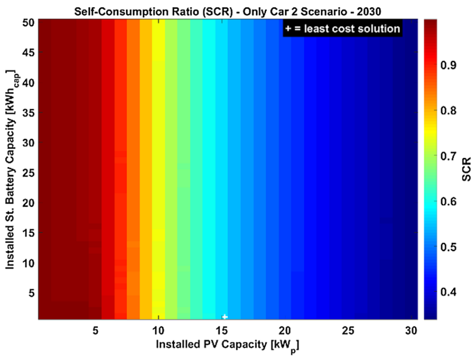

Fig. 14. Self-consumption ratio in households across Germany for the 'Only Car 2 Scenario' in 2030.

shown the presence of this variation across households in the different regions of the world. However, it also shows the immense potential for PV prosumers and makes an attempt at estimating the financial benefits for households across the different regions.

Despite an effort to capture the regional variations, conducting a global analysis in the context of residential PV prosumers involves a fair number of limitations. The assumptions regarding the PV prosumer model have been described extensively in the earlier sections. However, these assumptions entail a broader view of residential prosumers in the different regions of the world and limit an in-depth analysis. Electricity demand growth across the different regions is assumed according to standard growth assumptions, which do not factor in a higher rate of electrification that could have an overall impact on residential electricity demand in the different regions of the world. Similarly, load profiles across the different regions of the world are based on average household presumptions. Whereas, in reality household sizes and demand profiles vary substantially with income levels and regional factors. An attempt has been made to factor in the regional variations as far as possible. Additionally, with recent trends and practices households are varying their demands in response to retail electricity prices. This is another limitation, as far as differential pricing of electricity is considered. The current research assumes static retail electricity tariffs in the long-term, which could apply to many regions but with increased digitisation differential electricity tariffs could be a future prospect. Similarly, a standard feed-in tariff is assumed in the current research. Whereas, solar PV feed-in tariffs vary significantly across the different regions of the world. In addition, standard global costs are assumed for all the components of a PV prosumer household. While in reality, costs may vary substantially across the different regions of the world with varying tax structures and labour costs.

Regardless of the limitations, optimisation of energy system components presents valuable insights across all the regions, but further components could add value, e.g. by including seasonal storage technologies in an intelligent residential energy system. This involves conversion of surplus electricity during summer times into hydrogen and storing it. In winter times, the hydrogen can be re-converted via fuel

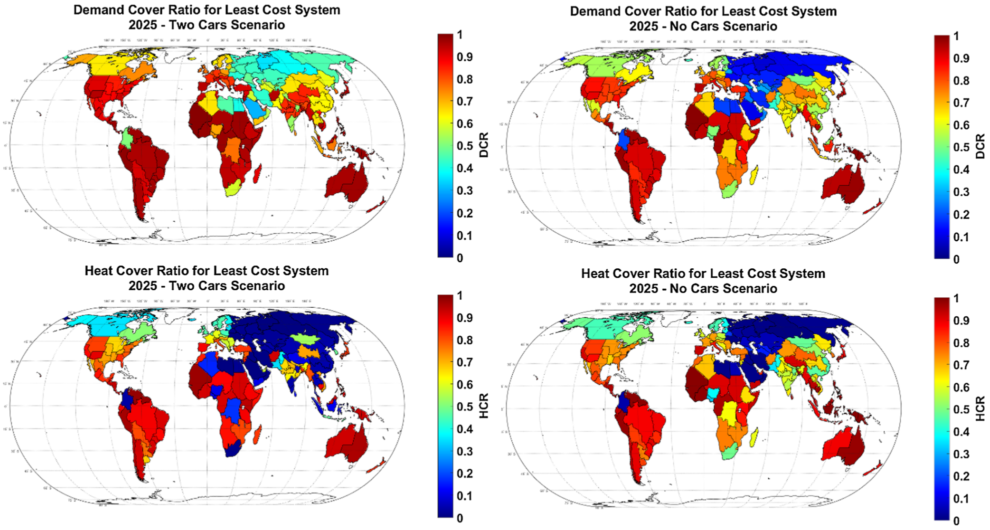

Fig. 15. Demand cover ratio (DCR) in households across all regions in 2025, for the 'Two Cars Scenario' (top left) and 'No Cars Scenario' (top right) and heat cover ratio (HCR) in households across all regions in 2025, for the 'Two Cars Scenario' (bottom left) and 'No Cars Scenario' (bottom right).

cells back into useable electricity and heat. Therefore, increasing the SCR and HCR. Residential seasonal storage solutions are already available (HPS, 2017). Additionally, smart home and home automation technologies with a variety of integrated energy management components are also becoming more widespread. There is a growing synergy with energy and communication technology transitions, which also entails societal changes as further explored by Ruotsalainen et al. (2017). These technologies enable consumers to optimise their energy use, match it with their needs, and when applicable, with their energy generation and storage, while saving money or energy in simple ways (Parag and Sovacool, 2016). Peer-to-peer (P2P) energy sharing is gaining a lot of attention, it involves technologies and models at the demand side of power systems, which are able to manage the increasing connections of prosumers and provide platforms for energy transactions. In P2P energy sharing, prosumers directly trade energy with each other to achieve a win-win outcome. From the perspectives of power systems, P2P energy sharing has the potential to facilitate local energy balance and increase self-sufficiency. P2P energy sharing is an emerging phenomenon that has the potential to reshape the paradigm of power systems and bring various benefits for both prosumers as well as power systems (Zhou et al., 2018). Furthermore, the role of prosumers in co-creating flexibility is a promising area to be further explored, offering greater potential for optimising energy utilisation as well as minimising overall ATCE across a substantial number of prosumers (Kubli et al., 2018). These aspects of the rapidly evolving prosumer segment need to be integrated in future research.

6. Conclusions

Combining PV generation systems with various energy storage technologies for electricity and heat have proven to be highly beneficial for PV prosumers, particularly for reducing ATCE, as shown earlier. Optimising ATCE and SCR is a challenge and depends on various external factors, such as electricity prices, solar conditions, policy support for PV prosumers and so on. Nevertheless, as indicated earlier a balance can be reached. Although the sensitivity of ATCE is not high for most of the cases, a balance is easy to find, at least for later years wherein PV capacities do not have a significant impact on ATCE.

A large amount of energy fed into the grid could pose problems (Hollinger et al., 2013). Substantial PV prosumer installations may result in challenges for distribution grid management, but it can also be a source of sustainable and affordable energy supply for society, while playing a vital role in climate change mitigation (Jäger-Waldau, 2018). From the results, it can be concluded that there is no standard least cost system design across all regions. Therefore, an optimisation of the system across different component configurations is a very beneficial exercise to enable informed decision making on appropriate system design and sizing. In the case of some regions, it may be beneficial to determine an optimal size for the TES and HP. For regions with moderate solar conditions, a TES of 800 L and a HP of 7 kW_{el} seem to be good choices, as indicated by the results. Whereas, for regions with good solar conditions and warm temperatures with lower heating demands (which is mostly hot water demand and some space heating for a few days in a year), lower system sizes will be ideal. As shown by Enkhardt (2018), having large number of PV prosumers can also have collective benefits such as, stabilising the local distribution grids, reducing grid infrastructure refurbishments and more flexible EV charging. Additionally, clusters of connected storage systems could take on the role of traditional grids (Enkhardt, 2018).

Integrating BEVs into residential PV systems is extremely beneficial for optimising energy usage as well asATCE, as indicated by the results. Furthermore, energy demand for driving can also be covered by PV generation. With increasing fuel costs, BEVs charged with low cost PV could provide not only an affordable transport option, but also a sustainable one. In addition, application of V2H enables higher SCR and lowerATCE, as indicated by the results. However, optimal usage of stationary batteries along with V2H vehicles needs further examining.

In comparison to 100% grid supply, optimised residential PV systems will be able to reduce ATCE by up to $50\%_{abs}$, as indicated by the results. This could amount to several thousand euros per annum in household savings, which could be the most economical energy designs in the coming years. Moreover, in some regions further savings could be realised with optimal seasonal storage. Summarising the results, residential PV Prosumer systems will be a very cost effective solution of

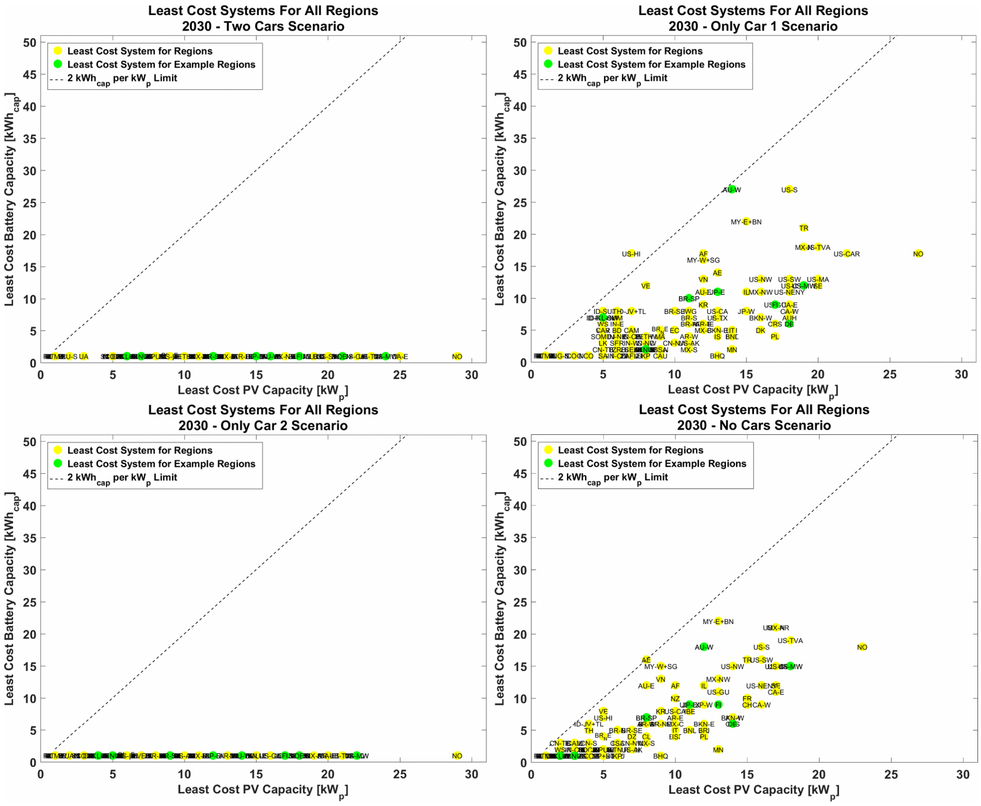

Fig. 16. Least cost system designs in 2030 for the 'Two Cars Scenario' (top left), 'Only Car 1 Scenario' (top right), 'Only Car 2 Scenario' (bottom left) and 'No Cars Scenario' (bottom right). The 8 regions are marked green. The 2 kWh_{cap}/kW_p line represents a projected cost efficiency limit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

generating and consuming energy in households and pursuing higher levels of energy self-sufficiency.

In this context, energy markets have to be redesigned for the prosumer era that could maximise residential and commercial energy sufficiency, democratise energy systems, and prepare society for ubiquitous, distributed, smart and integral energy activities. Thus, further

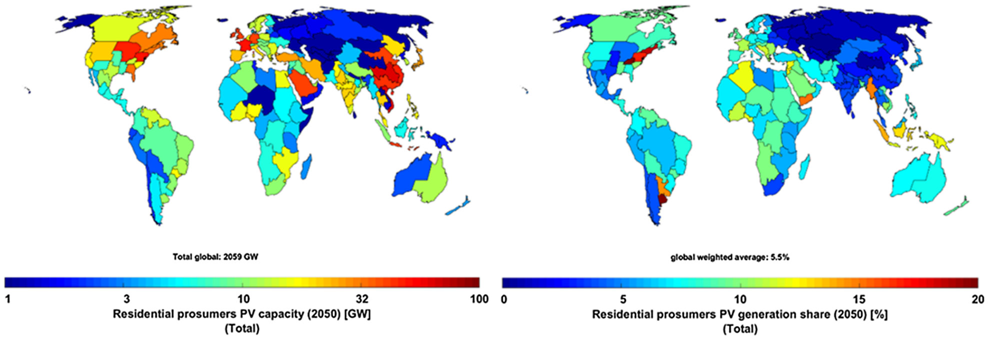

Fig. 17. Installed capacities (left) and electricity generation shares (right) of residential PV prosumers across the different regions of the world in 2050 (Ram et al., 2017a; Breyer et al., 2018).

investigation into the role of residential households as heat and electricity prosumers might provide constructive outcomes in the pursuit of sustainability and energy transitions regionally as well as globally.

Acknowledgements

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Appendix

See Tables A.1 and A.2.

Table A.1
Financial assumptions for the various PV Prosumer system components (Ram et al., 2017a; Schmidt et al., 2017; Kittner et al., 2017), for all regions and modelled years.

Financial Assumptions									
	Unit	2015	2020	2025	2030	2035	2040	2045	2050
PV Rooftop									
Capex	[€/kW$_p$]	1360	1090	890	760	680	610	550	500
Opex fix	[€/(kW$_p$·a)]	20	16	13	11	10	9	8	8
Lifetime	[a]	30	30	35	35	35	40	40	40
Stationary Battery									
Capex	[€/kWh$_{cap}$]	600	300	200	150	120	100	85	75
Opex fix	[€/(kWh$_{cap}$·a)]	24	9	5	3.75	3	2.5	2.125	1.875
Opex var	[€/(kWh$_{through}$·a)]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Lifetime	[a]	15	20	20	20	20	20	20	20
Heat Pump									
Capex	[€/kW$_{el}$]	1600	1500	1500	1400	1400	1300	1300	1200
Opex fix	[€/(kW$_{el}$·a)]	20.6	19.5	19.5	17.9	17.9	17.4	17.4	16.9
Lifetime	[a]	20	20	20	20	20	20	20	20
Heating Cartridge									
Capex	[€/kW$_{el}$]	570	570	570	570	570	570	570	570
Opex fix	[€/(kW$_{el}$·a)]	10	10	10	10	10	10	10	10
Lifetime	[a]	30	30	30	30	30	30	30	30
Thermal Energy Storage									
Capex	[€/kWh$_{cap}$]	50	40	30	30	20	20	20	20
Opex fix	[€/(kWh$_{cap}$·a)]	0.75	0.6	0.45	0.45	0.3	0.3	0.3	0.3
Lifetime	[a]	25	25	25	25	30	30	30	30

Table A.2
Efficiency assumptions for storage and energy conversion technologies, for all regions and modelled years.

Efficiency Assumptions							
	Unit	Stationary Battery	TES	Car 1	Car 2	HP	Heating Cartridge
Charging	[%]	96.8	100	96.8	96.8	–	–
Discharging	[%]	96.8	100	–	96.8	–	–
Standby losses	[%/h]	0	0.15	0	0	–	–
Electricity-to-Heat conversion nominal COP	–	–	–	–	–	3.8	1
Electricity-to-Heat conversion PV additional filling COP	–	–	–	–	–	3.0	1

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2019.04.081.

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Job creation during the global energy transition towards 100% renewable power system by 2050

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ABSTRACT

Aside from reducing the energy sector's negative impacts on the environment, renewable power generation technologies are creating new wealth and becoming important job creators for the 21st century. Employment creation over the duration of the global energy transition is an important aspect to explore, which could have policy ramifications around the world. This research focuses on the employment impact of an accelerated uptake of renewable electricity generation that sees the world derive 100% of its electricity from renewable sources by 2050, in order to meet the goals set by the Paris Agreement. An analytical job creation assessment for the global power sector from 2015 to 2050 is estimated and presented on a regional basis. It is found that the global direct jobs associated with the electricity sector increases from about 21 million in 2015 to nearly 35 million in 2050. Solar PV, batteries and wind power are the major job creating technologies during the energy transition from 2015 to 2050. This is the first global study presenting job creation projections for energy storage. The results indicate that a global energy transition will have an overall positive impact on the future stability and growth of economies around the world.

1. Introduction

The risks and impacts posed by devastating socioeconomic consequences of climate inaction have been conspicuously stressed in the International Panel on Climate Change (IPCC) 4th and 5th assessment reports (IPCC, 2007, 2014a) as well as the Stern review (Stern, 2007). In this regard, the Paris Agreement, negotiated at the 21st Conference of the Parties (COP21) in 2015 (UNFCCC, 2015), has set an important foundation on which the global community can build a sustainable future. With electricity generation accounting for around 25% of global greenhouse gas (GHG) emissions, reducing emissions in this sector is a critical component in the transition towards a low carbon development pathway (IPCC, 2014b). A global energy transition is well underway with nearly 160 GW of renewables (without considering large hydropower) been added in 2017, of which 98 GW was solar and 53 GW wind power (Frankfurt School-UNEP Centre/BNEF, 2017; GWEC, 2018). In addition, tumbling technology costs have propelled investments in renewable energy power generation and from a levelised cost of energy (LCOE) outlook, renewables have become a more attractive investment proposition than fossil fuels in many countries around the world (Ram et al., 2017a; Ram et al., 2018). The effects of the new energy system would not be restricted to energy production only, but would have consequences for the whole society (Breyer et al., 2017a).

Energy use is either the cause or the facilitator of economic growth. Moreover, sufficient evidence over the years point to the positive correlation between energy use, economic growth and employment (CDC and ODI, 2016). As the global energy system is a major economic sector with a share of around 8% in global gross domestic product (GDP) (IER, 2010), the prospects for investment and employment in the sector are significant to economies around the world. The physical implications of a shift towards greater shares of renewable electricity such as additional generation capacities, investment needs and reduction in GHG emissions have been explored for a range of scenarios in many countries as well as globally, as enlisted and analysed in Child et al. (2018). However, employment associated with the electricity sector and the impact of an accelerated uptake of renewables on employment creation in the

Abbreviations: A-CAES, Adiabatic compressed air energy storage; BNEF, Bloomberg New Energy Finance; BPS, Best Policies Scenario; CAPEX, Capital Expenditures; CCGT, Combined Cycle Gas Turbine; CPS, Current Policies Scenario; CSP, Concentrated Solar Thermal Power; EU, European Union; FLH, Full Load Hours; GDP, Gross Domestic Product; GHG, Greenhouse Gases; GW, Gigawatt; IEA, International Energy Agency; IMF, International Monetary Fund; IPCC, International Panel on Climate Change; ILO, International Labour Organization; IRENA, International Renewable Energy Agency; LCOE, Levelised Cost of Electricity; MW, Megawatt; OCGT, Open Cycle Gas Turbine; OPEX, Operational Expenditures; PtG, Power-to-Gas; PtH, Power-to-Heat; PV, Photovoltaics; TW, Terawatt; USD, United States Dollar

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sector, has received relatively lesser attention. A review was performed by Sheikh et al. (2016) to determine the criteria that are elements of the social and political perspectives, which found that renewable energy has the potential to play a significant role in fulfilling the employment criterion. As in other economic and technological shifts, transitioning to a low carbon economy will result in additional jobs being created, jobs being substituted, jobs being eliminated and existing jobs being transformed (UNEP, 2008). Combining different methods, as proposed by Fortes et al. (2015), is a way to advance scenario building by integrating different collective thinking and other socioeconomic parameters.

As the energy sector increasingly moves hand in hand with economic development, social priorities and environmental needs, an integration of social processes with technical and economic analyses of energy systems is therefore a necessity. In purview, this research evaluates the hypothesis of sound economic impacts from transitioning to a sustainable economy by determining the employment effects of achieving 100% renewable power supply by 2050, across the world structured into 9 major regions. The world is categorised into Europe, Eurasia, Middle East and North Africa (MENA), Sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America. The transition of power sectors across these regions, as showcased in Breyer et al. (2017b) and Ram et al. (2017a), serves as the basis for estimating jobs created during the transition period from 2015 to 2050. Additionally, job creation potential is estimated on a technology-wise basis as well as on a category-wise basis during the energy transition to provide better insights on the types of jobs created. Moreover, this research is the first to estimate potential job creation by the various storage technologies during the energy transition on a global basis. This is primarily due to the innovative aspects of the LUT Energy System Transition modelling tool (Breyer et al., 2017b; Ram et al., 2017a), which analyses power systems across the world on an hourly basis enabling detailed analyses of storage requirements.

Further, this research presents an overview of existing literature in Section 2. The detailed methods, various assumptions and other relevant material in estimating job creation during the energy transition are highlighted in Section 3. The following Section 4 presents the results on a regional basis and displays the jobs created on a technology basis as well as on a category basis. In addition, Section 5 discusses the results from a global perspective and draws a few comparisons to other such studies. Finally, Section 6 draws conclusions and possible implications of the results.

2. Literature review

In recent years, the job creation potential of renewable energy technologies in the context of the energy transition has received attention from some of the stakeholders including academia, government agencies, private sector and the civil society (Child et al., 2018). The International Renewable Energy Agency (IRENA) has estimated jobs associated with renewable energy to rise to around 16.7 million by 2030 (IRENA, 2013) and their annual review of global employment related to renewable energy shows that 10.3 million people were employed in 2017 (IRENA, 2018a). Jacobson et al. (2014) estimated jobs created and jobs lost for a long-term sustainable energy infrastructure that supplies 100% of energy in all sectors (electricity, transportation, heating/cooling, and industry) from wind, water, and solar power (without fossil fuels, biofuels, or nuclear power) for the state of California and found that it will create a net of 220,000 40-year construction plus operation jobs (442,200 new 40-yr construction jobs and 190,600 new 40-yr operation jobs, less 413,000 jobs lost in current California fossil- and nuclear-based industries). Further, Jacobson et al. (2017) estimate that their main scenario by 2050 (that is electricity generation with 100% wind, water, and solar power for all energy sectors) would create a net of 24.3 million permanent, full-time jobs across 139 countries of the world. This estimate includes creation of 52 million new ongoing jobs for 100% renewable electricity generation and transmission supplying for highly electrified energy sectors (including power, heat and transport) up to 2050, while 27.7 million jobs are lost in the current fossil fuel, biofuel, and nuclear industries (Jacobson et al., 2017). Various editions of the Energy [R]evolution, published since 2007, project probable employment outcomes across a broad range of scenarios (Greenpeace International, 2015). The latest edition offers a global estimate for energy sector employment to be 46.1 million by 2030 for the Advanced Energy [R]evolution scenario. Nevertheless, there are studies that have estimated the impact of renewable energy development on job creation to be negative, resulting in job losses. Almutairi et al. (2018) show a loss of 4.45 million jobs worldwide up to 2030 in the Renewable and Nuclear Energy (RNE) scenario (based on the predictions of the international energy outlook) compared to the business as usual (BAU) scenario. This study (Almutairi et al., 2018) has made an effort to estimate both the direct and indirect jobs associated with the different energy scenarios by assessing the overall impacts on the gross domestic product (GDP) of different countries. However, Markandya et al. (2016) found the net employment impacts from the transformation of the European Union energy sector in the period 1995–2009, when the European Union's energy structure went through a significant shift, away from the more carbon intensive sources, towards gas and renewables to be positive. Moreover, the research estimated the net employment generated from this structural change at 530,000 jobs in the European Union and further analysis showed that the change in the input structure of the European electricity and gas supply sector, motivated significantly by the desire to shift towards a green economy, had a net positive impact on employment (Markandya et al., 2016). Whereas, Böhringer et al. (2013) suggest with a computable general equilibrium analysis of subsidised electricity production from renewable energy sources (RES-E) in Germany that the prospects for employment and welfare gains are quite limited and hinge crucially on the level of the subsidy rate and the financing mechanism. To the contrary, by linking investments in energy sector and jobs created, Garrett-Peltier (2017) finds that on average, 2.65 full-time equivalent (FTE) jobs are created from 1 million USD spending in fossil fuels, while that same amount of spending would create 7.49 or 7.72 FTE jobs in renewables or energy efficiency. It is further concluded that each 1 million USD shifted from brown (includes fossil fuels and nuclear) to green energy will create a net increase of 5 jobs (Garrett-Peltier, 2017). The results of these studies are difficult, if not impossible to compare due to their differing assumptions and modelling approaches. However, one recurring theme seems to be the positive contribution of high shares of renewable energy uptake to the labour market thereby generating ample employment.

Employment trends vary significantly across the different energy generation technologies. There are a number of identifiable methods that have been used to quantify employment impacts of the changing energy sector and have been well documented in literature review studies, such as Breitschopf et al. (2011), Cameron and Van Der Zwaan (2015) and Meyer and Wolfgang Sommer (2014). However, in general, the various methods applied can be categorised into bottom-up and top-down approaches, or more specifically as using the analytical or input–output (IO) models (World Bank, 2011). Additionally, Llera et al. (2013) and Hondo and Moriizumi (2017), highlight a value-chain approach and a life-cycle approach respectively, for estimating job creation mainly from renewable energy deployment. Furthermore, the various studies consider different types of jobs associated with the energy industry; the common adopted classification is 'direct', 'indirect' and 'induced' jobs. IRENA (2011) elaborates a clear and operational definition of these terms, as well as their interpretation across studies. Lambert and Silva (2012) find that analytical studies using extensive surveys are found to be more appropriate for regional studies, while input–output methods are better suited to national and international studies.

In Jacobson et al. (2014, 2017), estimates of baseline jobs per unit energy in their main scenario are based on National Renewable Energy Laboratory's (NREL) Jobs and Economic Development Impacts (JEDI) models (NREL, 2013). These are economic IO models with several assumptions and uncertainties. In contrast, IRENA (2013) and Greenpeace International (2015) adopt simpler analytical approaches to estimating job impacts that also have a high level of transparency. This entails utilising job intensities or employment factors (EF), defined as the number of jobs derived from a certain energy technology capacity addition or investment. The EF approach utilised for estimates of job creation potential in Greenpeace's energy scenarios is documented by Rutovitz and Atherton (2009), an improved version is presented in Rutovitz and Harris (2012) and the latest version in Rutovitz et al. (2015). This research is an effort to further refine the methods and conduct a more comprehensive analysis of the net jobs created during an energy transition, which includes a broad range of technologies and is the first to estimate job creation potential of the complementary storage technologies. The research has also included estimates of decommissioning jobs across the various power generation technologies created during the energy transition up to 2050.

3. Methods and materials

For this research, an analytical approach towards estimating jobs in an energy transition scenario was adopted. Moreover, the methods were based on the approach highlighted in Rutovitz et al. (2015) and further modified and improved for better results as well as applied to a broader range of technologies.

3.1. The employment factor approach

Jobs generated during the global energy transition from 2015 to 2050 are estimated utilising the EF approach, adopted from Rutovitz et al. (2015). The EF method was utilised amongst the other methods (Breitschopf et al., 2011), due to its simplicity and effectiveness in estimating direct employment associated with energy generation, storage and transmission. One of the main advantages of the EF approach is that, it can be modified for specific contexts, as well as applied over a range of energy scenarios. The Fig. 1 gives an overview of the methods utilised to estimate jobs created during the energy transition from 2015 to 2050 across the different regions.

In the context of this research, the total direct jobs are a sum of jobs in manufacturing, construction and installation, operations and maintenance, fuel supply associated with electricity generation, decommissioning of power plants at the end of their lifetimes and transmission. The category of jobs are as follows,

- Manufacturing Jobs – encompasses the number of jobs necessary to manufacture a unit of power generation capacity. Manufacturing of equipment and components for a power plant project may require several weeks, months or at most a few years' worth of work. As such, they represent relatively temporary employment in comparison to the entire plant lifetime. Hence, they are expressed as job-years, or the total number of full-time jobs needed for manufacturing over the plant's lifetime (IRENA, 2013). Additionally, the manufacturing of equipment and components for power plants may occur outside the country where the power generation capacity is being installed. Many countries rely on importing, especially renewable energy technologies, as the domestic production is insufficient or non-existent yet. On the other hand, countries that export renewable energy equipment and components can generate employment, which is additional to that relating to their domestic energy capacity addition by producing for export markets (IRENA, 2013). To account for the degree of import dependence, the local manufacturing factor is considered which is further highlighted below.
- Construction and Installation Jobs – includes all the jobs associated with constructing and installing a unit of power generation capacity. It is assumed that a local workforce will undertake the installation and construction of all energy projects, as is in most cases. Similar to manufacturing, these are expressed as job-years, or the total number of full-time jobs needed for construction and installation over the plant's lifetime. These jobs are predominantly in the beginning phase of a power plant (that is in the first few years) and last during the period in which the power plants are built until the first operation. In this case, the construction and installation jobs are annualised over the construction period of a power plant, which is the time required for construction and installation of unit power plant capacities (in terms of per MW). The construction times for all technologies in years can be found in the Supplementary Material.
- Operation and Maintenance Jobs – comprises all the jobs associated with operating and maintaining the operational condition of a power plant over its technical operational lifetime. As power plants are usually designed to run for decades, operation and maintenance jobs last for a relatively longer duration and therefore interpreted as jobs per capacity of power generation. These jobs are considered for the lifetime of the respective power plants and are further annualised to get total number of jobs during the transition period. As and when power plants are decommissioned and new power plants replace the capacity, the O&M jobs continue to exist. A learning factor, which is correlated to the productivity increase in operational expenditures (Opex), is adopted to reflect the decline in O&M jobs as technologies and operational processes further mature.
- Fuel Jobs – includes all the jobs associated with fuel supply to power plants (nuclear, fossil and bioenergy). These are expressed as jobs per unit of primary energy, factoring the different rates of fuel consumption for power plants corresponding to the fuel utilised based on conversion efficiencies during the transition period.
- Decommissioning Jobs – consists of all jobs associated with the decommissioning of installed power plants at the end of their operational lifetimes, especially if plants are repowered or if certain elements are recycled or reused. These jobs are comparable to construction and installation jobs and are expressed as job-years, or the total number of full-time jobs needed for decommissioning over the plant's lifetime. These jobs are further annualised during the transition period to derive the total number of jobs created.
- Transmission Jobs – includes all the jobs associated with power transmission activities. In context to this research, transmission jobs are expressed in terms of investments made in transmission infrastructure, i.e. jobs per unit investments (in billion euros). As the LUT Energy System Transition modelling tool considers only key transmission infrastructure required, the full extent of jobs associated with transmission infrastructure is not reflected in this research. The jobs from transmission infrastructure will be a lot higher when more accurate transmission data is considered.
- Jobs Loss: The jobs lost in fossil fuel and nuclear power plants are corresponding to the decommissioned capacities of conventional power plants during the transition period. As renewables are mostly installed beyond 2020, jobs do not arise in conventional power plants and these plants are decommissioned at the end of their technical lifetimes, which creates additional decommissioning jobs.

Some of the parameters considered in the estimation of job creation potential of various power generation and storage technologies,

- Employment Factors – are the number of jobs per unit of installed capacity, separated into manufacturing, construction and installation, operation and maintenance, and decommissioning. Further, it is also jobs per unit of primary energy for fuel supply and jobs per unit of investment for transmission of power. EFs for this research were mainly adopted from Rutovitz et al. (2015), along with some modifications and estimates from a few other sources. These are

Fig. 1. Method for estimation of job creation during the energy transition. Abbreviations: Employment Factor (EF), Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

Solar Power Europe (2015) for rooftop PV, GTM Research and ESA (2016), Hart and Sarkissian (2016) and The Solar Foundation (2016) for battery storage, Arcadis (2018) and Government of U.K. (2015) for gas storage, RFF (2017), Evonik Industries (2010) and Oldham (2009) for decommissioning and The Brattle Group (2011) for transmission. The different EFs for the various power generation and storage technologies, along with transmission are shown in Table A1 in the Appendix.

- Decline Factors – job creation can be expected to reduce as technologies and production of these technologies mature. This maturing occurs as a result of the growing experience and volume in the energy industry (mainly renewables and storage); i.e. learning by doing and economies of scale (Cameron and Van Der Zwaan, 2015). In order to account for the maturity of technology and corresponding reduction in employment generation with increase in production capacities, EFs are correlated with the rate of reduction in capital expenditures (CAPEX) of the corresponding power generation and storage technologies during the transition period, in the case of manufacturing, construction and installation jobs. While, in the case of operation and maintenance jobs the EFs are correlated with the rate of decline in operational expenditures (OPEX) of the respective power generation and storage technologies through the transition period. CAPEX and OPEX values during the transition period from 2015 to 2050 can be referred to in the Supplementary Material.
- Regional Employment Multiplier – of the various regions are adopted to account for the differential labour intensive economic activity in the different regions across the world. Since the EFs considered are mainly from OECD countries, the regional employment multiplier accounts for the additional employment that will be generated in non-OECD countries, which needs adjustment for differing stages of economic development. In general, the lower the cost of labour in a country, the greater the number of workers that will be employed to produce a unit of any particular output be it manufacturing, construction or agriculture. Low average labour costs are closely associated with low GDP per capita, a key indicator of economic development (Rutovitz et al., 2015). Therefore, deriving a proxy factor correlated to average labour productivity, measured as GDP (or value added) per worker is the most reasonable indicator. The regional employment multipliers are expected to change over the transition period (2015–2050), as the differences in labour productivity evolve with regional economic growth. The projected change in GDP per capita derived from GDP growth and population growth is factored to adjust the regional employment multipliers for the 9 major regions over time. The method from Rutovitz et al. (2015) along with labour productivity data from International Labour Organization (ILO) (ILO, 2016) was used to determine the regional employment multipliers for the corresponding regions. Table A2 in the Appendix indicates these values.
- Local Manufacturing Factor – represents the percentage of local manufacturing across the various regions of the world. As manufacturing of mainly renewable energy and storage technologies is

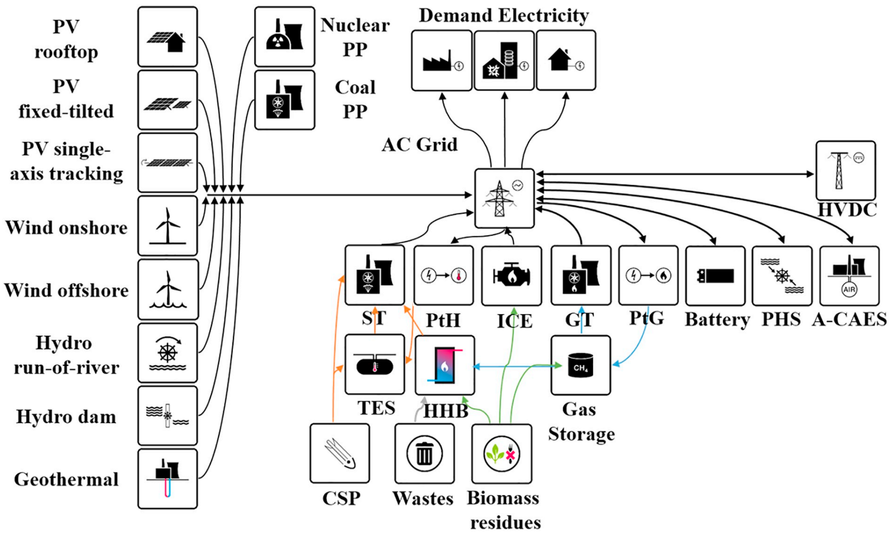

Fig. 2. The schematic representation of the LUT Energy System Transition model for the power sector with the various sources of power generation, transmission options, storage technologies and power demand sectors (Ram et al., 2017a).

quite unevenly distributed across the world, many regions still rely heavily on imports. Import and export proportions as well as current export and corresponding import regions are set according to current practices, which are derived from trade flows in the energy sector (predominantly renewables) and industrial activity in corresponding major regions adjusted to indicators from UNIDO (2013). Currently, the more industrialised regions of China, Europe and North America dominate the global export of renewable energy technologies. However, with economic growth in other regions, this research considers in an optimistic scenario that all major regions across the world will develop towards regional self-sustenance up to 2050. This entails all major regions having domestic manufacturing capabilities by 2050. In addition, the research has considered a conservative scenario in which global export-import conditions remain in present conditions (according to 2015 assumptions), to examine the deviation in jobs created. The values were mostly adopted from Rutovitz et al. (2015), UNIDO (2013) and PwC (2017); Table A3 in the Appendix indicates these values.

As indicated in Fig. 1, manufacturing EFs, and construction and installation EFs are applied to the newly installed capacities for each year during the transition period from 2015 to 2050. While, operation and maintenance EFs are applied to the cumulative installed capacity for every 5-year interval between 2015 and 2050. The fuel EFs are applied to annual electricity generation form the various power generation technologies that utilise fuel sources. The decommissioning EFs are applied to the annual decommissioned capacities of power generation and storage technologies during the entire transition period. The transmission EF is applied to the total annual investments in transmission for different regions during the transition period. The installed capacities, electricity generation, fuel consumption, decommissioned capacities and investments in transmission for the various power generation and storage technologies are adopted from the results of the LUT Energy System Transition model, as comprehensively documented in Bogdanov et al. (2019), Ram et al. (2017a) and Breyer et al. (2017b).

3.2. The LUT energy transition model

The LUT Energy System Transition modelling tool (Bogdanov et al., 2019; Bogdanov and Breyer, 2016; Kilickaplan et al., 2017; Ram et al., 2017a) simulates an energy system under given conditions, which is applied for 5-year time periods from 2015 to 2050. For each period, the model defines a cost optimal energy system structure and operation mode for the given set of constraints that are power demand, available generation and storage technologies, financial and technical assumptions, and limits on installed capacity for all applied technologies. The model is based on linear optimisation and performed on an hourly resolution for entire years of the transition period. The model ensures high precision computation and reliable results. The costs of the entire power system are calculated as a sum of the annualised capital expenditures including the costs of capital, operational expenditures (including ramping costs), fuel costs and the costs of GHG emissions for all available technologies under mitigation assumptions.

The energy system transition analyses also consists of distributed self-generation and consumption of residential, commercial and industrial PV prosumers, which are simulated with a different model describing the PV prosumer and battery capacity development. PV prosumers have the option to install their own rooftop PV systems with or without lithium-ion batteries, and draw power from the grid in order to fulfil their demand (Keiner et al., 2019; Ram et al., 2017b), while also having the option to feed-in to the grid their surplus electricity (Ford et al., 2017). The target function for PV prosumers is the minimisation of the cost of consumed electricity, calculated as a sum of self-generation, annual costs and the cost of electricity consumed from the grid, minus the cost of electricity sold to the grid. The share of consumers opting to install their own generation and storage is projected to gradually increase from 3% in 2015 (IEA-PVPS, 2016; SolarPower Europe, 2016) to 20% by 2050 (UBS, 2013). The share of PV prosumers increases in accordance with the logistic function, in steps of 3, 9, 15, 18 and 20%. For a given year, if self-consumption of electricity becomes economically feasible, then the share of prosumers for the following year increases, otherwise the share of potential prosumers remains the same. Bogdanov et al. (2019), Ram et al. (2017a) and Breyer et al. (2017b) provide the full set of technical as well as financial assumptions utilised in the modelling of the energy transition.

The model has integrated all crucial aspects of power systems: power generation, storage and transmission. The technologies introduced in the model are classified into the following categories:

– Technologies for electricity generation: renewable, fossil fuel and nuclear technologies
– Energy storage technologies
– Electricity transmission technologies

Fig. 2 displays the schematic representation of the LUT Energy System Transition model and all the power sector technologies considered for simulating the global energy transition (Bogdanov et al., 2019). Renewable energy technologies in the model comprise solar PV (optimally fixed-tilted, single-axis north-south tracking and rooftop), concentrating solar thermal power (CSP), wind turbines (onshore and offshore), hydropower (run-of-river and reservoir/ dam), geothermal and bioenergy (solid biomass, biogas and waste-to-energy power plants). Fossil fuel based power generation technologies considered are coal-fired power plants, oil-based internal combustion engines (ICE), open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT).

Storage technologies are further classified into the following categories:

– Short-term: Li-ion batteries and pumped hydro storage (PHS)
– Medium-term: adiabatic compressed air energy storage (A-CAES) according to Aghahosseini and Breyer (2018) and thermal energy storage (TES)
– Long-term: gas storage including power-to-gas technology, which allows production of synthetic methane for the energy system.

The transition to a fully renewable powered energy system has been carried out for the whole world, which is categorised into 9 major regions that are Europe, Eurasia, Middle East and North Africa (MENA), Sub-Saharan Africa, South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America (Ram et al., 2017a). The energy transition simulation takes into account the existing power grid, its development and impact on overall electricity transmission and distribution losses (Sadovskaia et al., 2018). All regions within a country are interconnected with either high voltage direct current (HVDC) or high voltage alternating current (HVAC) power lines, therefore increasing local flexibility while reducing overall national system costs.

All the financial and technical assumptions with the corresponding references to data sources for all energy system components are highlighted in Ram et al. (2017a). Electricity demand of the global power sector is estimated to increase from 23,141 TWh in 2015 to about 48,800 TWh in the year 2050, which represents a global average compound annual growth rate of 2.2% in the energy transition period, and is comparable to the assumption of 1.9% by the IEA (2016). The global power plant capacity is structured according to the major power generation and storage technologies and their corresponding country and region of location along with the year of commissioning, in an annual resolution (Farfan and Breyer, 2017).

3.3. Best policy scenario

A Best Policy Scenario (BPS) entails 100% electricity generation from renewable energy resources and various storage options across the different regions of the world, in line with the goals of the Paris Agreement. The development of the power sector is characterised by a dynamically growing electricity demand driven by developing and emerging countries and an increasing share of renewable electricity in the overall supply mix. The results show a growing renewable energy trend that will compensate for the phasing out of nuclear power production as well as for the continually reducing number of fossil fuel based power plants. As per the results, the installed capacity of renewables will reach about 14,000 GW in 2030 and more than 28,000 GW by 2050. A 100% electricity supply from renewable energy resources leads to around 23,600 GW of installed generation capacities of solar PV, wind energy, hydropower, bioenergy and geothermal power by 2050 as highlighted in Bogdanov et al. (2019) and Ram et al. (2017a). The share of renewable electricity in the overall mix will reach 99.65% of the electricity generated worldwide in 2050. Renewable power generation technologies, mainly solar PV and wind energy, are expected to contribute nearly 87% to the total electricity generation by 2050. Storage technologies play a vital role in enabling the transition towards a fully renewables powered energy system. The overall storage output covers 31% of the total electricity demand in 2050, of which batteries deliver 95%. The installed capacities are dominated by gas storage, whereas the overall output is dominated by battery storage. The levelised cost of electricity for the global power system declines from around 70 €/MWh in 2015 to about 52 €/MWh by 2050. Additionally, regional results of the energy transition worldwide can be found in Bogdanov et al. (2019) and Ram et al. (2017a).

4. Results

The resulting least cost energy mix comprising various power generation and storage technologies in each of the 9 major regions during the energy transition period from 2015 to 2050 from the Best Policy Scenario, serves as the basis for estimating the corresponding employment creation.

The results are presented according to the major regions followed by the global estimates.

4.1. Europe

Europe is one of the major economic centres of the world with an 18% share of global GDP (IMF, 2017), and amongst the biggest energy consumers across the world, with total electricity consumption of around 4000 TWh in 2015, which is estimated to rise to around 5400 TWh by 2050 (IEA, 2016). Europe has been at the forefront of the global energy transition with about 37% of installed power capacity and nearly 30% of electricity generation from renewables (REN21, 2017).

There were just over 2 million direct jobs in the energy sector across Europe in 2015, with more than 50% of these in the renewable energy sector. With the rapid increase in renewable energy installations up to 2025, jobs in the energy sector are seen to rise to around 3.7 million, and stabilise between 3.3 million by 2035 and 3.4 million by 2050 as shown in Fig. 3. Solar PV emerges as the major job creating sector with 1.73 million jobs by 2050, while bioenergy (675 thousand jobs by 2050) and hydropower (212 thousand jobs by 2050) create stable number jobs through the transition period. Whereas, the wind power sector is expected to create around 400 thousand jobs in 2025 (bulk of the share in onshore and a few thousand in offshore) and further as capacities installed are lesser with more cost effective solar PV, jobs created in wind are around 264 thousand by 2050. Storage technologies led by batteries are observed to start creating jobs from 2025 onwards, with a stable share until 2050 (277 thousand jobs in the battery sector). Whereas, jobs in the fossil fuel and nuclear sectors decline through the transition period and by 2050 are almost non-existent apart from a few thousand jobs associated with decommissioning of conventional power plants. This trend can already be observed across Europe with many countries opting to phase out coal and nuclear power generation, with some of the countries also divesting from conventional power generation projects (Agora Energiewende and Sandbag, 2018).

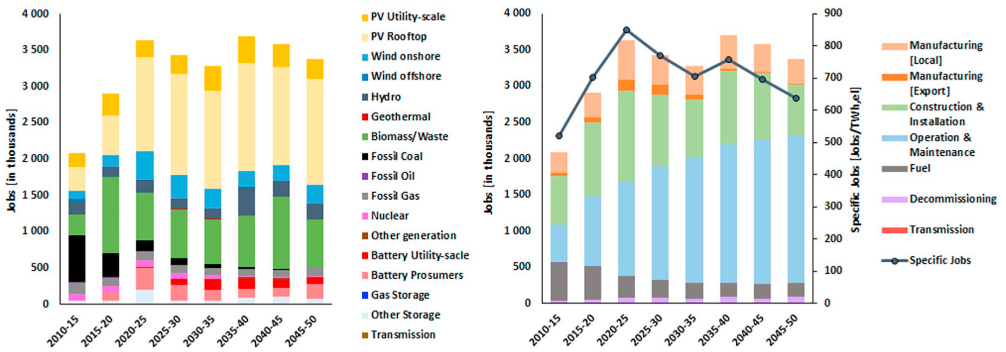

Fig. 3. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Europe.

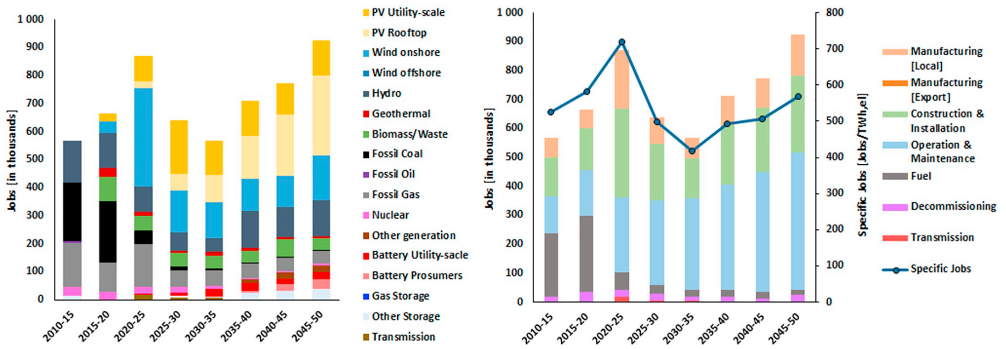

Fig. 4. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Eurasia.

The category-wise distribution of jobs for Europe during the transition period is shown in Fig. 3. Manufacturing, construction and installation of renewable energy technologies create a significant share of jobs enabling the rapid ramp up of capacity until 2025, beyond this period there are stable number of jobs created in these sectors up to 2050 with over a million jobs. Furthermore, manufacturing includes both for local use as well as for exports to other regions as indicated by Table A3 in the Appendix. The share of exports initially rise up to 2030 with over 4% of total jobs, beyond which it declines and manufacturing is predominantly to cater to the local power market across Europe. Fuel jobs continue to decline through the transition period reaching just 6% of total jobs by 2050, as capacities of conventional power plants continue to decline. To the contrary, operation and maintenance jobs continue to grow through the transition period and become the major job segment by 2050 with 61% of total jobs. As operation and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. This has the potential to create a positive effect in many countries across Europe that suffer from high levels of unemployment, especially amongst the youth. In January 2018, 3.65 million young people (under 25) were unemployed across the European Union (EU) (Eurostat, 2017). The electricity demand specific jobs, which indicates total number of jobs created annually for every TWh_{el} of annual electricity generation during the energy transition. As indicated in Fig. 3, the specific jobs were at 516 jobs/TWh_{el} in 2015, increasing to 859 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to 638 jobs/TWh_{el} by 2050.

4.2. Eurasia

Eurasia comprises countries that are amongst the emerging economies of the world, with around a 6% share of global GDP (IMF, 2017). This implies a rapidly growing appetite for energy, with total electricity consumption of around 1080 TWh in 2015 that is estimated to grow to 1630 TWh by 2050 (IEA, 2016). Hydropower has been the prominent resource in the region with around 50 GW of installed capacity in Russia. In recent years, renewables have been making inroads into power systems across the region and are expected to develop rapidly with the widespread presence of excellent resources (UNECE and REN21, 2017).

The total direct energy jobs in this region are set to increase with the initial ramp up of installations from about 566 thousand in 2015 to around 871 thousand by 2025, after a decline in 2030, it is observed to steadily rise to around 925 thousand by 2050. With great potential for wind power, bulk of the jobs from 2020 to 2030 are observed to be associated with wind power development creating around 353 thousand jobs in 2025. As solar PV delivers the least cost energy from 2030 onwards (Breyer et al., 2017a, 2017b; Ram et al., 2017a), along with driving up installed capacities, it emerges as the prime job creator in the region up to 2050 with about 411 thousand jobs, as shown in Fig. 4. The hydropower sector with 130 thousand jobs by 2050 is seen to provide stable number of jobs through the transition period, along with some jobs from geothermal and bioenergy sectors (combined 75 thousand jobs by 2050). Jobs associated with the storage sector begin to develop from 2040 onwards, but remain relatively lower than other regions with just about 58 thousand jobs by 2050, as hydropower in combination with robust transmission networks play a prominent role in reducing the need for storage.

The category-wise distribution of jobs for Eurasia during the transition period is as depicted in Fig. 4. Local manufacturing, construction and installation of renewable energy technologies create a significant share of jobs enabling the rapid build-up of capacities in the period 2020–2025 (508 thousand jobs), this is also due to the fact that most conventional power plants in this region are quite old and nearing their end of lifetimes that have to be replaced (Farfan and Breyer, 2017). This could serve as a co-benefit of the energy transition for countries across Eurasia. Beyond 2030, there are stable number of jobs created in these sectors up to 2050 with around 407 thousand jobs. Fuel jobs after an initial increase in 2020 (40% of total jobs), decline through the transition period as capacities of conventional power plants are replaced by renewables until 2030 and further decline up to 2050 reaching just about 2% of total jobs. On the contrary, operation and maintenance jobs continue to grow through the transition period and become the major job creating segment by 2050, with 51% of total jobs. As operation and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. As indicated in Fig. 4, the electricity demand specific jobs was at 516 jobs/TWh_{el} in 2015 and increases to 859 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to 638 jobs/TWh_{el} by 2050.

4.3. MENA

MENA is comprised of countries that are emerging economies as well as developed, with around 7% share in global GDP (IMF, 2017). This region is amongst the largest energy producers in the world, with an increasingly high share of demand (Aghahosseini et al., 2016). The total electricity consumption was around 1360 TWh in 2015, which is estimated to rise to 3320 TWh by 2050 (IEA, 2016). This region has immense solar resources, which can be harnessed to meet this growing demand.

With record low auctions for solar power across the MENA region, solar PV has emerged as the most attractive source of electricity generation (Dipaola, 2017). Both utility-scale and rooftop PV are seen to develop through the transition period to be the dominant source for power generation by 2050 (MEED, 2017; Ram et al., 2017a). Similarly, solar PV is the prime job creator through the transition period with almost a million jobs by 2050, as indicated in Fig. 5. Wind power generation creates a fair share of jobs during the period of 2020 to 2030 (260 thousand jobs in 2030), beyond which the shares are reduced, as PV becomes more cost competitive. Storage technologies in the form of batteries take off from 2030 onwards and lead to a decent share of jobs created up to 2050 (193 thousand jobs in the battery sector). The total number of direct energy jobs across the MENA region are observed to increase from just around 590 thousand in 2015 to nearly 1.7 million by 2050.

Fig. 5, also indicates the distribution of jobs across the different categories during the transition period in the MENA region. With rapid installation of capacities up to 2035, bulk of the jobs are created in the construction and installation of power generation technologies. Manufacturing jobs have a relatively lower share in the initial periods up to 2020 as the share of imports is high. From 2025 onwards, as domestic production capabilities build up, a higher share of manufacturing jobs are observed until 2050 with 15% of total jobs. The share of fuel related jobs continues to diminish from 2020 onwards through the transition period reaching just 1% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grows through the transition period up to 53% of total jobs by 2050. This means more stable jobs for a region suffering from high unemployment amongst the youth and a growing number of economic migrants. A higher share of investments in developing sustainable power infrastructure could be the right catalyst to create long-term jobs in this region (Ianchovichina et al., 2013). The electricity demand specific jobs increases from 435 jobs/TWh_{el} in 2015 to 788 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to around 509 jobs/TWh_{el} by 2050, as shown in Fig. 5.

4.4. Sub-Saharan Africa

Sub-Saharan Africa is a region with a large number of emerging economies, with just around a 3% share in global GDP (IMF, 2017), but is poised to be one of the fastest growing regions in the world. With rapidly growing population, unprecedented economic progress and need for reliable, modern energy access, the total electricity consumption that is around 484 TWh in 2015, is estimated to rise to 2747 TWh by 2050 (IEA, 2016). The renewable energy sector is growing in Sub-Saharan Africa, with 14 countries having set themselves targets and doubling investments to above 5 billion USD, between 2014 and 2015 (BNEF, 2017).

Countries such as South Africa, Kenya, Ethiopia and Rwanda have accelerated their renewable energy adoption and are leading the energy transition across Sub-Saharan Africa (BonelliErede, 2017). As this trend is observed to pick up across the region during the transition period with solar PV emerging as the dominant source of power generation by 2050 (Barasa et al., 2018; Ram et al., 2017a). Likewise, solar PV is observed to be the prime job creator through the transition period, with 65% of the total jobs created by 2050, as depicted in Fig. 6. A fair share of jobs are created by wind power (283 thousand jobs in 2025) and bioenergy (377 thousand jobs in 2025) initially, which tend to stabilise later on, as solar PV is far more cost competitive beyond 2030. Jobs created by storage technologies mainly driven by batteries, increase in share beyond 2030 and continue to grow up to 2050 (862 thousand jobs in the battery sector). While, jobs associated with fossil fuels, mainly coal and gas power generation, rapidly diminish across the region. Overall, the number of direct energy jobs are seen to grow massively from just under 1.2 million in 2015 to nearly 5.5 million by 2050.

Fig. 6, also indicates the distribution of jobs across the different categories during the transition period across Sub-Saharan Africa. With ramp up of installations up to 2035, bulk of the jobs are created in the construction and installation of power generation technologies. Manufacturing jobs have a relatively lower share in the initial periods up to 2020, as the share of imports is high. From 2025 onwards, as domestic production capabilities build up, a higher share of manufacturing jobs are observed until 2050 with 19% of total jobs. The share of fuel related jobs continues to diminish through the transition period from 63% of total jobs in 2015 to just 3% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grow through the transition period reaching 42% of total jobs by 2050. This could be the boost required for employment prospects in Sub-Saharan Africa, which are presently stagnating due to low productivity attributed to the region's lack of economic diversification (Brookings, 2017). The electricity demand specific jobs increase from 2399 jobs/TWh_{el} in 2015 to 3235 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to around 1990 jobs/TWh_{el} by 2050, as shown in Fig. 6. The electricity demand specific jobs are the highest in comparison to all other regions across the world as Sub-Saharan Africa continues to have a high labour intensity through the transition period (the labour intensity factors can be referred to in

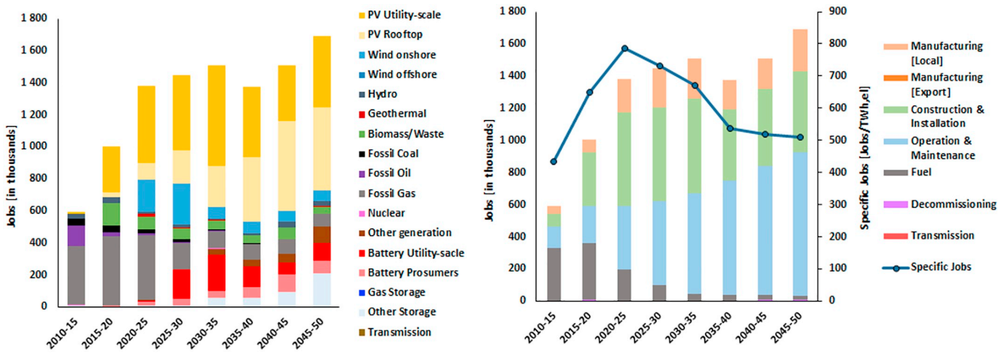

Fig. 5. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in the MENA region.

the Supplementary Material).

4.5. SAARC

SAARC consists of some of the most fast-paced growing economies, with around 9% share of global GDP and 21% of the global population (IMF, 2017). With rapidly growing population, unprecedented economic progress and need for reliable modern energy services, the total electricity consumption that is around 1694 TWh in 2015, is estimated to rise to 6979 TWh by 2050 (IEA, 2016; Gulagi et al., 2018). The region lead by India with around 50 GW of solar and wind power capacity has recently witnessed an increasing shift towards renewable energy (Buckley and Shah, 2018). Driven by policy initiatives and the tremendous drop in costs have made wind and solar PV the most attractive propositions for power generation.

In the last 2 quarters of 2017, only renewable energy capacities were added in the Indian power sector (Saurabh, 2018) and Sri Lanka has already made plans to generate 100% of their power from renewable energy sources (ADB and UNDP, 2017). This trend is set to continue with solar PV complemented by batteries to dominate the power share by 2050. Similarly, solar PV (4.18 million jobs) and battery storage (894 thousand jobs) sectors emerge as the major job creators across the region by 2050 as shown in Fig. 7. Wind power (504 thousand in 2030), hydropower (297 thousand jobs in 2020) and bioenergy (523 thousand jobs in 2025) create a fair share of the jobs in the initial periods of the transition. Beyond 2030, the shares decrease and stabilise until 2050. The storage sector led by batteries create a fair share of the jobs in 2030 with 23% of total jobs and continue to contribute until 2050 with a steady share. Whereas, the jobs associated primarily with coal and gas power generation diminish rapidly. The total number of direct energy jobs increase rapidly from over 4.2 million in 2015 to just over 7 million by 2030, thereafter stabilising around 5.8 million by 2050. This drop is primarily due to the rapid ramping up of power capacity installations to ensure energy access for the vast number of unelectrified people in this region up to 2030. Beyond that, capacity addition would be at a slower rate to fulfil economic development.

The category-wise distribution of jobs created in the SAARC region through the transition period is shown in Fig. 7. With a rapid ramp up of installations up to 2030, bulk of the jobs are created in the construction and installation of power generation technologies with 40% of total jobs in 2030. While, manufacturing jobs increase in share during 2020 to 2030, with some shares of exports (domestic manufacturing creates 25% and exports creates 2% of total jobs in 2030). The SAARC region is an importer as well as an exporter of power generation technologies (the shares of import and export can be referred to Table A3 in the Appendix). Beyond 2030, as production capabilities in other importing regions build up, a relatively lower share of manufacturing jobs are observed until 2050 (around 18% of total jobs). The share of fuel

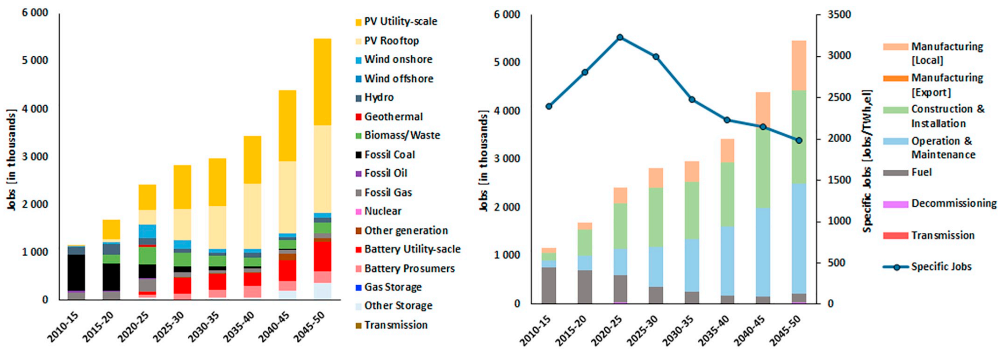

Fig. 6. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Sub-Saharan Africa.

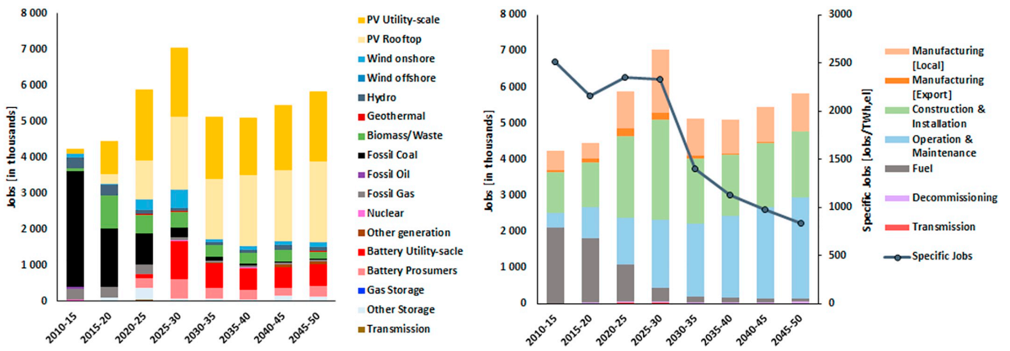

Fig. 7. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in the SAARC region.

related jobs continues to diminish through the transition period, as conventional power plants are replaced by renewable and storage technologies (from 49% of total jobs in 2015 to just 1% of total jobs by 2050). Whereas, the share of operation and maintenance jobs continues to grow through the transition period with 48% of total jobs by 2050. The electricity demand specific jobs decrease steadily from 2508 jobs/TWh_{el} in 2015 to 2335 jobs/TWh_{el} in 2030 with the rapid ramp up in renewable energy installations. Beyond 2030, it declines rapidly to around 834 jobs/TWh_{el} by 2050, as shown in Fig. 7. The electricity demand specific jobs have a rapid decline as most countries of SAARC have rapidly growing economies, which are expected to witness better economic conditions beyond 2030. Further improving up to 2050, resulting in a declining labour intensity through the transition period (the labour intensity factors can be referred to in the Supplementary Material).

4.6. Northeast Asia

The Northeast Asian region is comprised of the fastest growing economies, with around a 25% share of the global GDP and 22% of the global population (Haysom et al., 2015). With rapid industrialisation, unprecedented economic progress and a soaring appetite for energy, the total electricity consumption that is around 6847 TWh in 2015, is estimated to soar up to 15,078 TWh by 2050 (IEA, 2016; Bogdanov and Breyer, 2016). Renewable energy is high on the agenda for countries across Northeast Asia, with excellent wind and solar resources particularly in Mongolia (Breyer et al., 2015).

China has been leading not only in the region, but also globally with a cumulative solar PV capacity of around 130 GW and 163 GW of wind by the end of 2017 (Frankfurt School-UNEP Centre/BNEF, 2017). Additionally, Japan and South Korea have developed plans to increase the share of renewables in their respective power mixes (BNEF, 2017). Renewable energy capacities are observed to increase rapidly in the next couple of decades across the region (Ram et al., 2017a). Likewise, jobs are created from mainly wind (2 million jobs in 2025) and solar PV (3.5 million jobs in 2025) in the early stages of the transition. From 2030 onwards, solar PV is observed to be the main source of power generation and correspondingly creating the most number of jobs (6.7 million jobs by 2050) as indicated in Fig. 8. Storage technologies led by batteries are observed to create a fair share of jobs from 2030 onwards and continue unto 2050 with 1.3 million jobs in the battery sector. Whereas, jobs associated with the coal sector are seen to decrease rapidly. The total direct jobs are seen to increase from around 8 million in 2015 to 9.5 million by 2030 and after a decline, number of jobs rises back to around 10 million by 2050. Primarily with the replacements of power plants beginning to increase in the period from 2045 to 2050.

The distribution of jobs according to the different categories during the transition period across Northeast Asia is shown in Fig. 8. With a ramp up of installations until 2030, bulk of the jobs are created in the construction and installation of power generation technologies (39% of total jobs in 2030). Manufacturing jobs have a higher share in the initial periods up to 2030, beyond which the shares stabilise up to 2050. The Northeast Asian region contributes a major share of the global exports to all other regions (refer to Table A3 in the Appendix). However, the share of jobs created by exports reduce beyond 2030, as other regions are expected to increase their domestic production capabilities (exports creating just 36 thousand jobs by 2050). The share of fuel related jobs continue to diminish through the transition period from 43% of total jobs in 2015 to just 1% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs grows through the transition period from 13% of total jobs in 2015 to 48% of total jobs in 2050. Additionally, decommissioning jobs that include replacement of end of life power plants begin to create some jobs by 2050 (293 thousand jobs). The electricity demand specific jobs is reduced from 1187 jobs/TWh_{el} in 2015 to 675 jobs/TWh_{el} by 2050, as shown in Fig. 8. This is primarily due to the rising economic growth of the region forecasted for the future, resulting in much lower labour intensity by 2050.

4.7. Southeast Asia

The Southeast Asian region including Australia, New Zealand and the Pacific Islands is comprised of rapidly growing economies, with around 7% share of global GDP (IMF, 2017). With rapid economic growth in most of these countries, the need for energy is ever increasing and some of the more developed countries have a high rate of consumption to sustain. In this context, the total electricity consumption that is around 1208 TWh in 2015, is estimated to soar up to 4222 TWh by 2050 (IEA, 2016; Gulagi et al., 2017). Renewables have grown rapidly as a power source across Southeast Asia, with their installed capacity at around 15 GW in 2016 (IRENA, 2018b).

By the end of 2017, cumulative installed capacity for solar PV in Australia was around 6.4 GW with close to 1.8 million rooftop installations (AEC, 2018). Whereas, New Zealand aims to produce 90% of their electricity from renewable sources by 2025 (Electricity Authority, 2016; Ford et al., 2017). With the trend across the region indicating a shift towards renewable energy, it can be observed that solar PV along with battery storage emerge as the primary power source by 2050 (Gulagi et al., 2017; Ram et al., 2017a). Likewise, solar PV and battery

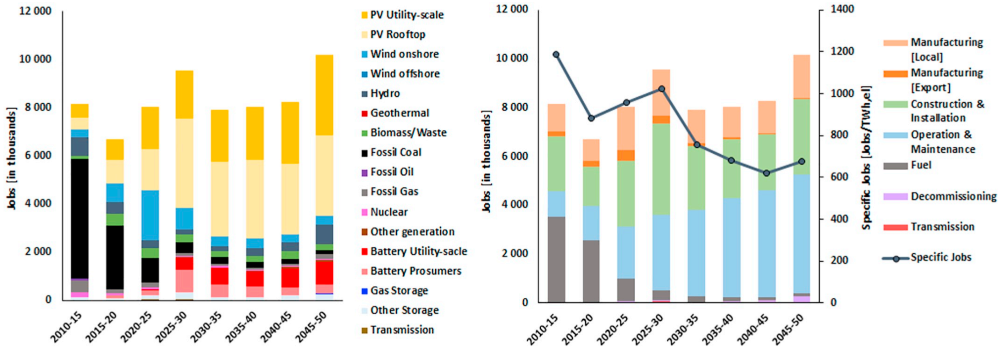

Fig. 8. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Northeast Asia.

storage sectors create the major share of jobs through the transition period as shown in Fig. 9. Biomass and hydropower create a higher share in the initial periods up to 2025, but continue to create some jobs through the transition period. Wind power sector creates some jobs during 2020 to 2030 (96 thousand jobs in 2025), beyond which fewer jobs are created as solar PV becomes more cost effective and installations increase in share with 2.1 million jobs by 2050. The storage sector led by batteries create a fair share of the jobs from 2030 onwards and continues through to 2050 with 414 thousand jobs in the battery sector by 2050. This could happen lot earlier as countries such as Australia are already witnessing both utility-scale as well as prosumer scale battery installations (AEC, 2018). Jobs associated with coal and gas power generation are seen to decline rapidly. The total number of direct energy jobs increases significantly from around 1.2 million in 2015 to over 3.3 million in 2030, beyond which there is a decline to under 2.5 million by 2040, after which there is a steady increase up to around 3.2 million by 2050.

A category-wise distribution of jobs in the region through the transition period is shown in Fig. 9. With rapid installation of capacities up to 2030, bulk of the jobs are created in the construction and installation of power generation technologies with 42% of total jobs by 2030. Manufacturing jobs have a relatively lower share in the initial periods up to 2020 as the share of imports is relatively high. Beyond 2025 as domestic production capabilities build up, a high share of manufacturing jobs are observed until 2050 (from 21% of total jobs in 2035 to 17% of total jobs by 2050). The share of fuel related jobs continues to diminish from 2020 onwards through the transition period reaching just 2% of total jobs by 2050, as conventional power plants are replaced by renewable and storage technologies. Whereas, the share of operation and maintenance jobs continues to grow through the transition period with 49% of total jobs by 2050. The electricity demand specific jobs increases from 997 jobs/TWh$_{el}$ in 2015 to 1541 jobs/TWh$_{el}$ in 2030 with the rapid ramp up in renewable energy installations. Beyond 2030, it declines steadily to around 748 jobs/TWh$_{el}$ by 2050, as highlighted in Fig. 9.

4.8. North America

North America is comprised of the major economic centres of the world, the USA, Canada and a rapidly emerging economy in Mexico, with a 19% share of global GDP (IMF, 2017), and is one of the largest energy consumption centres across the world, with total electricity consumption of around 5284 TWh in 2015. This is estimated to rise to 7069 TWh by 2050, mainly driven by the rapid growth of Mexico as well as stable electricity demands from the USA and Canada (IEA, 2016; Aghahosseini et al., 2017). Renewable energy has been on the rise in the recent years across all the 3 countries. By the end of 2017, the USA had installed capacities of 91 GW of wind and 52 GW of solar in its

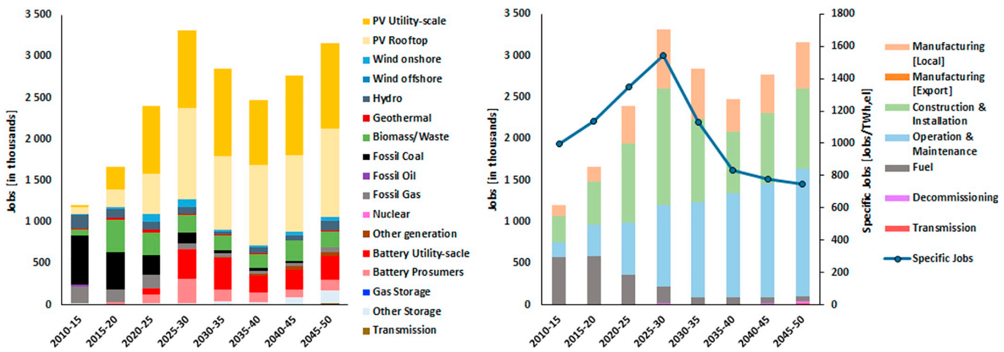

Fig. 9. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Southeast Asia.

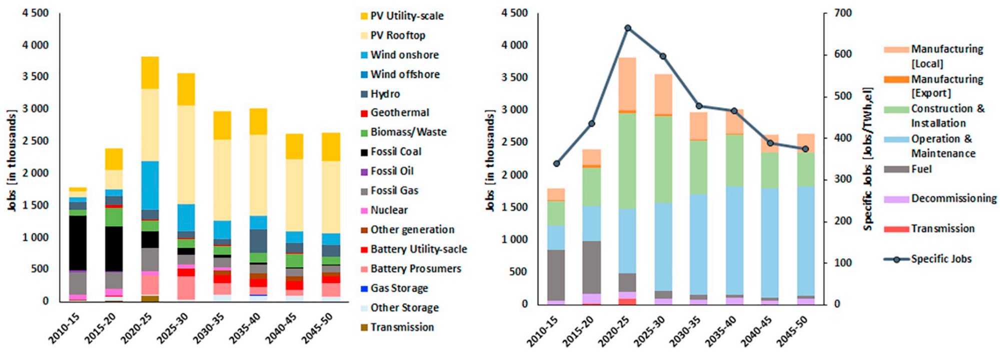

Fig. 10. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in North America.

power mix. There has been a steady rise in the share of renewable power generation in Canada and the latest power generation auctions in Mexico yielded some of the lowest bids, with an average in the range of 17–18 €/MWh (Bellini, 2017; Rabson, 2017).

Mexico has set a target of at least 35% of total electricity generation by 2024 to be from renewable energy sources (REN21, 2017). The trend is set to continue in the USA and Canada too, and a combination of wind, solar PV, hydropower and battery storage are seen as the most economical power generation sources by 2050 (Ram et al., 2017a). Similarly, solar PV (1.62 million jobs in 2025) along with wind (762 thousand jobs in 2025) emerge to be the dominant job creating sectors during the transition period as shown in Fig. 10. Additionally, hydropower (180 thousand jobs by 2050) and bioenergy (180 thousand jobs by 2050) create a stable share of jobs through the transition period. Storage led by batteries begin to create jobs from 2025 onwards with a stable share until 2050 with 330 thousand jobs in the battery sector. Whereas, coal and gas power generation associated jobs are seen to decline rapidly. Overall, jobs are set to increase from around 1.8 million in 2015 to nearly 3.8 million, with the rapid ramp up in installations up to 2025 and then a steady decline towards nearly 2.7 million by 2050.

The category-wise distribution of jobs in North America during the transition period is shown in Fig. 10. Manufacturing, construction and installation of renewable energy technologies create a significant share of jobs enabling the rapid ramp up of capacity until 2030, beyond this period there are stable number of jobs created in these sectors up to 2050. Furthermore, manufacturing includes both for local use as well as for exports to the other regions as indicated by Table A3 in the Appendix. The share of manufacturing jobs along with a marginal share of exports initially rise up to 2025 (21% and 1% of total jobs respectively), beyond which they decline. As manufacturing is predominantly to cater to the local power markets across North America with domestic manufacturing having a share of 11% of total jobs by 2050 and only 4 thousand jobs for exports. Fuel jobs continue to decline through the transition period reaching just 2% of total jobs by 2050, as capacities of conventional power plants continue to decline. On the contrary, operation and maintenance jobs continue to grow through the transition period and become the major job creating segment by 2050 with 64% of total jobs. As operation and maintenance jobs last through the lifetime of power plants, they offer relatively stable long-term job prospects. This has the potential to create a positive effect in many parts of the USA that suffer from persistent unemployment (U.S. Bureau of Labor Statistics, 2018). The electricity demand specific jobs initially increase from 339 jobs/TWh_{el} in 2015 to 666 jobs/TWh_{el} in 2025 with the rapid ramp up in renewable energy installations. Beyond 2025, it declines steadily to 374 jobs/TWh_{el} by 2050 as highlighted in Fig. 10.

4.9. South America

The South American region including Central American countries is comprised of growing economies, with around a 6% share of global GDP (IMF, 2017). With steadily increasing economic growth in most of the countries, the need for energy is rising. The total electricity consumption that is around 1180 TWh in 2015, is estimated to rise up to 2420 TWh by 2050 (IEA, 2016; Barbosa et al., 2017). A distinctive feature of South America's power generation mix is the predominance of hydropower and bioenergy, due largely to the high shares in Brazil, which generates about 40% of the total regional electricity (IRENA, 2016).

In recent years, South America has witnessed an impressive growth in renewable power generation, whose installed capacities have more than tripled between 2006 and 2015, from 10 GW to 36 GW (IRENA, 2016; REN21, 2017). While in absolute terms most of that growth has been in bioenergy and onshore wind primarily in Brazil, solar PV has also grown significantly in Chile, Peru and Uruguay (BNEF, 2017). This trend is seen to rapidly increase in the near future and continue through the transition period, with solar PV complemented by hydropower, wind and biomass emerging as the main sources of power generation by 2050 (Barbosa et al., 2017; Ram et al., 2017a). Likewise, jobs are predominantly created in the bioenergy (827 thousand jobs by 2020) and hydropower (357 thousand jobs by 2025) sectors during the initial periods of the transition up to 2030 as shown in Fig. 11. Beyond which, solar PV (930 thousand jobs by 2050) along with battery storage (202 thousand jobs by 2050) emerge as the major job creators. Storage led by batteries create jobs from 2025 onwards and maintain a stable share (9% of total jobs in 2025) through the transition period until 2050 (12% of total jobs). Whereas, coal, gas and oil power generation associated jobs decline rapidly, almost disappearing by 2025. With the brisk build up in installations, the total number of direct energy jobs rise from just under 1 million to nearly 2.2 million by 2025 and a steady decline thereafter towards 1.6 million by 2050.

A category-wise distribution of jobs in South America through the transition period is shown in Fig. 11. With rapid installation of power generation capacities in the initial period of 2020 to 2030, bulk of the jobs are created in the construction and installation of power generation technologies with 40% of total jobs by 2025. Manufacturing jobs have a relatively lower share in the initial periods with a high share of imports. Beyond 2030, the share of manufacturing jobs are observed to stabilise until 2050 (16% of total jobs), with increase in domestic production capabilities. The share of fuel related jobs continues to diminish through the transition period reaching just 3% of total jobs by 2050, as conventional power plants are replaced by renewable and

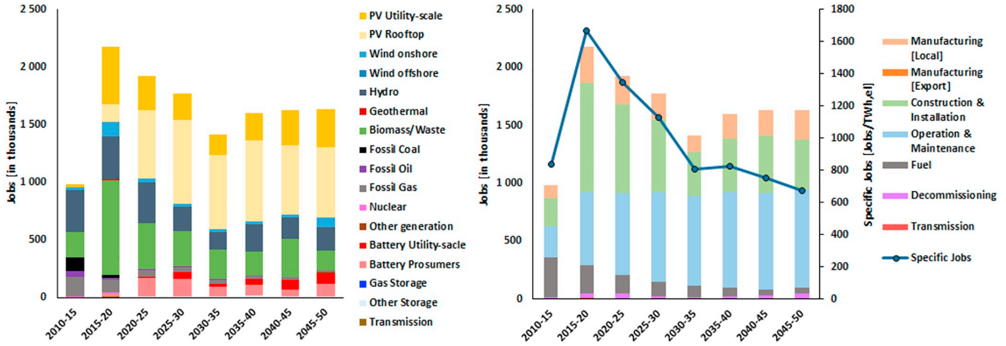

Fig. 11. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in South America.

storage technologies. Whereas, the share of operation and maintenance jobs grows through the transition period with 52% of total jobs by 2050. A small share of decommissioning jobs with around 3% of total jobs by 2050, are created through the transition period with the continuous replacement of power plants at the end of their lifetimes. The electricity demand specific jobs rapidly increases from 835 jobs/TWh$_{el}$ in 2015 to 1669 jobs/TWh$_{el}$ in 2020 with the rapid ramp up in renewable energy installations. Beyond 2020, it declines steadily to around 674 jobs/TWh$_{el}$ by 2050, as highlighted in Fig. 11.

4.10. Global

With the rapid ramp up of installed capacities, a growing share of renewable power generation technologies are observed to compensate for the phasing out of nuclear power production as well as for the continually reducing number of fossil fuel power plants globally (Breyer et al., 2017b; Ram et al., 2017a). This strong growth in the renewable energy sector leads to an increase of around 70% more direct power sector jobs by 2030, and the overall jobs created are 1.5 times as high in 2050, compared to 2015. Jobs created continue to rise to reach around 34 million direct energy jobs by 2030. Beyond this point, they decline to around the 30 million range and then steadily increase to nearly 35 million by 2050 as shown in Fig. 12. This is mainly due to large capacities being replaced and reinvested in, as they would reach end of their lifetimes with decommissioning contributing around 2% of total jobs by 2050. Solar PV (22.2 million jobs by 2050), batteries (4.5 million jobs by 2050) and wind energy (1.4 million jobs by 2050) are the major job creating technologies during the entire transition period from 2015 to 2050. In the case of wind energy, around 7.3 million jobs are created in the period from 2020 to 2030, beyond that, as solar PV becomes more cost effective they drive majority of the installations until 2050 and jobs in the wind sector are stabilised. While, hydropower (1.9 million jobs by 2050) and bioenergy (2.3 million jobs by 2050) create a stable share of jobs through the transition period. Solar PV is observed to replace coal as the major job creating energy resource, with around 64% of total jobs by 2050, as compared to just 10% of total jobs in 2015. Additionally, it is well complemented by battery storage creating around 13% of total jobs by 2050. Whereas, jobs in the coal, gas and nuclear power sectors are observed to decline rapidly as shown in Fig. 12.

A category-wise classification of jobs in manufacturing, construction and installation, operation and maintenance, fuel supply, decommissioning and transmission created during the energy transition from 2015 to 2050 is shown in Fig. 12. Fuel sector jobs are set to decline from 44% of the total jobs in 2015 to just around 2% of the total jobs by 2050, as fossil fuels and nuclear power capacities decline. On the other hand, it can be observed that operation and maintenance jobs have the most significant increase in the share of the total jobs created from 15% in 2015 to 50% by 2050. This indicates that the transition towards a 100% renewable power system enables creation of more stable jobs,

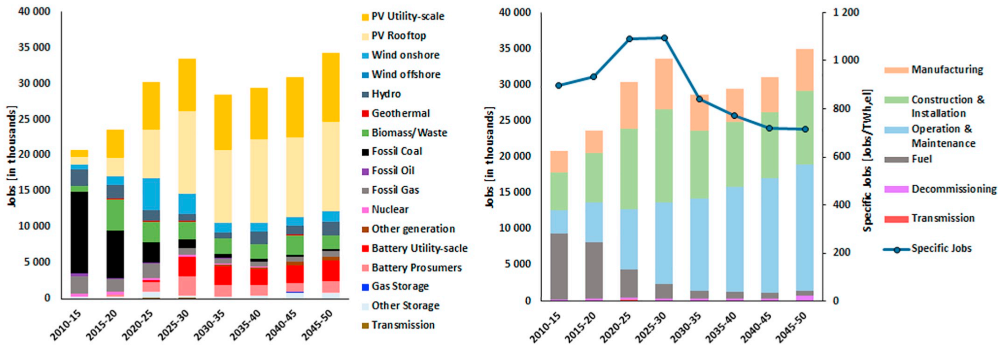

Fig. 12. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 globally.

which can contribute to stable economic growth of countries mainly in the developing regions of the world and provide a means of tackling youth unemployment (Ali, 2014). In many parts of the world, this could be a catalyst to improve social wellbeing as well as political stability (Kollewe, 2010). Furthermore, Fig. 12 also illustrates the development of the electricity demand specific jobs, which remain quite stable through the transition period. With 897 jobs/TWh_{el} in 2015 and rising up to 1091 jobs/TWh_{el} in 2030 due to a large share of investments during this period, beyond 2030 it declines steadily to around 715 jobs/TWh_{el} in 2050.

5. Discussion

With respect to labour markets across the world, many regions are facing stagnating economies accompanied by high and rising unemployment rates, particularly amongst the youth. Unemployment rates of youngsters in Europe reached 23.5% in the first quarter of 2013, more than twice the rate for the overall population and in some countries, more than half of young people under the age of 25 are unemployed (EC, 2013). Likewise, global unemployment levels and rates have been high in the last few years and are expected to remain high in the range of 5.8% bringing total unemployment to over 200 million in 2017 (ILO, 2017). Moreover, vulnerable forms of employment (those that lack access to contributory social protection schemes) are expected to remain above 42% of the total employment in 2017, accounting for around 1.4 billion people worldwide (ILO, 2017). At the same time, the risk of social unrest or discontent has heightened across many regions of the world. The ILO's social unrest index, which seeks to proxy the expressed discontent with the socioeconomic situation in countries, indicates that average global social unrest increased between 2015 and 2016 (ILO, 2017; Kollewe, 2010). Therefore, the creation of employment opportunities is a major policy priority, especially for countries with high levels of unemployment and underemployment, be it a long-term issue or the immediate consequence of an economic recession. In this context, the renewable energy sector has weathered the latest financial and economic crisis successfully, as compared to many other industries (IRENA, 2013). Moreover, it has become a relatively mature economic sector with steady technological progress, falling production costs and rising labour productivity. As the global transition towards sustainable energy continues, renewable energy labour force requirements are set to increase (Behrens et al., 2014; Greenpeace International, 2015; Jacobson et al., 2017).

The global employment creation in the power sector with increased shares of renewable power generation capacity will have a net positive effect, which is the number of jobs created by installing new capacities of renewable energy are significantly higher than the number of jobs associated with fossil and nuclear power generation. As shown by results from the previous section as well as other studies IRENA (2013), Behrens et al. (2014), Greenpeace International (2015), EPFL (2018) and Jacobson et al. (2017). This research estimates the total direct energy jobs to reach 34 million by 2050 for the global power sector only. In comparison to 52 million new ongoing jobs (net of 24.3 million after considering job losses) form wind energy, hydropower and solar energy (WWS) generators with transmission for the entire energy sector (power, heat and transportation), as estimated by Jacobson et al. (2017). In comparison to Greenpeace International (2015), which estimates energy jobs to reach 46.1 million by 2030, the results of this reserch show total direct energy jobs at around 34 million by 2030. Additionally, Greenpeace International (2015) estimate solar PV to contribute around 9.7 million jobs by 2030, while this research estimates total solar PV jobs at around 18.7 million by 2030, mainly due to higher installed solar PV capacity in this research resulting from a cost optimised energy mix. The methods of this research were adopted for the case of South Africa, which is further highlighted in Oyewo et al. (2019) and the results were compared with Wright et al. (2017) that adopt a different model for job estimation. Wherein, the decarbonised scenario and the least cost scenario with 'expected costs' are estimated to create 331 thousand jobs and around 380–392 thousand jobs by 2050, respectively (Wright et al., 2017). The results of Oyewo et al. (2019) indicate a comparable share during the transition ranging from 408 thousand jobs in 2035 to 278 thousand jobs by 2050. Nevertheless, both the results from Wright et al. (2017), as well as Oyewo et al. (2019) indicate a difference of 100 thousand jobs or more between the conservative Current Policy Scenario (CPS) and the more progressive Best Policy Scenario.

Most renewable energy and storage technologies are still in their initial phases of development and are expected to grow rapidly, in proportion to their current lower levels of installations. From the point of view of regional and national labour markets, the pattern varies across different renewable power generation and storage technologies. As there is limited activity in some of the countries, rapid growth in others, steady growth in some of the others, and a relatively mature industry elsewhere (IRENA, 2013). In this research, as part of the BPS with an optimistic outlook all major regions worldwide are expected to reach 100% local manufacturing capabilities by 2050. However, a conservation approach in which manufacturing shares and export-import shares are expected to remain as in 2015 through the transition period until 2050 were estimated. The major beneficial regions were China (with additional 523 thousand jobs) and Europe (204 thousand additional jobs) and to a lesser extent North America (46 thousand additional jobs). Whereas, rest of the regions lose jobs and Sub-Saharan Africa is impacted the most with a loss of 603 thousand jobs by 2050. Globally, 334 thousand jobs are reduced by 2050 as compared to the optimistic scenario with self-sustaining local manufacturing across the major regions. In general, it can be noticed that despite having higher shares of imports for some regions, the total number of jobs created will still be higher as renewables will create more localised O&M jobs as indicated earlier. Indeed, employment benefits of renewable energy could go to countries that start early and build strong export markets. This aspect has been observed in the results of some of the exporting regions presented in the earlier section. Nevertheless, from a long-term perspective, the export-import shares across the different regions of the world are expected to stabilise and self-sustaining economies are foreseen by 2050 (PwC, 2017; UNIDO, 2013). This regional and technological variation in global job creation through the energy transition period is captured in Fig. 13.

The regional distribution of jobs created in the 9 major regions through the transition period is shown in Fig. 13. The share of jobs in Europe remains quite stable in the range of 10% to 13% through the transition period. Similarly, the share of jobs in Eurasia remains stable ranging from 2% to 3% of the global jobs created through the transition. In case of the MENA region, the share of jobs increases from 3% in 2015 to 5% in 2035 and thereafter remain stable until 2050. A steady increase in the share of jobs from 6% in 2015 to 16% by 2050 is observed in the region of Sub-Saharan Africa, through the transition period. On the contrary, the share of jobs in the SAARC region decreases slightly from about 20% in 2015 to 17% in 2050. Whereas, a significant decrease in the share of jobs, from 39% in 2015 to 29% by 2050 is observed in Northeast Asia. Both the SAARC and Northeast Asian regions have high economic growth rates currently, which are expected to drop to lower levels and flatten out over the long-term as higher levels of development are accomplished. In Southeast Asia and the Pacific Rim, the share of jobs created are observed to increase initially from 6% in 2015 to 10% in 2030, and thereafter a marginal decline to 9% in 2050. An initial increase in the share of jobs from 9% in 2015 to 13% in 2025 is observed for North America, beyond which the share decreases to 8% by 2050. Likewise, an initial increase from 5% in 2015 to 9% in 2020 is seen for South America, further declining to 5% by 2050 thereafter. The primary reason for the initial rise in the share of jobs during the initial periods of the transition across these regions is the massive capacity additions that are expected in this period.

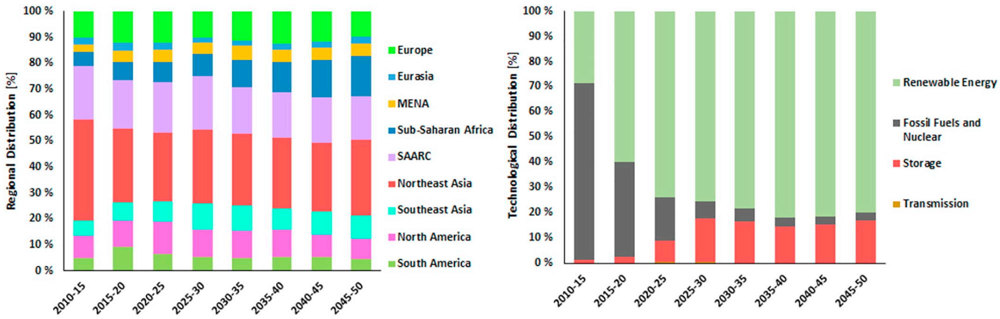

Fig. 13. Regional distribution of jobs created (left) and technological distribution of jobs created (right) during the energy transition from 2015 to 2050 globally.

The share of fossil fuels and nuclear power based jobs are observed to decline through the transition period, from about 70% in 2015 to a mere 3% in 2050, as indicated in Fig. 13. These jobs are primarily associated with decommissioning of the remaining fossil and nuclear power plants that are approaching the end of their lifetimes. Renewable energy accounts for around 80% of total direct energy jobs by 2050, in contrast to just about 28% in 2015, as they emerge to be the least costing sources for power generation (Breyer et al., 2017b; Ram et al., 2017a; Ram et al., 2018). The storage sector creates around 17% of the jobs in 2030, with the steady ramp up in installations and cost competitiveness. Beyond 2030, they continue to maintain a stable share of 17% of the jobs created until 2050, as shown in Fig. 13. Renewable energy and storage generate up to 92% of the total jobs by 2030, which is comparable to the results of Greenpeace International (2015), in which renewable energy accounts for 86% of energy jobs by 2030. Transmission contributes just a marginal share of jobs in the range of 0 to 1%, through the transition period. As the LUT Energy System Transition model does not account for the additional distribution networks, these estimates are limited to inter-regional transmission within countries of the different major regions. A significantly higher number of jobs are currently associated with the transmission and distribution of power, e.g. an analysis of jobs in the USA, showed around 500 thousand people were directly employed in the electricity transmission and distribution sector in 2013 (U.S. Department of Energy, 2017). Hence, the potential transmission and distribution jobs created during the energy transition period will be a lot higher with additional power infrastructure needed.

A number of studies have demonstrated that the exploitation of renewable energy sources for electricity production creates a greater number of jobs than that supplied by conventional power plants. That is for every megawatt of installed capacity, it is estimated that renewable energy sources create between 1.7 and 14.7 times more jobs than natural gas based power generation plants and up to 4 times more jobs than those supplied with coal fired power plants (Cameron and Van Der Zwaan, 2015). Renewable energy is already contributing more towards job creation in many markets across the world. In the specific case of the USA, solar power generating capacity represents only slightly more than 1% of the total power capacity, whereas coal contributes around 26% to the power mix. However, solar workers are already twice as numerous, compared to those in the highly automated coal industry (The Solar Foundation, 2017; U.S. Department of Energy, 2017). Likewise, the number of direct jobs estimated in this study can fall short of the actual number of total jobs including indirect and induced jobs created by the installation of renewable power generation and storage technologies.

As the employment level increases during the global energy transition, the employment structure of the energy sector may shift towards more highly qualified workers, particularly due to the relatively higher level of qualifications required to manage renewable power generation and storage technologies (UNEP, 2008). This means that the energy transition will provide not only more jobs, but also better-qualified ones. Many job opportunities will be created along the different categories of the value chain, as the results presented in the earlier sections indicate. With an increasing requirement for individuals with diverse skill-sets and talents foreseen in the near future, significant efforts in training and education will be needed to provide the labour market with the necessary skills.

IRENA estimates that achieving the objective of universal access to modern energy services by 2030 could create 4.5 million jobs in the off-grid renewables-based electricity sector (IRENA, 2013). There is growing evidence that decentralised renewable energy solutions can create value locally in terms of both employment and fostering economic growth (WRI, 2017). The benefits of transitioning to renewable energy and electrifying rural communities extend far beyond better employment opportunities (Winkler et al., 2011). For the world's poorest people, increased energy access means more time for children to study after school, greater productivity and income for families, and improved health outcomes (WRI, 2017). Although rural electrification is not directly part of this research, creating good quality renewable energy jobs that will enable poverty reduction in rural, underdeveloped regions is a crucial added benefit, which is often overseen.

6. Conclusions

This research has affirmed the proposition that renewable energy technologies create more jobs than conventional energy technologies and hence generate greater socioeconomic benefits. Additionally, this is the first research estimating potential jobs created by storage technologies, enabled by the unique hourly simulation capabilities of the LUT Energy System Transition model. As showcased in the previous sections, developing renewable power generation and storage capacities can make a significant contribution to job creation in the long run. The results indicate that job losses in fossil fuels and nuclear power sectors are more than outweighed by the job creation in renewable power generation and storage sectors. This if further emphasised in the Fig. 13, with renewable energy contributing to around 80% of the jobs created by 2050.

The employment patterns in manufacturing and distribution of renewable energy and storage technologies are similar to those in other capital investment goods industries. Manufacturing represents 16% of the total jobs created globally and vary from 10% in Europe to 19% in Sub-Saran Africa for 2050. Quite different are the patterns in construction and installation, as the work is mainly project based. Construction and installation jobs have a share of 29% globally and vary from 20% in North America to 35% in Sub-Saharan Africa in 2050. The patterns of employment in the operation and maintenance segment are indeed more stable. As, operation and maintenance jobs have a 50% share globally and vary from 42% in Sub-Saharan Africa to 64% in North America for 2050. Evidently, the total employment created tends to grow rapidly when a significant number of new installations are implemented as shown by the regional as well as global results, particularly in the period of 2020 to 2030. The electricity generation specific jobs at 897 jobs/TWh_{el} in 2015 rise up to 1091 jobs/TWh_{el} in 2030 and then decline steadily to around 715 jobs/TWh_{el} in 2050. The decline in specific jobs is predominantly due to improving learning rates of technologies, which account for higher level of efficiency in industrial processes. Higher productivity due to economic growth further reduce the specific jobs, an effect which affects all technologies, not only renewable ones. Despite the decline, the total jobs created compensate for the jobs lost in the conventional energy sector. This indicates that even with increasing industrial efficiencies and continued learning for renewable energy and storage technologies, a high volume of jobs can be expected in the long term. While for the case of South Africa in a separate study (Oyewo et al., 2019), jobs were estimated using the methods of this research, which showed that the specific jobs further decline with higher shares of conventional technologies in a Current Policy Scenario (CPS) as compared to a Best Policy Scenario (BPS) with higher shares of renewable energy.

Finally, it appears that there is considerable growth potential for renewables and renewable employment creation in a variety of markets across the world, as shown in earlier sections. However, these markets have to be triggered by stable and sensibly designed policy instruments and investment strategies, such as long-term supporting schemes (e.g. feed-in tariffs) and a global approach towards climate protection (e.g. carbon tax or cap and trade systems) in order to leverage existing opportunities from renewables (Ram et al., 2017a). Additionally, a reform in energy prices and exorbitant subsidies for the fossil fuel and nuclear sectors is much required (Coady et al., 2017). Although this study has suggested a favourable increase in employment, a reorganisation of a country's power system could have far more significant benefits to its entire economy. This indicates that more integrated assessments of job impacts are necessary as the penetration of renewable energy increases in future energy systems.

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Appendix A

Table A1
Employment factors used in the estimation of jobs created during the energy transition from 2015 to 2050. (Abbreviations: Mfc. – Manufacturing, C&I – Construction and Installation, O&M – Operation and Maintenance, Dcm. – Decommissioning).

Technologies	Mfc. [job-yrs /MW]	C&I [job-yrs /MW]	O&M [jobs/MW]	Fuel [jobs/PJ]	Dcm. [job-yrs /MW]	Source
Wind onshore	4.70	3.20	0.30		0.72	Rutovitz et al., 2015
Wind offshore	15.60	8.00	0.20		2.99	Rutovitz et al., 2015
PV Utility-scale	6.70	13.00	0.70		0.80	Rutovitz et al., 2015
PV Rooftop	6.70	26.00	1.40		1.21	Solar Power Europe, 2015
Biomass	2.90	14.00	1.50	29.90	0.32	Rutovitz et al., 2015
Hydro Dam	3.50	7.40	0.20		2.22	Rutovitz et al., 2015
Hydro RoR	8.75	18.50	0.50		5.55	Assuming 2.5 times the value as Hydro Dam
Geothermal	3.90	6.80	0.40		0.21	Rutovitz et al., 2015
CSP	4.00	8.00	0.60		1.33	Rutovitz et al., 2015
Biogas PP	2.90	14.00	2.25	29.90	0.32	Rutovitz et al., 2015, 1.5 times more O&M jobs as Biomass PP
Waste-to-energy	2.90	14.00	2.25	29.90	0.32	Rutovitz et al., 2015, 1.5 times more O&M jobs as Biomass PP
Methanation	2.90	14.00	2.25		0.32	Rutovitz et al., 2015, 1.5 times more O&M jobs as Biomass PP
Coal PP (Hard Coal)	5.40	11.20	0.14	39.70	1.65	Rutovitz et al., 2015
Nuclear PP	1.30	11.80	0.60	0.001 (Jobs/GWh)	0.95 (Jobs/MW)	Rutovitz et al., 2015
OCGT	0.93	1.30	0.14	15.10	0.21	Rutovitz et al., 2015
CCGT	0.93	1.30	0.14	15.10	0.21	Rutovitz et al., 2015
Steam Turbine	0.93	1.30	0.14		0.21	Assuming same as Gas Turbine
PtH	1.86	2.60	0.28		0.21	Assuming 2 times the value as GT
ICE	0.93	1.30	0.21	15.10	0.44	Rutovitz et al., 2015, 1.5 times more O&M jobs as GT
Gas Storage	0.00	0.12	0.01		0.11	Gov. of UK, 2015
PtG	1.86	2.60	0.28		0.21	Assuming 2 times the value as GT
Battery large-scale	16.90	10.80	0.40		0.80	0.5 times of prosumer storage
Battery prosumer	16.90	21.60	0.80		1.21	Derived from USDOE, 2017
Pumped Hydro Storage	7.00	14.80	0.40		4.44	Assuming 2 times the values for Hydro Dam
A-CAES	8.45	10.80	0.40		0.40	Assuming 1/2 the values for Batteries (large-scale)
Transmission	Employment factor with regard to investments – 5045 jobs/b€					The Brattle Group, 2011

The decommissioning employment factors are derived from (RFF, 2017), (Evonik, 2010) and (Oldham, 2009). Further details can be found in the Supplementary Material.

Table A2
Regional employment multipliers, based on labour productivity across the different regions used in the estimation of jobs created during the energy transition from 2015 to 2050. (Abbreviations: EUR – Europe, MENA – Middle East and North Africa, SSA – Sub-Saharan Africa, SAARC – South Asian Association for Regional Cooperation, NEA – Northeast Asia, SEA – Southeast Asia, NA – North America, SA – South America).

Regions	Regional employment multipliers							
	2015	2020	2025	2030	2035	2040	2045	2050
EUR	1.05	1.08	1.10	1.13	1.17	1.19	1.20	1.22
Eurasia	1.86	1.80	1.75	1.70	1.65	1.65	1.65	1.65
MENA	2.26	1.94	1.66	1.51	1.37	1.32	1.28	1.23
SSA	7.49	6.42	5.51	5.00	4.54	4.38	4.24	4.09
SAARC	5.18	3.99	3.07	2.56	2.13	2.00	1.88	1.76
NEA	2.22	1.89	1.60	1.50	1.41	1.42	1.42	1.43
SEA	2.52	2.20	1.93	1.77	1.63	1.58	1.52	1.47
NA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SA	3.14	2.69	2.31	2.10	1.90	1.84	1.78	1.72

The regional employment multipliers, which are based on labour productivity factors are derived from (ILO, 2016) and (IMF, 2017). Further details can be found in the Supplementary Material and a description is provided in the methods section.

Table A3
Share of local manufacturing and corresponding share of imports across the different regions used in the estimation of jobs created during the energy transition from 2015 to 2050. (Abbreviations: EUR – Europe, MENA – Middle East and North Africa, SSA – Sub-Saharan Africa, SAARC – South Asian Association for Regional Cooperation, NEA – Northeast Asia, SEA – Southeast Asia, NA – North America, SA – South America).

Regions	Share of local manufacturing [%]								Region of import/import shares [%]			
	2015	2020	2025	2030	2035	2040	2045	2050	EUR	NA	SAARC	NEA
EUR	90	90	90	90	100	100	100	100	–	25	–	75
Eurasia	40	50	60	70	80	90	100	100	25	–	25	50
MENA	30	30	40	50	60	70	80	90	25	–	25	50
SSA	30	30	40	50	60	70	80	90	25	15	10	50
SAARC	70	80	90	100	100	100	100	100	25	15	–	60
NEA	100	100	100	100	100	100	100	100	–	–	–	–
SEA	90	90	90	90	100	100	100	100	30	–	30	40
NA	80	90	90	90	100	100	100	100	50	–	–	50
SA	50	60	70	80	90	100	100	100	25	50	–	25

The development of the shares of local manufacturing in the different regions during the energy transition period from 2015 to 2050 and the corresponding regions of import, along with the shares of import are based on data gathered from (Rutovitz et al., 2015), (UNIDO, 2013) and (PwC, 2017).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2019.06.008.

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Publication IV

Ram, M., Osorio-Aravena, J.C., Aghahosseini, A., Bogdanov, D., and Breyer, C.

Job creation during a climate compliant global energy transition towards 100% renewable energy across the power, heat, transport and desalination sectors by 2050

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Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050

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A B S T R A C T

Driven by climate mitigation goals countries around the world are prioritising low-cost renewables for economic growth and recovery from the aftermath of the global pandemic. It is quite clear that sustainable technology choices result in broader socioeconomic benefits, as is shown by countries that have been early movers in transitioning their energy sectors towards higher shares of renewables. There is growing interest in better understanding the direct impact on employment by energy transitions with concerns over jobs lost in the conventional energy sectors, which will be crucial in informing decision making around the world. This research focuses on the net employment impacts of an accelerated uptake of renewable energy that envisages the world deriving 100 % of its energy from renewable sources by 2050, compatible with the ambitious goals of the Paris Agreement. Direct energy jobs associated with the power, heat, transport, and desalination sectors increase substantially from about 57 million in 2020 to nearly 134 million by 2050. Value chains in renewables and sustainable technologies are found to be more labour intensive than extractive fossil fuels. The results indicate that a global energy transition will have positive impacts on future stability and growth of economies around the world.

1. Introduction

The Paris Agreement, negotiated at the 21st Conference of the Parties (COP21) in 2015 [1], has set an important foundation for the global community to aspire and move towards building a sustainable future. A global energy transition is at the heart of realising sustainable development goals, as the energy sector accounts for over three-quarters of global greenhouse gas (GHG) emissions [2,3]. Despite a share of just around 2–6% in global gross domestic product (GDP) [4], the energy sector is a major economic contributor with significant prospects for investments and employment in countries around the world. As the energy sector is increasingly intertwined with economic welfare, social priorities and environmental needs, an integration of social processes along with technical and economic analyses of energy systems are emerging as a necessity. The techno-economic implications of a shift towards high shares of renewable energy such as additional generation capacities, investment needs and reduction in GHG emissions have been explored for a range of scenarios in many countries as well as globally [5–9], as enlisted and analysed by the Centre for Alternative Technology [10]. As in other economic and technological shifts, transitioning to a low carbon economy will result in additional jobs being created, jobs being substituted, jobs being eliminated and existing jobs being transformed [11]. Combining different methods as proposed by Fortes et al. [12], is a way to advance scenario building by assimilating different ideas and approaches along with key socioeconomic parameters.

Employment impacts form a crucial aspect of energy policy, as highlighted by Fischer et al. [13] in the case of Germany, where jobs are one of the five controversial issues in the debate on the “Energiewende”. In recent years, employment impacts of renewable energy technologies in context to the energy transition has received attention from many stakeholders including academia, multilateral and intergovernmental agencies, private sector, and civil society. Employment trends can vary significantly for the different energy technologies across their value chains including production, generation, storage, transmission and distribution, and

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flexibility options. There have been a number of efforts to quantify employment impacts of the changing energy sector and have been well documented in literature review studies, such as Breitschopf et al. [14], Meyer and Sommer [15] and Cameron and Van Der Zwaan [16] and the net impacts on employment have been verified with actual data by the International Labour Organisation (ILO) [17] and Proença and Fortes [18].

In general, there are different types of jobs associated with the energy industry; the commonly adopted classification is 'direct', 'indirect' and 'induced' jobs. As the International Renewable Energy Agency (IRENA) [19] elaborates, direct energy jobs are the ones associated directly to an activity in the value chain of a particular energy technology, whereas, indirect and induced jobs include those jobs that are either created by auxiliary activities or activities that are an outcome of enabling energy availability. The various approaches to estimate employment impacts of deploying energy technologies can be categorised into bottom-up and top-down approaches, or more specifically as using the analytical or input−output (IO) models [20]. Lund and Hvelplund [21] have described and promoted Concrete Institutional Economics as a tool and methodology of designing strategies to utilise economic crises and investments in sustainable energy as a driver of job creation and have applied it to the case of Denmark [21,22]. Additionally, a value-chain approach [23] and a life-cycle approach [24] have been adopted for estimating job creation mainly from the adoption of renewable power generation technologies. Jacobson et al. [5,25] estimate the baseline jobs per unit energy in their main scenario, which are based on National Renewable Energy Laboratory's (NREL) Jobs and Economic Development Impacts (JEDI) models [26]. These are economic input-output (IO) models with several assumptions and uncertainties. In contrast, IRENA [27,28] and Greenpeace [29] adopt simpler analytical approaches to estimating job impacts that also have a high level of transparency. This entails utilising job intensities or employment factors (EF), defined as the number of jobs derived from the capacity addition or investment in a certain energy technology through the value chain and the technical lifetime. The EF approach utilised for estimates of job creation potential in Greenpeace's energy scenarios is provided by Rutovitz et al. [30], which results from a continuous refinement of the methods and updating of employment factors corresponding to developments in energy technologies. Ortega et al. [31] have further proposed a dynamic employment factor approach considering trade and technology learning effects, which were applied to the countries of the European Union (EU) and the results were validated successfully with historical data in the time frame 2008−2012. The EF approach is ideal to explore direct energy jobs linked to deployment of energy technologies and enables comprehensive analyses of the associated value chains to determine comprehensive direct job creation resulting from energy transitions, as documented in Ram et al. [32]. Ram et al. [32] have further refined the EF approach with the consideration of regional labour productivity, technology learning effects and decommissioning of power plants and estimated the net direct energy jobs created during an energy transition globally, but limited to the power sector only. However, this research is an effort to further advance and expand the methods from Ram et al. [32] from the power sector to other energy sectors and conduct a more comprehensive analysis of the net direct energy jobs created during an energy transition, which includes a broad range of energy technologies, as highlighted in Table S1 in the supplementary material. It is additionally the first research to estimate the job creation potential of complementary heat storage and power-to-X technologies (including the production of hydrogen and e-fuels) across the energy sector comprising power, heat, transport, and desalination demands. The research has also included estimates of decommissioning jobs across the various energy technologies and estimated jobs linked to transmission and distribution of electricity created during the energy transition in the next three decades (2020−2050), which is based on comprehensive data collation of actual jobs across different countries and regions of the world. It also estimates the jobs involved in the production and trade of fossil fuels across different major regions of the world.

A comprehensive literature review is conducted to determine the most ideal EFs for all technologies in the energy system that are presented in Table S1. The components of the energy system are classified into power generation technologies, heat generation technologies, combined heat and power technologies, storage technologies (electricity and heat) and fuel production technologies (fossil and synthetic). The EFs are categorised as manufacturing, construction and installation, operation and maintenance, fuel supply and decommissioning to capture the entire value chain in energy conversion and supply (refer to Section 1.1 and Table S1 in the supplementary material). In addition, transmission and distribution grid jobs are linked to electricity generation (refer to section 1.1 and Table S8 in the supplementary material), which are linearly extrapolated to determine jobs with the corresponding electricity generation in the future across the different regions of the world. These are comprised of Europe, Eurasia, Middle East and North Africa (MENA), sub-Saharan Africa (SSA), South Asian Association for Regional Cooperation (SAARC), Northeast Asia, Southeast Asia, North America and South America (for the full composition of these regions refer to Bogdanov et al. [33]). The divergence in labour productivity and intensity is captured with regional productivity factors across nine major regions of the world. The effects of scaling and automation are captured through declining labour intensity factors linked to the declining costs of energy technologies (both capital expenditure and operational expenditure). The global job creation through the transition is an aggregate of the job creation computed across the nine major regions of the world, which also considers exports and imports of fossil fuels and manufactured technologies exchanged across the nine major regions. The methods, EFs and assumptions (Table S1 to Table S8) are presented briefly in the methods and materials section and further in detail in Section 1 of the supplementary material.

This research evaluates the hypothesis of sound economic impacts from transitioning to a sustainable energy future by determining the employment effects of achieving 100 % renewable energy supply to the power, heat, transport and desalination sectors by 2050 in a high electrification scenario, across the world structured in nine major regions based on 145 detailed regions. The transition of power, heat, transport and desalination sectors across these regions, as showcased in Ram et al. [34] and Bogdanov et al. [33], serves as the basis for estimating jobs created during the transition period from 2020 to 2050. Additionally, the job creation potential is estimated on a technology-wise basis as well as on a category-wise basis through the energy value chain during the energy transition to provide better insights on the types of jobs created. This is primarily enabled by the innovative aspects of the LUT Energy System Transition modelling tool [33], which analyses cost optimal energy systems across the world on high levels of geospatial (145 regions) and temporal (hourly) resolutions, and which has been identified as one of the most sophisticated tools for long-term energy system transition modelling [35].

2. Methods and materials

For this research, an analytical approach towards estimating direct energy jobs corresponding to the value chain during an energy transition across the different regions of the world was adopted. Further, a dynamic approach with learning effects of technologies through the transition years and change in labour intensities across the different regions of the world are considered. The methods are based on the approach highlighted in Ram et al. [32] and Rutovitz et al. [30] and further modified and improved for better results as well as applied to a broader range of energy technologies across the power, heat, transport and desalination sectors (see Table S1). The Employment Factor (EF) method was adopted amongst the other methods [14], due to its simplicity and effectiveness in estimating direct employment associated with energy generation, storage, flexibility options and transmission and distribution of electricity. One of the main advantages of the EF approach is that it can be modified for specific contexts, as well as applied over a range of energy scenarios [31]. In the context of this research, the total direct jobs are a sum of jobs in manufacturing, construction and installation, operations and maintenance, fuel supply associated with electricity and heat generation, decommissioning of energy plants at the end of their lifetimes and transmission and distribution of electricity. This is further highlighted in Fig. S1 and the approach is explained in detail in section 1.1 in the supplementary material.

Some of the parameters considered in the estimation of the job creation potential of various energy technologies include employment factors, which are the number of jobs per unit of installed capacity, separated into manufacturing, construction and installation, operation and maintenance, and decommissioning. It is also jobs per unit of primary energy for fuel supply and jobs per unit of transmitted and distributed electricity, decline factors are linked to the decline in capital expenditure (Capex) and operational expenditure (Opex) of the different energy technologies, job creation can be expected to reduce as technologies and production of these technologies mature (refer to section 1 in the supplementary material). This maturing occurs because of the growing experience and volume in the energy industry (mainly renewables, storage, and e-fuels production), which are captured by Capex and Opex. Regional employment multipliers for the various regions are adopted to account for the differential labour intensive economic activity in the different regions across the world, which are normalised with OECD (represented by North America in this research) for the other regions in the world having relatively higher labour intensities compared to North America (refer to Table S2 and section 1.1 for more details). The import-export shares for manufacturing and fossil fuels production, which represents the percentage of local manufacturing/local fossil fuel production (according to the fuel coal, oil and gas) across the various regions of the world, linking the importing and exporting regions are taken into account. These are presented in Table S4 to Table S7. Jobs associated with transmission and distribution of electricity were linked to the generated electricity of the different regions rather than the investments in transmission networks as in Ram et al. [32]. This allows for a more comprehensive coverage of jobs in transmission and distribution of electricity, as these are based on actual jobs in countries and regions as listed in Table S8 in the supplementary material.

Further on, the manufacturing EFs and construction and installation EFs are applied to the newly installed capacities for each year during the transition period from 2015 to 2050. While operation and maintenance EFs are applied to the cumulative installed capacities for every 5-year interval between 2015 and 2050. The fuel EFs are applied to annual electricity and heat generation form the various power and heat generation technologies that utilise fuel sources along with the fuel demand for the various transport modes. The decommissioning EFs are applied to the annual decommissioned capacities of energy technologies during the entire transition period. The transmission and distribution of electricity EF is applied to the total annual electricity generated across the different regions during the transition period. The new and cumulative installed capacities, electricity generation, fuel consumption and decommissioned capacities for the various energy technologies are adopted from the results of the LUT Energy System Transition model, which is comprehensively documented in Bogdanov et al. [33]. The detailed methods, assumptions and EFs are presented in the supplementary material in section 1, Figure S1 highlights the EF approach and Table S1 lists the various EFs for all energy technologies. Section 1.1 details the EF approach with all assumptions listed in Table S1 and Table S2, while section 1.2 gives a brief overview of the LUT Energy Transition Modelling tool. Section 2 of the supplementary material presents the results of jobs created in each of the major regions highlighted in Figure S2 to Figure S37. Additionally, the jobs estimated globally and for each major region is presented in Table S10 to Table S18, along with estimations for 92 countries and regions around the world in Table S19. The 92 countries/regions structuring is defined in Ram et al. [34] and Bogdanov et al. [33]. This is a first of its kind research attempt at a comprehensive assessment of the job creation impacts during an energy transition towards 100 % renewable energy across power, heat and transport sectors with energy demand for desalination in a high electrification scenario, with an exhaustive list of technologies that cover both electricity and heat storage along with production of hydrogen and e-fuels. Moreover, results are presented from global, regional and country perspectives on sectoral, technological and value chain basis over the transition period.

3. Results

The results of Ram et al. [34] and Bogdanov et al. [33], which form the basis for estimating the jobs creation, highlight a few trends during the energy transition until 2050. First, the energy transition across the power, heat, transport, and desalination sectors is driven by massive electrification, with 89 % of primary energy demand comprised of electricity in 2050. Second, the global energy system undergoes a complete defossilisation and reaches zero GHG emissions in 2050. Third, storage and power-to-X technologies along with green hydrogen and e-fuels emerge as critical components of the new carbon neutral energy system. These trends lead to a rapid ramp-up in installed capacities of renewable electricity generation technologies, compensating for the phasing out of fossil fuels and nuclear based energy capacities around the world. In this context, the overall direct energy sector jobs increase significantly from about 57 million in 2020 to around 134 million by 2050, as highlighted in Fig. 1. Driven by strong growth in the renewable energy sector, coupled with direct and indirect electrification the direct power generation jobs are more than tripled in 2050 with 69 million, as compared to 20 million jobs in 2020. As compared to Ram et al. [32] that analysed exclusively the global power sector transition and found direct jobs to increase from about 20 million in 2015 to 35 million in 2050. While, in this research, which is based on high electrification across the other energy sectors of heat and transport, the jobs for electricity generation are nearly twice as much in 2050 owing to the high electricity generation covering demand from the entire energy system during the transition. While in the heat sector, jobs created decline in the initial periods due to high levels of electrification and increase later in the transition to about 28 million jobs with the complete defossilisation in 2050. Similarly, jobs associated with fuels mainly for the transport sector decline initially with the decline in utilisation of fossil fuels as a consequence of phasing in electric road vehicles and increase later in the transition with the production of e-fuels, reaching 5 million jobs in 2050. Storage jobs take off in the 2030s reaching about 10 million jobs by 2050. The high levels of electrification also drive the transmission and

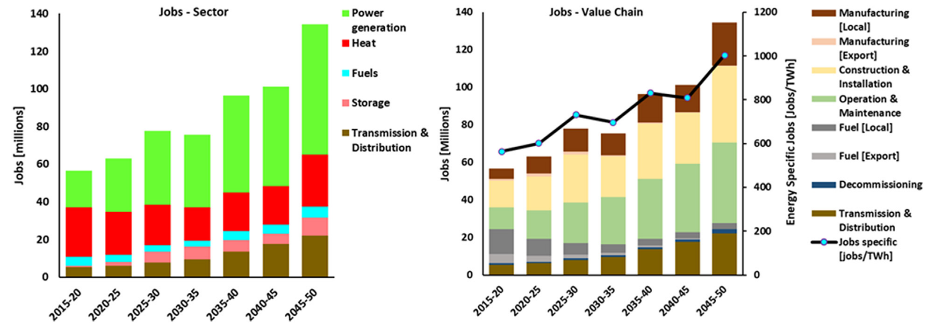

Fig. 1. Jobs across the different energy sectors (left) and jobs across the energy value chain with the development of final energy demand specific jobs (right) during the energy transition from 2015 to 2050 globally.

distribution grid jobs through the transition reaching about 22 million jobs in 2050, see Fig. 1.

Direct energy jobs through the value chain in manufacturing, construction and installation, operation and maintenance, fuel supply, decommissioning and transmission created during the energy transition from 2020 to 2050 are shown in Fig. 1. Manufacturing of energy technologies leads to a significant increase in manufacturing jobs from around 6 million in 2020 to over 23 million in 2050, which includes some shares of export quantities, however, in this research the major regions are expected to domestically manufacture energy technologies by 2050. Thereby, ensuring more domestic job creation. Jobs associated with the operation and maintenance of energy technologies create the greatest number of jobs by 2050, with around 42 million jobs around the world. Similarly, construction and installation of energy technologies leads to over 40 million jobs by 2050. Jobs associated with the production and supply of fossil fuels, both domestic and exports are set to decline from around 32 % of the total energy jobs in 2020 to just around 3 % of the jobs by 2050, with mainly decommissioning of fossil fuels and nuclear power capacities. Global export volumes of fossil fuels account for around 8 % of total energy jobs in 2020 and are eliminated by 2050 with no exports of fossil fuels, as countries transition to adopting locally produced e-fuels and some bioenergy. However, countries with excellent renewable resources, thriving ecosystems with favourable costs of production for e-fuels could emerge as exporters, creating more direct energy jobs.

The trends in job creation indicate that the transition towards a global 100 % renewable energy system across the power, heat, transport and desalination sectors enables the creation of more stable and local jobs, which can contribute to stable economic growth of countries, mainly in the developing regions of the world as a means of tackling high unemployment rates, especially amongst the youth [36]. In many parts of the world, this could be a catalyst to raise social welfare and create conducive environments for political stability [37]. Furthermore, Fig. 1 also illustrates the development of the final energy demand specific jobs, which increases through the transition period, from 563 jobs/TWh in 2020 to 1000 jobs/TWh in 2050. This indicates that an energy system based on renewables creates nearly twice as many jobs for every unit of energy demand covered, as compared to the current fossil fuels based energy system. The energy system transition can be realised in a cost neutral pathway [33,34], as energetically inefficient and less labour intensive combustion processes are largely substituted by highly efficient and more labour intensive renewable electricity-based solutions. This implies that more jobs could be created with a transition towards more sustainable energy technologies resulting in lower levelised cost of energy.

3.1. Technological and sectoral distribution

Driven by direct and indirect electrification, power generation grows substantially through the transition to meet the rapidly increasing electricity demand. As the other energy sectors of heat and transport increasingly rely on electricity for heat generation, charging batteries and producing e-fuels. Generating the least cost energy, solar PV emerges as the prime electricity generation source and in the process creating 60 million jobs by 2050. Almost a tenfold increase from just around 7 million in 2020, as can be seen in Fig. 2. Most of the jobs are from utility-scale solar PV with 44 million jobs in 2050, while solar PV prosumers covering residential, commercial, and industrial segments provides about 16 million jobs around the world in 2050. In the case of wind energy, around 8 million jobs are created in the period from 2020 to 2025, beyond which solar PV becomes more cost effective in many part of the world leading to jobs in the wind energy sector to be stabilised at around 5 to 6 million from 2025 to 2050. While, hydropower, geothermal and bioenergy create a stable share of jobs through the transition period as highlighted in Fig. 2. On the contrary, coal and gas power jobs decline drastically from nearly 50 % of the power generation jobs in 2020, to just a few thousand in 2050, which are predominantly decommissioning jobs. Similarly, nuclear power jobs are almost non-existent by 2050, which is mainly a consequence of unviable economics of nuclear energy [38,39], as shown in Fig. 2. Solar PV replaces coal as the major job creating energy resource, with around 87 % of total power generation jobs by 2050, which indicates that renewable energy technologies can more than compensate for the jobs lost in the conventional power industry. However, there will be challenges of reskilling and training of personnel to enable switching jobs, which can be well managed with innovative social engineering and policy making.

The heating demand consisting of domestic hot water demand, space heating, biomass for cooking and industrial process heat is predominantly covered by the range of heating technologies indicated in Fig. 2 and Table S1 in the supplementary material. In contrast to the power generation, heat sector jobs decline initially and then increase later in the transition with complete defossilisation of the sector, eventually with around 28 million jobs by 2050 as highlighted in Fig. 2. Fossil fuels and bioenergy jobs comprise most of the heat sector jobs in 2020, coal is the highest contributor

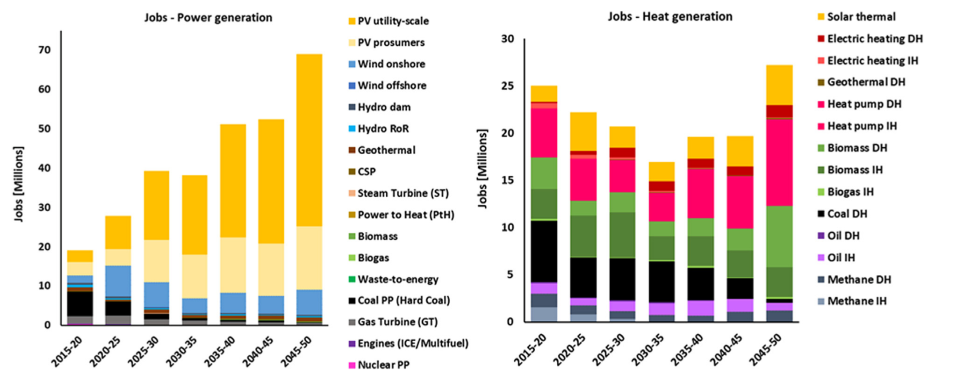

Fig. 2. Jobs across power generation technologies (left) and jobs across heat generation technologies (right) during the energy transition from 2015 to 2050 globally.

with nearly 6 million jobs. However, fossil-based jobs in the heat sector decline through the transition, which are replaced with jobs related to heat pumps, electric heating, and solar thermal leading to an additional 3 million jobs in 2050, compared to 25 million jobs in 2020.

Combined heat and power (CHP) plants contribute around 1.5 million jobs in 2020, which are predominantly from coal and gas plants as shown in Fig. 3. Bioenergy jobs comprising biomass, biogas and waste-to-energy technologies contribute a major share of the jobs as the fossil fuels based CHP jobs decline through the transition. However, with increasing integration of the power and heat sectors coupled with the adoption of more efficient heat pumps and electric heating results in fewer operational CHP plants by 2050. This results in the overall reduction in jobs to around 700 thousand, mainly bioenergy CHP jobs in 2050 as highlighted in Fig. 3.

Jobs in the storage sector encounter massive growth with nearly 6 million jobs in the period 2025 to 2030, with predominantly battery jobs both at the utility scale and prosumer scale as shown in Fig. 3. Some shares of jobs in pumped hydro and compressed air energy storage grow up to 2030. This is mainly driven by massive capacity additions of battery storage required by 2030 to complement the growth in renewable electricity generation. Furthermore, by 2050 there are close to 10 million jobs in the storage sector, which are mainly associated with battery technology as it emerges as the most cost effective storage technology as highlighted in Fig. 3. Additionally, there could be a significantly higher number of jobs in the battery industry driven by the demand for batteries from electric vehicles in the transport sector. This research is limited to batteries in the energy system, including the energy demand for transport (with high shares of electrification) and does not account for the batteries required for battery electric vehicles (BEV), which could be very significant and mainly corresponds to the jobs in the automotive industry.

Jobs associated with the production of fuels, which are predominantly fossil fuels decline through the transition from about 18 million in 2020 to around 4 million in 2050, as highlighted in Fig. 4. The demand for coal, oil and gas is expected to decline with increasing electrification driven by low cost renewable electricity resulting in the decline of corresponding jobs through the transition.

Contrary to the diminishing role of fossil fuels, e-fuels are expected to play a critical role in the future energy system across the power, heat, and transport sectors. As indicated by Fig. 4, the

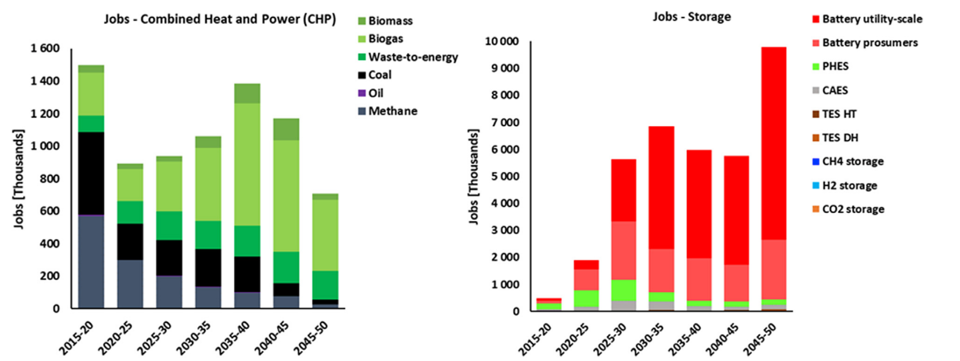

Fig. 3. Jobs across the different combined heat and power technologies (left) and jobs across the different storage technologies (right) during the energy transition from 2015 to 2050 globally.

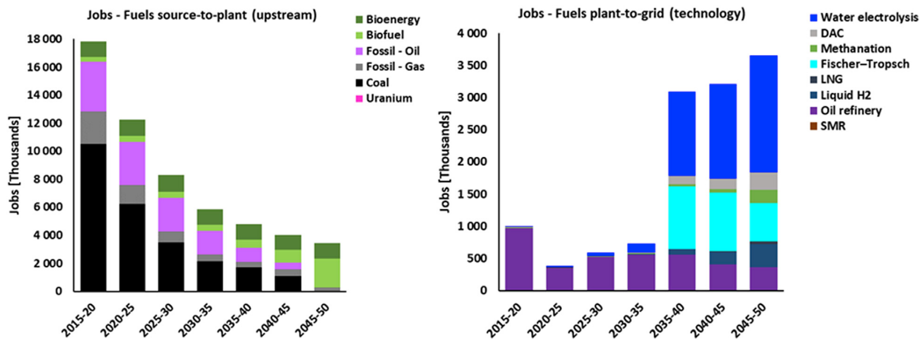

Fig. 4. Jobs across the different fuel sources (left) and jobs across the different fuel technologies (right) during the energy transition from 2015 to 2050 globally.

production of hydrogen, synthetic natural gas (SNG) and Fischer-Tropsch fuels contribute to a substantial number of jobs in the later part of the transition with over 3.6 million jobs in 2050. A bulk of the jobs are from water electrolysers, mainly to produce hydrogen. The strong rise in jobs around 2040 is a consequence of the underlying scenario [33,34], but may be triggered even earlier with an advanced industry ramp-up.

The sectoral analyses of job creation indicate that power generation will create the bulk of energy jobs in the future, driven by the massive electrification of the heat and transport sectors. This research shows that the power generation along with the transmission and distribution of electricity has the potential to create over 70 million direct jobs by 2050. This is primarily driven by structural changes in the energy system with most energy demand covered by electricity in future highly electrified energy systems. Job creation in the heat sector is rather stable with the sustenance of over 20 million jobs through the transition. Whereas storage and e-fuel production have great potential to create over 13 million direct jobs by 2050. Overall, the energy transition towards 100 % renewable energy across the power, heat, transport, and desalination sectors has a net positive impact on jobs created. The power generation alone has the potential to create a significantly greater number of jobs, than jobs lost in the conventional energy sector, mainly fossil fuels and nuclear. However, the impacts of employment creation during the energy transition can vary according to the region of the world and the corresponding energy system.

3.2. Regional distribution

Global direct energy job creation through the transition period from 2015 to 2050 is an aggregate of the job creation estimated across nine major regions, where the transition to 100 % renewable energy in the power, heat, transport, and desalination sectors is projected. The regional distribution of jobs across the major regions through the transition period is shown in Fig. 5. The share of jobs in Europe grows substantially from about 7 % in 2020 to 12 % by 2050 of total energy jobs in the world. This is mainly driven by high shares of electrification across the energy sectors and production of domestic e-fuels, creating around 16 million direct energy jobs in 2050. While the share of jobs in Eurasia initially decline from about 8 % of global energy jobs in 2020 to around 6 % in 2030, and thereafter stabilise at around 7 % by 2050. As most Eurasian countries are exporters of fossil fuels, a decline in these jobs contributes to declining shares in global energy jobs, however, in the later part of the transition more jobs are created as a result of massive uptake of renewables and e-fuels leading to 9 million jobs across Eurasia in 2050. Similarly, in the MENA region, the share of jobs decreases from 7 % in 2020 to 5 % in 2050 of global energy jobs. As the region is amongst the highest exporters of fossil fuels, jobs associated with the production of fossil fuels declines through the transition (the shares of local production, import shares and import regions of fossil fuels are presented in Table S5 to Table S7 in the supplementary material). However, in terms of total jobs created there are 6 million jobs in 2050, compared to about 4 million jobs in 2020 across MENA. This indicates that despite the loss of jobs in fossil fuel exports, a transition to high shares of renewables creates ample the number of domestic jobs in these regions. On the contrary, sub-Saharan Africa experiences the highest growth in total energy jobs created across the world, increasing from just around 2 million in 2020 to 12 million by 2050. As most of the energy infrastructure is yet to be built in this region, there is massive potential for developing renewable energy and creating jobs for the local populations. The SAARC region comprising south Asian countries and Northeast Asia together account for over 50 % of the global energy jobs in 2020, and this share is sustained through the transition with just below 50 % in 2050. Whereas the total energy jobs more than double by 2050 with 26 million across SAARC and 39 million across Northeast Asia. Both SAARC and Northeast Asia are currently driven by high economic growth rates, which are expected to drop to lower levels and flatten out over the long-term as they reach higher levels of development resulting in lower levels of labour intensity. In Southeast Asia and the Pacific countries, the share of jobs created are observed to decline from 8 % in 2020 to 6 % in 2050 of global energy jobs. Coal exporting countries such as Indonesia and Australia, contribute to the decline in the share of jobs. Whereas the transition to renewables results in increasing jobs from 4 million in 2020 to 8 million in 2050 across the region. In the case of North America, the share of global energy jobs remains stable through the transition at around 10 %. With a more diversified energy sector the total energy jobs across North America more than double from 5 million in 2020 to 12 million by 2050. The total energy jobs across South America nearly double from 3 million in 2020 to 6 million by 2050. While the share in global energy jobs from the regions declines from 6 % in 2020 to 4 % in 2050, mainly driven by the loss of fossil fuel exports in some of the countries of the region. The region has excellent renewable resources and has the potential to tap into these to create stable and long-term employment. The detailed job creation analyses through the

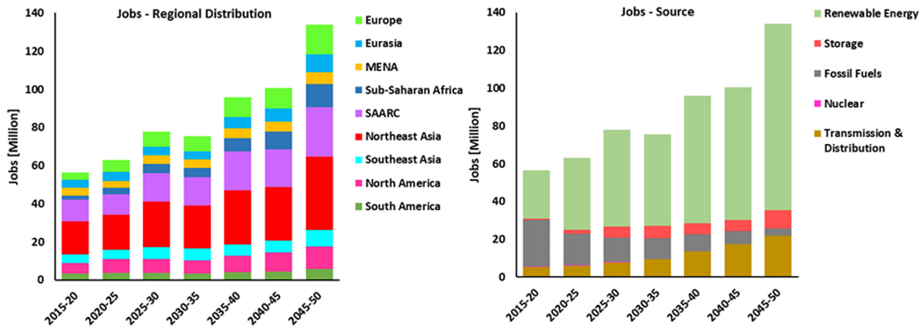

Fig. 5. Regional distribution of jobs (left) and distribution of jobs according to the source of energy (right) during the energy transition from 2015 to 2050 globally.

transition in each of the major region is further highlighted in Section 2 of the supplementary material with Figure S2 to Figure S37. Additionally, total direct energy jobs have been estimated for 92 countries and regions around the world, applying energy specific jobs of major regions to the corresponding final energy demands of respective countries and regions, which is highlighted in Figure S38. The estimated jobs during the energy transition from 2015 to 2050 are presented in the supplementary material with Table S9 for global estimates, Table S10 to Table S18 for each of the nine major regions and Table S19 presents the job estimates across the 92 countries and regions.

The source based distribution of global energy jobs through the transition is highlighted in Fig. 5. It is evident that renewable energy technologies will create the most energy jobs, with nearly 100 million jobs in a high electrification pathway to a carbon neutral global energy system by 2050. Contrarily, the share of fossil fuels and nuclear based jobs are observed to decline through the transition period, from about 50 % in 2020 to a mere 3 % in 2050, as indicated in Fig. 5. These jobs are primarily associated with decommissioning of the remaining fossil and nuclear power plants that are approaching the end of their lifetimes. Renewable energy accounts for around 75 % of total direct energy jobs by 2050, in contrast to about 45 % in 2020, as they emerge to be the least costing sources for power generation [33,34]. The storage sector creates around 10 million jobs in 2050, with the steady ramp-up in installations and cost competitiveness beyond 2030, as shown in Fig. 5. High shares of electrification across the different energy sectors and widespread installations of renewable energy generation capacities along with large scale battery storage capacities will entail the need for increase in electricity transmission and distribution infrastructure, which creates steady and long-term jobs. Jobs associated with transmission and distribution of electricity is expected to grow form about 5 million in 2020 to nearly 22 million by 2050, as highlighted in Fig. 5.

Most renewable energy and storage technologies are still in their initial phases of development and are expected to grow rapidly, relative to their current levels of installations around the world. However, the pattern varies across different renewable power generation and storage technologies as there is limited activity in some countries, rapid growth in others, steady growth in a few, and relatively mature markets in the rest [27]. In this research, as part of the underlying Best Policy Scenario (BPS) with an optimistic outlook, the nine major regions are expected to reach 100 % local manufacturing capabilities by 2050 (local manufacturing shares and import shares with corresponding import regions are presented in Table S4 in the supplementary material). However, presuming a conservation approach in which manufacturing shares and export-import shares are expected to peak in 2025, and domestic manufacturing grows through the transition period until 2050. The major beneficial regions would be Northeast Asia with additional 600 thousand jobs, SAARC with 400 thousand jobs, Europe with 270 thousand jobs, Southeast Asia with 210 thousand jobs and to a lesser extent North America with 73 thousand additional jobs. Whereas, the rest of the regions would have fewer local manufacturing jobs with sub-Saharan Africa impacted the most. On the other hand, fossil fuel export jobs continue to decline through the transition and are comparatively less labour intensive as compared to renewable energy generation technologies. In general, it can be noticed that despite having higher shares of imports or higher shares of fossil fuel exports in some regions, the total number of jobs created will still be higher as renewables will create more localised construction and installation as well as operation and maintenance jobs as indicated in Fig. 1. Indeed, employment benefits from renewable energy could go to early mover countries, which start early and create strong export markets with better cost competitiveness. This aspect has been observed in the results of some of the exporting regions presented in the earlier section. Nevertheless, from a long-term perspective, the export-import shares across the different regions of the world are expected to stabilise and self-sustaining economies are foreseen by 2050 [40,41]. This regional and technological variation in global job creation through the energy transition period is captured in Fig. 5.

4. Discussion

The global employment creation in the energy sector with increased shares of renewable energy generation will have a net positive effect, which indicates that the number of jobs created by installing new capacities of renewable energy and complementary technologies are significantly higher than the number of jobs associated with the production and supply of fossil fuels and nuclear energy generation across the world. These results are validated by other studies such as Jacobson et al. [5,25,42], IEA [43], IRENA [27,28], Behrens et al. [44], Greenpeace [29], Dominish et al. [45], EPFL [46] among many others, which all tend to indicate that higher shares of renewables do have net positive impacts on employment. This research estimates the net employment generation from a global energy transition across the power, heat, transport, and desalination sectors to be 134 million direct energy jobs by 2050. There are four recent studies that estimate employment impacts in the context of global energy transitions, which are Jacobson et al. [25], Dominish et al. [45], IRENA [28] and IEA [43]. Jacobson et al. [25] estimate nearly 55 million total energy jobs in 2050 (net of 29 million after considering jobs lost) form wind energy, water and solar energy (WWS) generators with transmission for the entire energy sector (power, heat and transportation). Dominish et al. [45], quantitatively estimate that in 2050, there will be 29.6 million energy sector jobs in the 5.0 °C scenario, 50.4 million energy jobs in the 2.0 °C scenario, and 47.8 million energy jobs in the 1.5 °C scenario. In IEA's net zero emissions 2050 (NZE2050) scenario, clean energy employment increases by 14 million to 2030, while employment in oil, gas and coal fuel supply and power plants declines by around 5 million, leading to a net increase of nearly 9 million jobs resulting in a total of 49 million energy jobs in 2030 [43]. IRENA [28] estimates 100 million jobs in the energy sector by 2050, however, the energy transition pathway results in just 65 % renewable energy in the total primary energy supply in 2050. Moreover, storage technologies and the production of e-fuels have not been considered. Comparatively, IEA [43], Jacobson et al. [25] and Dominish et al. [45] have lower estimates of jobs created in 100 % renewable energy systems, as they have considered only renewable energy generation, with limited technology options, in addition to a lower final energy demand. It is increasingly evident that 100 % renewable energy systems will require complementary storage and flexible technology options, along with renewable electricity based e-fuels mainly in hard to abate sectors such as marine, aviation and others. Therefore, these sectors and jobs created by the adoption of these technologies must be factored for more comprehensive analyses on the employment impacts of 100 % renewable energy systems. IRENA [28] estimates job creation in energy efficiency, energy flexibility and grid, but still relies on fossil fuels for much of the primary energy demand, which is not compatible with climate change mitigation goals and does not result in a carbon neutral energy system. However, the findings of IRENA [28] indicate a net positive impact with higher shares of renewables than the current plans of countries around the world. In comparison to this research, a 100 % renewable energy system around the world can provide an additional 34 million energy jobs in context to IRENA's energy transition pathway and around 48 million additional energy jobs in context to the current plans of countries by 2050.

Several studies have demonstrated that the exploitation of renewable energy sources for electricity production creates a greater number of jobs than that supplied by conventional power sources and is analysed by Cameron and Van Der Zwaan [16]. It is found that for every megawatt of installed power capacity, renewable energy sources create between 1.7 and 14.7 times more jobs than natural gas based power generation and up to 4 times more jobs than those supplied with coal fired power generation [16]. A similar conclusion was drawn by Cai et al. [47] that for every one percent increase in the share of solar PV generation there could be a 0.68 % increase in total employment in China, larger than any other power generation technology. Renewable energy is already contributing more towards job creation in many markets across the world and studies for Chile [48] and Japan [49] show the potential for a lot more, particularly in the power sector. Renewables in the heat sector too have the potential to create substantially more number of jobs as highlighted by Connolly et al. [50] for the transition of the European heat sector until 2050. In the specific case of the USA, solar power generating capacity represents only slightly more than 1 % of the total power capacity, whereas coal contributes around 26 % to the power mix. However, solar workers are already twice as numerous, compared to those in the highly automated coal industry [51,52]. Likewise, the number of direct jobs estimated in this study can fall short of the actual number of total jobs including indirect and induced jobs created by the installation of renewable power and heat generation, storage technologies, production of e-fuels and transmission and distribution of electricity.

The direct energy jobs estimated in this research were validated with some approximations and estimates from other research. This research estimates around 57 million jobs in the period 2015 to 2020, which is in the range of the IRENA [28] estimate of 58 million jobs in 2017. While, Dominish et al. [45] estimate around 30 million direct jobs in 2015, which seems to be rather conservative. The IEA energy employment database shows that in 2019, the energy industry − including electricity, oil, gas, coal and biofuels − directly employed around 40 million people globally [58]. ILO [17] estimates jobs in the electricity sector to be about 25 million in 2014, in comparison this research finds 20 million direct energy jobs in the power sector and 5 million jobs in the transmission and distribution of electricity for the period 2015 to 2020. This is also validated by the results of Ram et al. [32] that estimate about 20 million direct jobs in 2015 and over 24 million jobs in 2020 across the global power sector. IRENA [59] estimates around 30 million jobs in the fossil fuels industry, in comparison this research estimates nearly 19 million jobs in the coal, oil and gas industries (jobs are estimated from source to plant, mainly upstream jobs). However, estimating fossil fuel jobs varies significantly with the consideration of value chains and the informal nature of the industry mainly in developing and undeveloped regions of the world adds to uncertainties. ILO [60] estimates around 6 million jobs in the global petroleum industry and Pai et al. [61] estimate over 7 million jobs in the coal industry around the world. In comparison, this research estimates 7 million jobs in the oil and gas industry and 12 million jobs in the coal industry. Pai et al. [61] also note that China accounts for over 6 million coal jobs, thus it is reasonable to assume that there are a lot more jobs in the coal industry around the world with majority in countries such as India, Indonesia and South Africa where the coal industry is still very labour intensive.

Jobs have always been a contentious topic, with most opinions swayed by political commentary about the adverse impacts of an energy transition on employment in a particular state, region, or country [62]. Over the recent past, several studies have examined and analysed the net employment effects of energy transitions. Although the majority of them conclude that the net employment effects will be positive, as concluded by Lund and Hvelplund [63] in a study conducted as early as 1998. While, some studies are less optimistic about net employment creation, and the outcomes seem to depend very much on the methodology [64]. Stavropoulos and Burgerv [64] found that estimations with induced effects are generally less optimistic about net employment creation in the wake of the energy transition. A comparative analysis of direct employment of renewable and non-renewable power plants found renewables to be generally higher, but under some circumstances non-renewables to be comparable [65]. However, this research is focused on estimating only direct energy jobs and the net jobs resulting from a global energy transition towards 100 % renewable energy. The net positive impacts have also been verified with actual data, the ILO [17] have found evidence by linking decades-long trends in employment in the electricity generation sector to the sources of electricity generation itself and by analysing the indirect linkages. Results from the analyses showed that increases in generation from non-hydropower renewables favour employment in the electricity sector, with important differences observed in developed and developing countries [17]. Moreover, the study also found that renewables offered higher indirect employment effects as well. Even assessments on a power plant level have indicated better prospects for local economic growth and job creation, as highlighted by a feasibility study for a coal power plant in Thailand [66].

It must be noted and acknowledged that as is with most research methods there are limitation with this research as well. The method relies on extensive and comprehensive literature review for EFs, which in the case of most energy technologies are quite robust with verified employment effects. Whereas some energy technologies are still in the nascent stages of development and still require scaling to a great extent for the employment effects to be analysed and verified. In addition, there are prevailing uncertainties about the development of certain regions and countries around the world, given the geopolitical challenges and economic ambiguities for the future. Moreover, the effects of changes in electricity prices, labour policies and wages and household incomes are mostly uncertain from a long-term perspective. Further limitations of this research extend from perceived limitations of 100 % renewable energy systems, which are mostly related to stability of power systems in handling variable renewable energy and availability of materials to enable the transition to 100 % renewables in a sustainable manner. Stability of the power system in handling variable renewable energy has been discussed in detail by Brown et al. [53] concluding that from the time scale of seconds up to seasons, stable power systems are regularly enabled in well-designed 100 % renewable power systems. Recent research by Denholm et al. [54] clearly confirmed for the case of the US that no fundamental technical reason has been identified as to why a 100 % renewable power system could not be achieved. While issues of materials limitations are increasingly studied for 100 % renewable energy systems and investigated in high detail for the most exclusive materials in Junne et al. [55], concluding that substantially more comprehensive research has to be conducted and mitigation strategies to be explored. Most critical materials seem to be manageable, such as Cobalt and Lithium [56], whereas, Neodymium and Dysprosium can be substituted with new technical solutions [57]. However, continuous research efforts in improving the data availability and upgrading current information will help in addressing many of the uncertainties and a few others can be overcome with reasonable assumptions. Similarly, Proenca and Fortes [18] analysed empirically the relationship between renewable energy deployment and job creation, by employing econometric methods from panel data analysis. The research was focused on the EU and analysed the relationship between historical values of renewable power generation installed capacities and corresponding employment over the period 2000 to 2016. The results suggested a positive relationship between the two variables, showing an increase of 0.48 % in employment for each 1 % increase in renewable power generation capacity [18]. This can be substantiated with the findings of this research indicating that the final energy demand specific jobs nearly double from 563 jobs/TWh in 2020 to about 1000 jobs/TWh in 2050.

5. Conclusions

Jobs are critical in enabling well-functioning economies and, more importantly, in ensuring political and societal stability around the world. The disruptive impact of the COVID-19 crisis on workers, labour markets, and livelihoods has further underlined the importance of employment generation along with the global green economic recovery across countries. With respect to labour markets across the world, many regions are facing stagnating economies accompanied by high and rising unemployment rates, which is further exacerbated by the COVID-19 pandemic. Global unemployment levels and rates have been high in the last few years and are expected to remain high with more than 470 million people worldwide lack adequate access to paid work as such or are being denied the opportunity to work the desired number of hours [67]. Moreover, the risk of social unrest or discontent has heightened across many regions of the world with high unemployment rates. The ILO's social unrest index, which seeks to proxy the expressed discontent with the socioeconomic situation in countries, indicates that average global social unrest increased in the last few years [67]. Therefore, employment generation is a major policy priority, particularly for countries with high levels of unemployment and underemployment. This could either be a long-term issue or the immediate consequence of an economic recession as induced by the current COVID-19 pandemic. In this context, the renewable energy sector has weathered previous financial and economic crises successfully, as compared to many other industries and is also resilient in the current situation [27,68]. Moreover, it has become a relatively mature economic sector with steady technological progress, falling production costs and rising labour productivity. As the global transition towards sustainable energy continues, renewable energy labour force requirements are set to increase [5,29,44]. This is the first research estimating potential jobs created by heat storage technologies and the production of hydrogen and e-fuels in the context of a global energy transition until 2050, enabled by the hourly simulation capabilities of the LUT Energy System Transition model. The results emphasised in Fig. 5, affirm that renewable energy technologies have the potential to create a significant number of jobs in a global climate compliant energy transition scenario, contributing to around 74 % of the jobs created by 2050.

As the employment levels increase during the global energy transition, the employment structure of the energy sector may shift towards more highly qualified workers, particularly due to the relatively higher level of qualifications required to operate and manage renewable power generation and storage technologies [45]. This means that the energy transition will provide not only more jobs, but also better-qualified ones. Many job opportunities will be created along the different categories of the value chain, as the results presented in the earlier sections indicate. This poses a challenge with the increasing demand for personnel with diverse skill-sets and talents in the near future. Therefore, significant efforts in training and education will be needed to provide the labour market with necessary skills and reskilling of labour in certain cases. Finally, it appears that there is considerable growth potential for renewables and renewable employment creation in a variety of markets across the world, as shown in earlier sections. However, these markets have to be triggered by stable and sensibly designed policy instruments and investment strategies, such as long-term supporting schemes (e.g. feed-in tariffs or portfolio standards) and a global approach towards climate protection (e.g. carbon tax or cap and trade systems) in order to leverage existing opportunities from renewables [33,34]. Although this research has highlighted the net increase in employment, a reorganisation of a country's energy system could have far more significant benefits to the entire economy. This indicates that more integrated assessments of employment impacts are necessary as the penetration of renewable energy increases in future energy systems. But more importantly, this can be compatible with the ambitious goals of the Paris Agreement and the global community can benefit from declining GHG emissions and reduced local air pollution levels, while boosting economic growth with lower energy costs and higher job creation.

Authors contribution statement

Manish Ram: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft. Juan Carlos Osorio-Aravena: Methodology, Investigation, Data curation. Arman Aghahosseini: Investigation, Data curation. Dmitrii Bogdanov: Investigation, Software. Christian Breyer: Conceptualization,

Methodology, Investigation, Writing – review & editing, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121690.

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Pathway towards achieving 100% renewable electricity by 2050 for South Africa

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ABSTRACT

Transition to a cost effective and fossil carbon-free energy system is imminent for South Africa, so is the mitigation of issues associated with the 'water-energy nexus' and their consequent impacts on the climate. The country's key fossil carbon mitigation option lies in the energy sector, especially in shifting away from the coal-dependent power system. Pathways towards a fully decarbonised and least cost electricity system are investigated for South Africa. The energy transition is simulated for five scenarios, assessing the impact of various factors such as sector coupling, with and without greenhouse gas (GHG) emission costs. South Africa's energy transition is simulated using an hourly resolved model until 2050. This modelling approach synthesises and reflects in-depth insights of how the demand from the power sector can be met. The optimisation for each 5-year time period is carried out based on assumed costs and technological status until 2050. The modelling outcomes reveal that solar PV and wind energy, supplying about 71% and 28% of the demand respectively in the Best Policy Scenario for 2050, can overcome coal dependency of the power sector. The levelised cost of electricity increases just slightly from 49.2 €/MWh in 2015 to 50.8 €/MWh in the Best Policy Scenario, whereas it increases significantly to 104.9 €/MWh in the Current Policy Scenario by 2050. Further, without considering GHG emissions costs, the cost of electricity slightly increases from 44.1 €/MWh in 2015 to 47.1 €/MWh in the Best Policy Scenario and increases up to 62.8 €/MWh in the Current Policy Scenario by 2050. The cost of electricity is 25% lower in the Best Policy Scenario than in the Current Policy Scenario without factoring in GHG emissions costs and further declined to 50% with GHG emissions costs. The Best Policy Scenario without GHG emissions costs led to 96% renewables and the remaining 4% is supplied by coal and gas turbines, indicating pure market economics. The results indicate that a 100% renewable energy system is the least-cost, least-water intensive, least-GHG-emitting and most job-rich option for the South African energy system in the mid-term future. No new coal and nuclear power plants are installed in the least-cost pathway, and existing fossil fuel capacities are phased out based on their technical lifetime.

1. Introduction

South Africa is the fifth most populated country in Africa, with a population of 56.7 million in 2017 and an annual average population growth rate of 1.2%, occupying an area of 1.219 million km^2 (World Bank, 2017). The country's GDP is 349b€ with a growth rate of 1.3% in 2017 (World Bank, 2017). The electricity demand is expected to increase from 245 TWh in 2015 to 522 TWh in 2050, with an annual average growth rate of 2.3% (Wright et al., 2017). South Africa, like any other coal-abundant country, is susceptible to huge environmental crises, due to over-reliance on coal-generated electricity (Baker and Sovacool, 2017; Klausbrucker, 2016). Coal-fired power plants account for over 90% of electricity production in South Africa (Menyah and Wolde-Rufael, 2010). The country is listed amongst the world's most fossil carbon-intensive economies and is ranked as the 7th largest emitter of greenhouse gas (GHG) per capita (Alton et al., 2014). In Africa, South Africa remains the largest CO_2 emitter and accounts for 42% of the continent's emissions (Alton et al., 2014). South Africa commits, as defined in national policy, a peak, plateau and decline GHG emissions trajectory range, with emissions by 2025 and 2030 in a range of between 398 and 614 Mt_{CO2eq}, as per the 2015 intended nationally determined contribution (DEA, 2015). The country's main fossil carbon mitigation option lies in shifting away from its coal dependence in the power sector (DEA, 2015), which complies with the Paris Agreement on

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Nomenclature

A-CAES	adiabatic compressed air energy storage
BPS(s)	Best Policy Scenario(s)
CAPEX	capital expenditures
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CHP	combined heat and power
CPS(s)	Current Policy Scenario(s)
CSP	concentrating solar thermal power
DOE	Department of Energy
GT	gas turbine
GHG	greenhouse gas
HVDC	high voltage direct current
IRENA	International Renewable Energy Agency
IPPs	Independent Power Producers
IRP	Integrated Resource Plan
LCOC	levelised cost of curtailment
LCOE	levelised cost of electricity
LCOS	levelised cost of storage
LCOT	levelised cost of transmission
OCGT	open cycle gas turbine
OPEX	operational expenditures
PHES	pumped hydro energy storage
PV	Photovoltaic
RE	renewable energy
RoR	run-of-river
SNG	synthetic natural gas
ST	steam turbine
TES	thermal energy storage
VRE	variable renewable energy
WACC	weighted average cost of capital
ZAR	South Africa Rand

climate change (Delina and Sovacool, 2018). Transition towards renewable energy is highlighted in the Paris Agreement for mitigating climate change (Delina and Sovacool, 2018). Fig. 1 shows the total active installed capacities, by the end of 2014 in South Africa, and illustrates the almost complete reliance on fossil fuel (Farfan and Breyer, 2017). Additional background information on South Africa is available in the Supplementary Material (Section 1).

A brief summary of various studies on the trend of RE share in the South African energy system is presented in Table 1.

This article explores the paradigmatic and dynamic pathway to a fully decarbonised and least cost electricity solution for South Africa in the mid-term future. A 100% RE scenario for South Africa is simulated using an hourly resolved model, from 2015 to 2050, covering the power sector demand. Furthermore, the water-energy nexus is explored through analysing the water footprint of the different energy scenarios. In addition, another crucial aspect for South Africa is the creation of local employment, which is further analysed for the different energy scenarios in this research. The paper is structured as follows: the research methodology is described in Section 2. Results are presented and analysed in Section 3. In Section 4, the results are discussed and compared with related studies. Conclusions and policy implications are presented in Section 5.

2. Methods

2.1. Overview

The South African energy system was modelled with the LUT Energy System Transition Model described in (Bogdanov and Breyer, 2016; Breyer et al., 2018; Bogdanov et al., 2019). The energy system model is a linear optimisation tool developed to determine the optimal investment and generation technology mix required to meet the electricity demand in South Africa from 2015 until 2050. The main objective of this research is to understand the transition pathways to a fully RE-based power system for South Africa. The optimisation for each time period (5-year intervals) is carried out on the basis of assumed costs and technological status until 2050 for all energy technologies involved. The installed capacities of the different types of power plants from 1960 to 2015 is considered according to Farfan and Breyer (2017). Additionally, the water footprint analyses are based on Lohrmann et al. (2019) and employment creation is based on Ram et al. (2017a). After 2015, there are no additional capacities of fossil fuel resources allowed. The existing fossil power plants are phased out based on their lifetimes. However, gas turbines can be installed after 2015, due to their lower GHG emissions, higher efficiency, and the possibility to accommodate bio-methane and synthetic natural gas in the power system in a later

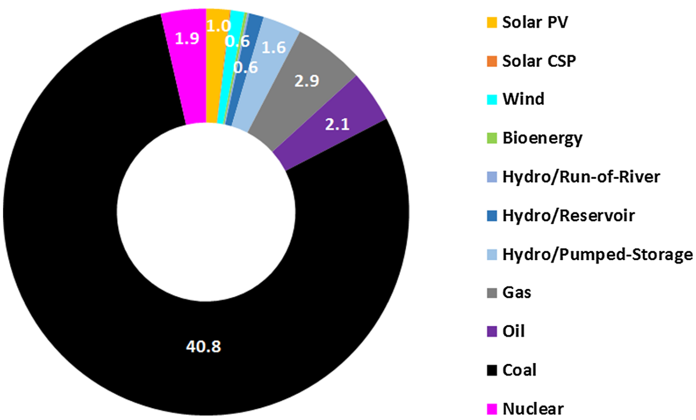

Fig. 1. Total installed active power capacities (in GW) by the end of 2014 in South Africa (Farfan and Breyer, 2017).

Table 1
Studies on trends of renewable energy shares in the South African energy system.

Reference	Findings
Greenpeace (2011)	The Advanced Energy [R]evolution scenario projects a renewable electricity share in the South African energy system of 49% by 2030 and 94% by 2050. The installed capacity of RE will reach 59 GW in 2030 and 114 GW in 2050. Solar PV, wind energy and CSP dominate the shares of installed capacity, contributing 40 GW, 27 GW and 35 GW respectively by 2050.
IEA (2015)	The South African power system is dominated by coal with 54.2 GW and 42.9 GW in the Baseline and Efficiency scenarios respectively, by 2030. RE installed capacity is 20.1 GW (23%) of 86.6 GW in the Baseline scenario, and 23.7 GW (31%) of 77.4 GW in the Efficiency scenario.
IEA (2014)	The New Policy Scenario assumes RE installed capacity of 35 GW and fossil power plants of 73 GW by 2040. Coal dominates the installed capacity with 53 GW (49%). Coal and nuclear contributes 243 TWh (61%) and 47 TWh (12%) respectively of the total electricity generation at 401 TWh by 2040.
IRENA (2013)	Under the Renewable Promotion Scenario, South Africa's RE installed capacity reached 37.5 GW (43%) and fossil is 50.2 GW (57%). Coal dominates the installed capacity with 41.5 GW (47%), followed by wind energy and solar PV with 17.3 GW (20%) and 13.9 GW (16%) respectively by 2030.
Wright et al. (2017)	The least cost ('Expected' costs) scenario achieves over 70% RE penetration by the year 2050, with a significant investment in solar PV and wind energy as expected, with gas turbines providing system flexibility and adequacy with hydropower and biomass. Storage and remaining coal capacity assist in system adequacy. By 2050, energy mix is dominated by solar PV with 140 GW and followed by wind with 73 GW. Solar PV and wind dominate in this scenario due to a further cost reduction assumed for PV and wind. The decarbonised scenario achieves over 90% RE penetration by 2050. Solar PV and wind energy dominate the total installed capacity, with 84 GW and 83 GW respectively by 2050. In addition, solar PV and wind energy are complemented by biomass (16 GW), CSP (13 GW), hydro (9 GW) and gas turbines (43 GW).
WWF Vision 2030 (2014)	RE capacity of 35 GW (37%) and 18 GW (24%) is projected for the high-demand and low-demand scenarios respectively, by 2030. While, renewable electricity generation is 78 TWh (19%) for the high-demand scenario and 39 TWh (11%) for the low-demand scenario.

phase. The RE capacity share increase cannot exceed 4% per year (3% per year from 2015 to 2020), in order to avoid disruptions.

2.2. Model overview

The power system used in this study was developed to match generation and power demand for every hour of the simulated year. The model is based on linear cost optimisation of energy system parameters under certain constraints. The model is compiled using MATLAB R2016a (MathWorks, 2016), while the optimisation is carried out in MOSEK version 8 (Mosek, 2017). The key target function of the model is to optimise the system, so that the total annual energy system cost is minimised. This cost is calculated as the addition of the annual costs of the installed capacities of each technology, operational expenditures, and costs of generation ramping. In addition, the energy system takes into account self-generation and consumption of electricity for residential, commercial and industrial end-users. Another mini-transition hourly model describes the PV prosumers systems and optional battery development capacity. The respective capacities of rooftop PV systems and optional batteries are installed by the prosumers. The target function for prosumers is the minimisation of cost of consumed electricity, calculated as the sum of self-generation, annual costs, and the cost of electricity consumed from the grid. Excess electricity is sold to the grid at 0.02 €/kWh by prosumers, when their own demand is satisfied, but not more than 50% of total self-generation. The prosumer demand is limited to 20% of the total demand. The prosumer constraints ensure that the 20% is not reached within the first time step. Thus, the model determines a step-wise progression from a maximum of 6% in the first

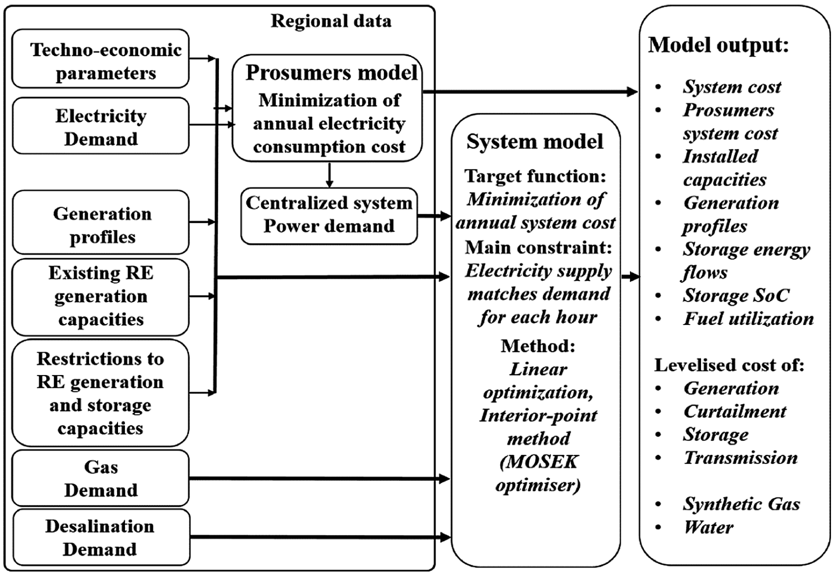

Fig. 2. Main inputs and outputs of the LUT Energy System Model (Bogdanov and Breyer, 2016).

time step to 9%, 15%, 18% and 20% in subsequent time steps if the economic model of prosumers indicates benefits of PV self-generation. PV self-consumption is considered as an exogenous input into the system optimisation. The energy system is optimised in addition to the prosumer capacities, which avoid any distortion of the overall system. The model overview is shown in Fig. 2. Detailed model description, equations and applied constraints can be found in (Bogdanov and Breyer, 2016; Breyer et al., 2018; Bogdanov et al., 2019).

South Africa was structured into 9 sub-regions based on the existing provincial structure, namely, Gauteng (ZA-GT), Mpumalanga (ZA-MP), KwaZulu-Natal (ZA-NL), North West (ZA-NW), Limpopo (ZA-LP), Western Cape (ZA-WC), Free State (ZA-FS), Eastern Cape (ZA-EC) and Northern Cape (ZA-NC). All the sub-regions are interconnected with transmission grids as shown in Fig. 3.

2.3. Applied technologies

The main technologies applied for the South African energy system modelling include electricity generation, storage, transmission and energy sector bridging technologies to provide more flexibility to the complete energy system. Fig. 4 shows the block diagram of the energy transition model.

2.4. Modelling assumptions

2.4.1. Financial and technical assumptions

The financial and technical assumptions for all energy system components are applied in 5-year time steps. This includes operational expenditures (OPEX), capital expenditures (CAPEX) and technical lifetimes from 2015 to 2050 for the applied technologies, as provided in the Supplementary Material (Table S1). The technical assumptions concerning storage technologies (efficiency and power to energy ratio), fuels, and transmission grids can be found in the Supplementary Material (Tables S2–S4).

The weighted average cost of capital (WACC) is set to 7% in this study. However, for residential PV prosumers WACC is set to 4% due to lower financial return requirements. The cost recovery is mostly considered for a wider aggregate range of investors, which includes a mix of debt and equity financing. On this basis, the commercial and industrial investors require higher returns on equity margins than private investors. Therefore, WACC is split into two categories in this study. The WACC variation does not substantially alter the cost of the energy system (Breyer et al., 2017). Additionally, the risk profile of nuclear and coal is much higher than RE, which should result in a higher WACC level for nuclear energy and coal compared to RE technologies (Ram et al., 2018), however, these higher risks are not taken into account in the research.

The electricity prices for residential, commercial and industrial consumers for the year 2015 were retrieved from (Eskom, 2015). The electricity price was calculated until 2050 according to Gerlach et al. (2014) and Breyer and Gerlach (2013). The electricity prices during the transition are calculated according to the assumptions from Gerlach et al. (2014) 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. The electricity prices for South Africa are provided in the Supplementary Material (Table S5). An average currency exchange rate for a period of 5 years from 2013 to 2018 was considered, at 16.67 €/ZAR (equal to 0.06 ZAR/€).

The upper limits for all RE technologies were estimated according to Bogdanov and Breyer (2016) and lower limits are obtained from Farfan and Breyer (2017). Upper and lower limits of RE and fossil fuels are provided in the Supplementary Material (Tables S6 and S7). For all other technologies, upper limits are not specified. However, for solid biomass residues, biogas, and waste-to-energy plants it is assumed, due to energy efficiency reasons, that the available and specified amount of the fuel is used during the year.

2.4.2. Resource potential for renewable technologies

The feed-in profiles for solar PV optimally tilted and single-axis tracking ground-mounted power plants, wind energy and CSP are calculated according to Bogdanov and Breyer (2016) and Afanasyeva et al. (2018), based on resource data of NASA (Stackhouse and Whitlock,

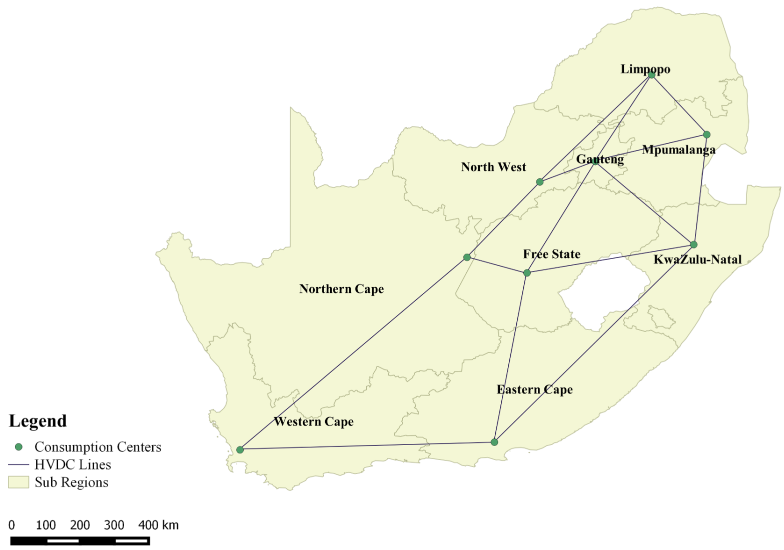

Fig. 3. South African sub-regions and transmission lines configuration.

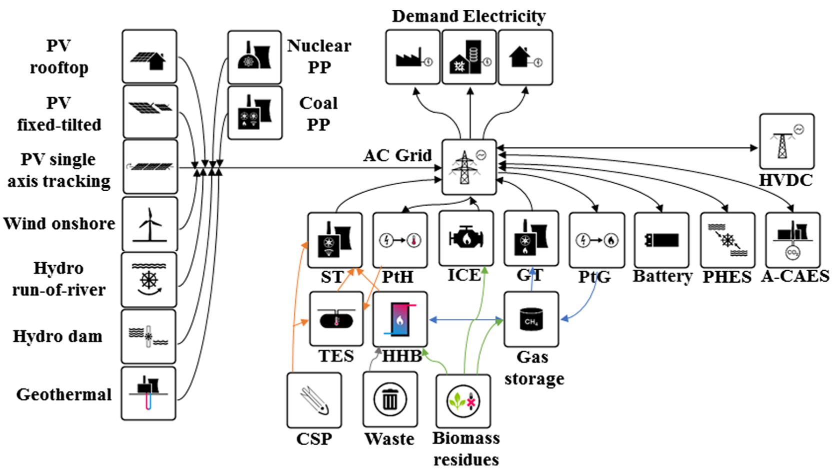

Fig. 4. Block diagram of the LUT Energy System Transition model used for South Africa (Breyer et al., 2018). Abbreviations not introduced elsewhere include PP-power plant, ST- steam turbines, PtH – power-to-heat, ICE – internal combustion engine, GT gas turbines, A-CAES – adiabatic compressed air storage, PtG – power-to-gas, PHES – pumped hydro energy storage, TES – thermal-energy-storage, HHB – hot heat burner, CSP – concentrated solar thermal power.

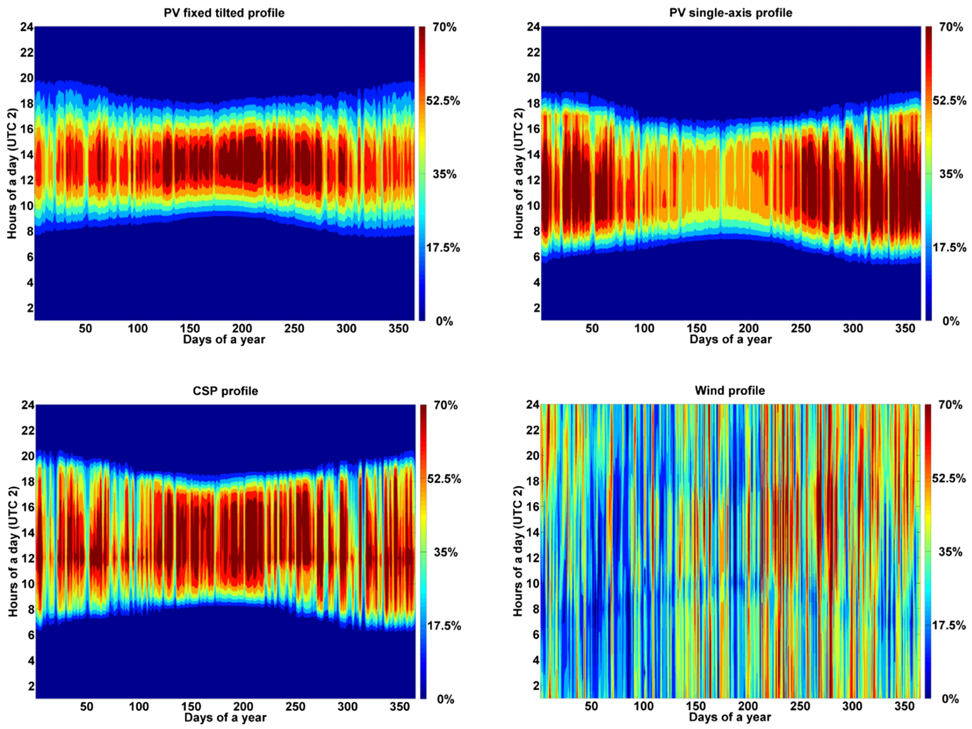

Fig. 5. Aggregated feed-in profiles for optimally tilted (top left) and single-axis tracking PV (top right), CSP solar field (bottom left), and wind power plants (bottom right) in South Africa.

2008; 2009), reprocessed by the German Aerospace Centre (Stetter, 2012). The obtained NASA dataset is in a temporal resolution of 3 h for the year 2005 and spatial resolution of 1° × 1°. An Enercon wind turbine (E-101) with a rated power of 3 MW and 150 m hub height is used to compute the wind feed-in profiles. The full load hours (FLH) feed-in profiles are calculated based on real weather conditions for the year 2005 on a 0.45° × 0.45° spatially and hourly temporally resolved data using a weighted average formula, this methodology is described in Bogdanov and Breyer (2016). It is assumed that 0–10% best areas are weighted by 0.3, 10–20% best areas are weighted by 0.3, 20–30% best areas are weighted by 0.2, 30–40% best areas are weighted by 0.1 and 40–50% best areas are weighted by 0.1%. The hydropower feed-in profiles are computed based on the monthly resolved precipitation data for the year 2005 as a normalised sum of precipitation in the regions. Such an estimate leads to a good approximation of the annual generation of hydropower plants (Verzano, 2009). Full load hours of various resources are presented in the Supplementary Material (Tables S11–S13 and Fig. S1) and visualised in an hourly resolution in Fig. 5. Fig. S1 shows the geographic diversity in wind and solar resources across the country.

The potentials for biomass and waste resources are taken from German Biomass Research Centre (DBFZ, 2010) and are classified according to Bogdanov and Breyer (2016). The costs for biomass are calculated using data from the International Energy Agency (IEA, 2012) and Intergovernmental Panel on Climate Change (IPCC, 2011). For solid waste, a 50 €/ton gate fee was assumed for 2015, which increased up to 100 €/ton in 2050.

2.4.3. Electricity demand

The hourly electricity load profile is calculated as a fraction of the total demand for each sub-region based on synthetic load data weighted by the sub-regions population (Toktarova et al., 2018). Fig. 6 shows the aggregated load curve and long-term electricity demand for South Africa. Electricity demand is taken from Wright et al. (2017). The population in South Africa is expected to grow from 54 million in 2015 to 66 million in 2050 (UN, 2015), while the average per capita electricity demand rises from 4.9 to 8.2 MWh as shown in Fig. 6 (right). The electricity demand until 2050 is provided in the Supplementary Material (Table S5).

2.4.4. Scenarios

In this study, five scenarios were studied for the South African energy transition analyses, which are briefly described in Table 2.

3. Results

3.1. Analysis of financial outcome of the transition for all scenarios

The average financial results for the studied scenarios are expressed as levelised cost of electricity (LCOE), levelised cost of electricity for primary generation (LCOE primary), levelised cost of curtailment (LCOC), levelised cost of storage (LCOS), levelised cost of transmission (LCOT), levelised cost of import (LCOI), fuel costs and CO_{2eq} emission costs, as shown in Fig. 7 from 2015 to 2050. The LCOE in the BPSs is observed as shown in Fig. 7 (a and b). The LCOE increase until 2025, due to decommissioning of fossil power plants and concurrent replacement with RE capacities. From 2025 onwards, the LCOE declines, as low-cost solar PV and wind energy dominate the system in the BPS. Whereas, the LCOE in the BPSnoCC increases until 2035 and gradually declines afterwards until 2050. By 2050, the LCOE obtained in the BPS is 50.8 €/MWh and 47.1 €/MWh in BPSnoCC, as shown in Fig. 7 (a and b). The contrary trend is observed in the CPS, as the LCOE increases throughout the transition. By 2050, the LCOE obtained in the CPS is 104.9 €/MWh as shown in Fig. 7c. Fuel and GHG emissions costs account for more than 50% of the LCOE in the CPS by 2050. Yet, the LCOE obtained in the CPS without GHG emissions costs (CPSnoCC) is 62.8 €/MWh as shown in Fig. 7d, which is still higher in comparison to the LCOE obtained in the BPSs by 24% in 2050. Additional results on costs for all scenarios are available in the Supplementary Material (Table S14 and Figs. S2–S4).

3.2. Analysis of required installed capacities and electricity generation mix during the transition

The system architecture changes gradually as the fossil generators leave the system and are replaced by RE technologies, particularly in the BPSs. Fig. 8 presents the installed capacities from 2015 until 2050 and absolute numbers are available in the Supplementary Material (Tables S8–S10) for all scenarios. By 2050, the total installed capacity is 321 GW, 295 GW and 134 GW in the BPS, BPSnoCC and CPS, respectively. In the BPSs, the solar PV and wind energy shares dominate the total installed capacity by 2050. The installed solar PV capacity is 241.7 GW, 233.4 GW and 15.8 GW in the BPS, BPSnoCC, and CPS respectively by 2050. While wind energy installed capacity is 51.2 GW, 36.8 GW and 30.4 GW in the BPS, BPSnoCC and CPS respectively by 2050. By 2050, the total installed capacity of thermal power plants is 26.6 GW, 23.8 GW and 81.3 GW in the BPS, BPSnoCC and CPS, respectively. The application of GHG emissions costs resulted in a fast and high penetration of RE installed capacities as observed in the BPS in comparison to BPSnoCC. The total capacity requirement in the BPSnoCC is low, due to the influence of thermal plants operating on high FLH. Key power

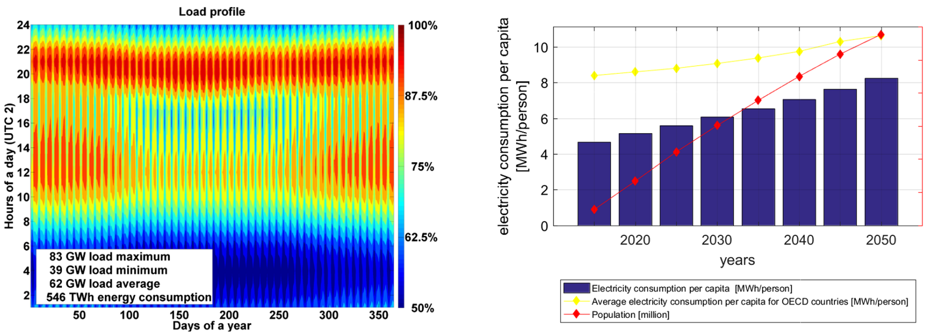

Fig. 6. Aggregated load curve for South Africa for 2050 (left) and long-term demand from 2015 to 2050 (right).

Table 2
Overview on scenarios.

Scenario name	Description
Best Policy Scenario (BPS)	This scenario targets 100% RE by 2050. In addition, GHG emissions costs are considered and only electricity demand is covered. The Best Policy Scenario naming is considered on basis of 100% RE, zero GHG emissions, most job-rich and least-water intensive characteristics.
Best Policy Scenario no GHG emissions costs applied (BPSnoCC)	In this scenario, no GHG emissions costs are assumed.
Current Policy Scenario (CPS)	In this scenario, respective installed capacities according to the Integrated Resource Plan (IRP) from now until 2050 were taken into account, in modelling the South African energy transition in the mid-term future (Wright et al., 2017).
Current Policy Scenario no GHG emissions costs (CPSnoCC)	In this scenario, no GHG emissions costs are assumed. Thus, only the financial implications of this scenario are discussed.

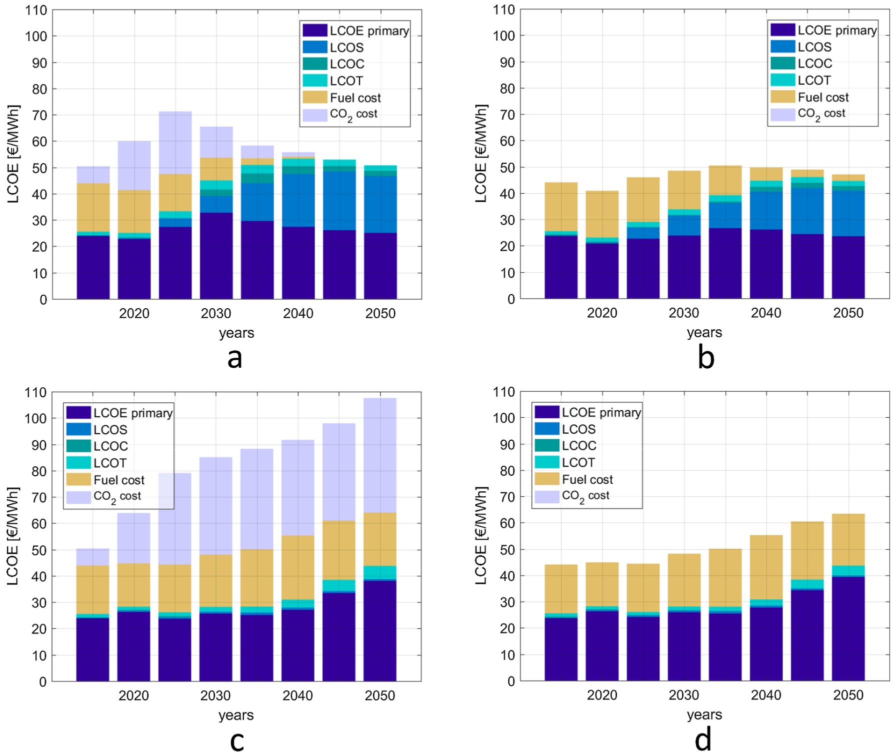

Fig. 7. Levelised cost of electricity for BPS (a), BPSnoCC (b), CPS (c), and CPSnoCC (d).

capacities required for the energy transition for South Africa are provided in the Supplementary Material (Tables S8–S10).

Fig. 9 depicts the electricity generation mix in all scenarios from 2015 to 2050. The coal-dependent power system can be substituted by a mix of solar PV and wind energy, complemented by hydropower and biomass as observed in BPS and BPSnoCC as shown in Fig. 9 (a and b). The results of this research indicate that from 2035 onwards, solar PV and wind energy can drive the deep decarbonisation of the South African power system in the BPSs. By 2050, solar PV and wind energy contributes 459 TWh and 181 TWh in the BPS as shown in Fig. 9a. Whereas, the solar PV and wind supply shares decrease to 441 TWh and 131 TWh respectively in the BPSnoCC as shown in Fig. 9b, due to the influence of fossil power plants operating on higher FLH until 2050. Nevertheless, in the BPSnoCC the share of RE generation reaches 95.6% by 2050, which implies a high cost competitiveness of RE technologies, particularly solar PV and wind energy. Wind energy contribution remains constant from 2030 onwards, which is a consequence of the continued cost decline of solar PV and battery storage, also observed for the case of Turkey (Kilickaplan et al., 2017). Fig. 9c shows the generation mix in the CPS. Coal, nuclear and wind energy dominate with 155 TWh, 152 TWh and 114 TWh of the total generation respectively by 2050. Coal-based electricity supply declines from 2030 onwards as the shares of RE capacities and gas turbines increase in the energy system, while nuclear energy contribution increases from 2040 onwards in the CPS. The share of electricity imports increases from 2030 onwards, as hydropower imports from Inga is considered according to the IRP

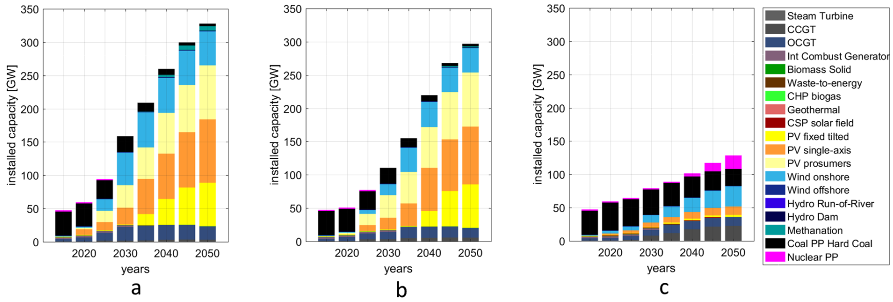

Fig. 8. Installed generation capacities for BPS (a), BPSnoCC (b) and CPS (c) from 2015 to 2050.

(Wright et al., 2017). Additional graphical results of electricity generation by technology for all scenarios are presented in the Supplementary Material (Fig. S5).

3.3. Assessments of system flexibility during the transition for all scenarios

The flexibility of the power system due to a high share of variable renewable energy (VRE) and dynamic load is analysed in this section. The power system flexibility is analysed in context of storage requirement and utilisation, grid integration and the role of gas turbines for deep decarbonisation of coal-dependent South African power system.

3.3.1. Analysis of storage utilisation and required capacities during the transition

Storage capacity requirement and utilisation are crucial in the BPSs due to high penetration of RE in these scenarios. By 2050, the cumulative installed storage capacity is 16.3 TWh, 2.5 TWh and 0.01 TWh in the BPS, BPSnoCC and CPS, respectively. Gas storage dominates the total storage capacity in the Best Policy Scenarios by 2050. By 2050, gas storage contributes 15.7 TWh in BPS, 1.9 TWh in BPSnoCC and 0.008 TWh in CPS as shown in Fig. 10. The high shares of gas storage in the BPSs are required to smoothen the synoptic and compensate the seasonal variation of RE resources. The shares of gas storage capacities increase from 2040 onwards in BPS, as the RE shares increase to about 80%. Gas storage includes the PtG technology, which allows production of SNG for the power system. The PtG option provides the system with the highest flexibility and integrates most of the excess electricity generated. The prosumer and utility-scale battery storage capacities increased from 2030 onwards in the BPSs. In the CPS, PHES provides the entire storage need for the year 2015 and contributes to the storage mix until 2050. TES dominates the storage mix from 2020 to 2045, due to CSP installed capacities. The heat generated through CSP and power-to-heat is stored in the TES. The gas storage capacity increases until 2030 and remains stable afterwards. The storage capacity in the CPS grows until 2035, and declines afterwards due to an increasing share of nuclear energy from 2040 onwards.

Fig. 11 shows the storage throughput during the transition and absolute numbers are presented in the Supplementary Material (Tables S15–S17). Battery storage dominates with respect to storage throughput during the transition in the BPS and BPSnoCC as shown in Fig. 11(a and b). Hybrid PV-battery systems evolve to a highly economic option for the energy system. The daily charge and discharge of batteries is needed due to high solar PV penetration in the system. Utility-scale and prosumer battery storage output shows huge relevance during the transition, while gas storage, TES and PHES complement depending on RE variability timescales in the system. Prosumer battery dominates in terms of output until 2030. In the CPS, PHES and TES dominate the system until 2030 as shown in Fig. 11c. Nevertheless, storage capacity requirement and utilisation in terms of throughput is low in the CPS, due to the dominance of thermal power plants. The storage requirement in terms of installed capacity and utilisation observed for all scenarios during the transition is found to be directly proportional to the level of RE penetration. More graphical results on the state of charge of storage technologies in all examined scenarios are available in Supplementary Material (Figs. S6–S10).

Battery discharge to PtG is observed in the BPSs. This phenomenon (Battery-to-PtG effect (Gulagi et al., 2018)) is observed nearly throughout the years. During the night and early hours of the day when demand is low, energy stored in batteries is discharged to electrolyser units to produce gas, which is stored for long term. By 2050, battery-to-PtG discharge is around 12 TWh in each of the Best Policy Scenarios as part of the least cost solution, representing 2% of the electricity demand in 2050. Batteries discharging to PtG is observed from 2035 onwards, when RE share is around 80% in the BPSs.

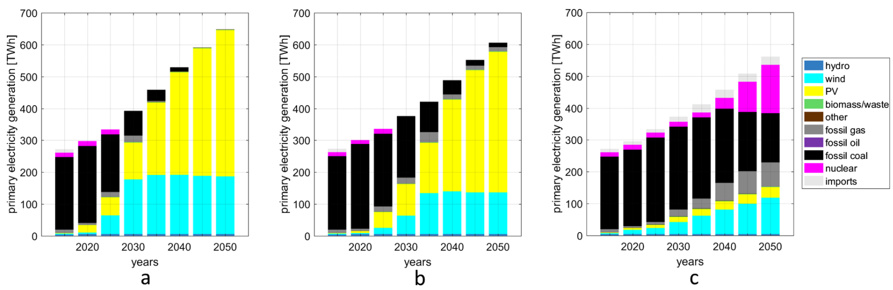

Fig. 9. Electricity generation mix for BPS (a), BPSnoCC (b) and CPS (c) from 2015 to 2050.

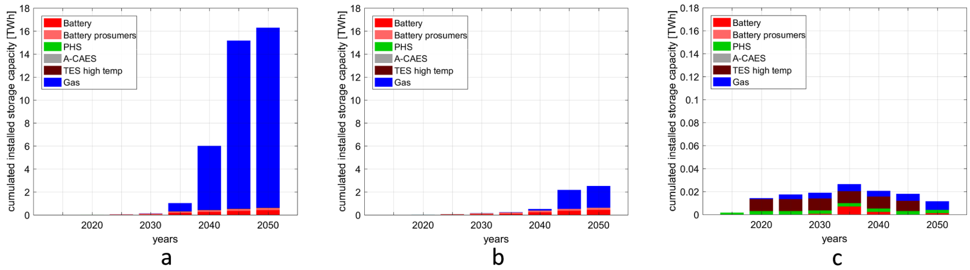

Fig. 10. Cumulative installed capacities of storage technologies for BPS (a), BPSnoCC (b) and CPS (c) from 2015 to 2050.

3.3.2. Assessment of transmission grid utilisation during the transition

The level of grid utilisation varies from time to time in BPS and BPSnoCC, while it is constant in the CPS as shown in Fig. 12. Grid utilisation in the BPS and BPSnoCC occurs mostly in the summer and spring periods, and reduces in autumn and winter times as shown in Fig. 12 (a and b). The summer and spring periods, are the best seasons for solar and wind resource availability. During the autumn and winter periods, gas storage compensates the seasonal variation of RE resources. In the CPS, thermal power plants are site specific and require maximum grid utilisation in shifting energy across the country. The grid utilisation is intense during the daytime working hours and at night, but low in the early morning hours in the CPS. The net grid export between sub-regions ranges from 167 TWh to 197 TWh in the BPSs and 242 TWh in the CPS by 2050. This implies that sub-regions are more independent in producing their own electricity in the BPSs than in the CPS. In the BPS, it is observed that sub-regions with best RE resources are net exporters and others are net importers. The Northern Cape province is the main exporting region due to excellent RE resources and low demand. Fig. 13 shows the direction and amount of electricity transmitted across the country. The thickness of the flow indicates the amount of electricity transferred between the regions in TWh. North Cape becomes the main exporting region by 2050 in a fully RE system in comparison to the current situation in which Mpumalanga province supplies almost the entire country's electricity demand due to huge power plants located in the province.

3.3.3. Analysis of gas technology relevance during the transition in the Best Policy Scenarios

The gas turbines usage is observed during low RE resource availability, particularly in the winter period. By 2050, the capacity of gas turbines is 23 GW each in BPS and 20 GW in BPSnoCC. The average FLH of gas turbines decline from about 2600 h in 2015 to 700 h in BPS and to 800 h in BPSnoCC by 2050. In addition, gas turbines are a relevant peaking technology because they are economically and technically more rampable to produce high amounts of power when required. By 2050, gas turbines generate approximately 16 TWh in the BPS and 17 TWh in BPSnoCC. Gas turbines are comprised by about 87% OCGT and 13% CCGT in the BPS as the least cost mix, with 482 FLH for OCGT and 2146 FLH for CCGT.

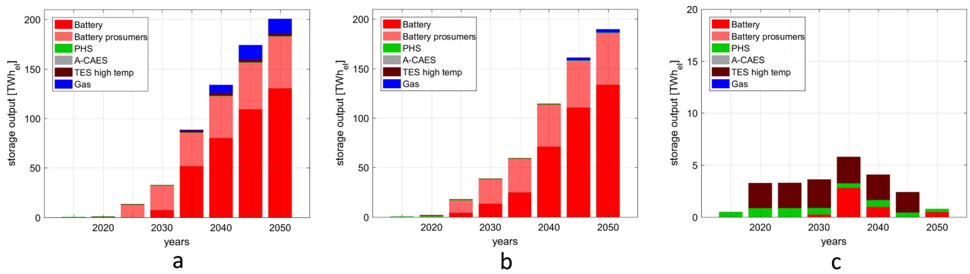

Fig. 11. Cumulative storage output for BPS (a), BPSnoCC (b) and CPS (c) from 2015 to 2050.

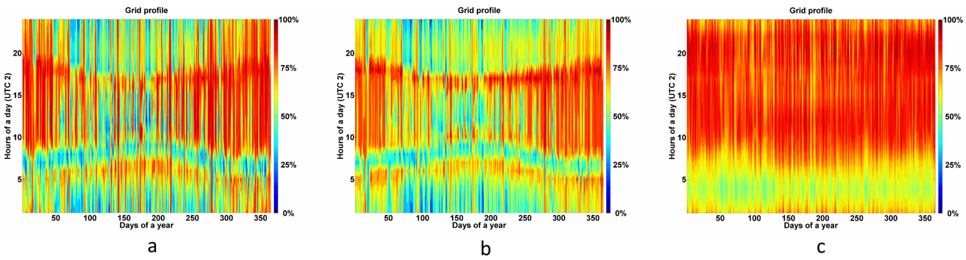

Fig. 12. Grid profile for BPS (a), BPSnoCC (b) and CPS (c) for 2050. (Grid profile is the hourly distribution of electricity demand over the entire year).

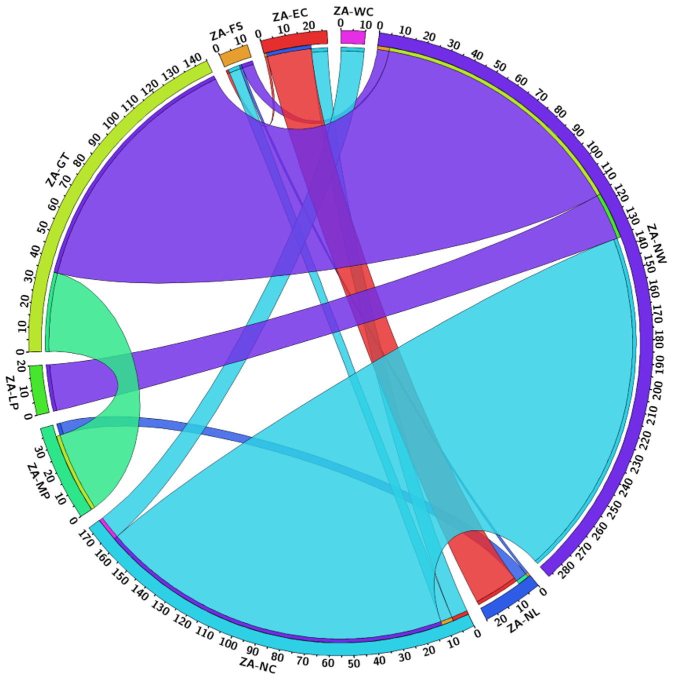

Fig. 13. Electricity transmission between the sub-regions for 2050 in the BPS.

3.4. Analysis of sub-region optimised fully renewable system structure by 2050

This section presents the sub-regional installed capacity projection for a fully RE system in 2050 as shown in Fig. 14. Solar PV dominates the share of total installed capacities, particularly solar PV single-axis tracking followed by PV prosumers. Solar PV single-axis tracking installed capacity is 95 GW in BPS, representing 39.4% of total solar PV capacity. While the installed capacity of PV prosumers is 81 GW in each of the scenarios. Solar PV installations are observed in all sub-regions due to even distribution of solar resources across the country. However, the highest share of installed solar PV capacity is found in the Northern Cape sub-region, due to excellent solar resource in this province. Solar PV emerges as the least cost option to meet electricity demand by 2050. Nevertheless, there are excellent wind sites in South Africa, particularly the Eastern Cape, Western Cape and Northern Cape. Beside solar PV, wind energy plays an important role in the transition. The total wind capacity is approximately 51 GW in BPS. Solar PV and wind energy drive most of the system in South Africa by 2050. Additional graphical results on sub-regional electricity generation, installed capacity, regional storage capacities and regional storage annual throughput in 2050 can be found in the Supplementary Material (Figs. S11–S14).

3.5. Analysis of GHG emissions under various transition scenarios

The GHG emissions trajectory during the transition for all scenarios is illustrated in Fig. 15. The red curve shows the ratio of CO_2 emitted per kWh of electricity. The emissions trend in the BPSs is visualised as shown in Fig. 15 (a and b). The emissions trend in BPS and BPSnoCC shows a similar pattern, as GHG emissions plateau by 2020 and decline afterwards in both scenarios. From 2025 onwards, emissions decrease substantially as coal-fired plants are replaced by RE capacities, mainly solar PV and wind energy in the BPSs. By 2050, a zero emissions system is achieved in the BPS. Deep decarbonisation of 75% to 71 Mt_{CO2eq} in 2030 and 98% to 10.2 Mt_{CO2eq} in 2040 as shown in Fig. 15a for BPS. The BPSnoCC shows a slower reduction in GHG emissions and zero emissions is not reached by 2050. However, deep decarbonisation of 70% to 89 Mt_{CO2eq} in 2035 and 96% to 16 Mt_{CO2eq} is still achieved for the BPSnoCC in 2050, as shown in Fig. 15b. The GHG emissions trend in the CPS is visualised in Fig. 15c. The annual GHG emissions reach its peak in 2030 and gradual decline afterwards as coal contribution in terms of capacity and generation declines in the system. In the CPS, GHG emissions decline from 214 Mt_{CO2eq} in 2030 to 151 Mt_{CO2eq} in 2050.

3.6. Water demand by power plants and job creation during the transition

3.6.1. Water demand of thermal power plants

Water withdrawal and water consumption of thermal power plants were calculated based on the water use intensity factors provided by Macknick et al. (2012) and using the methodology of Lohrmann et al. (2019). For the analysis, the subset of thermal power plants exceeding 50 MW was selected. This corresponds to 47.6 GW and accounts for 0.85% of the total thermal power generation capacity of South Africa. Fig. 16 depicts the exact location of the active thermal power plants presented for the analysis.

In 2015, total water consumption (combined freshwater and saline water) for thermal generation was 0.346 km^3, whereas total water withdrawal was 2.72 km^3. From the perspective of freshwater extractions, 0.331 km^3 of freshwater was consumed (96% of the total water

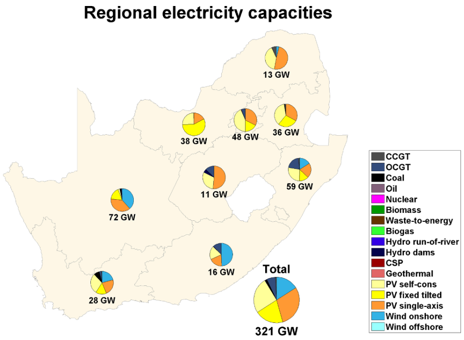

Fig. 14. Installed generation capacities for BPS across the nine sub-regions of South Africa for 2050.

consumption) and 0.399 km^3 of freshwater was withdrawn (15% of the total water withdrawals). Currently, coal-based power plants account for 100% of the freshwater consumed. The 'leader' among regions in freshwater extractions is the Mpumalanga province constituting for 83% of all freshwater extractions for the power sector of South Africa.

The development of freshwater demand for both scenarios is illustrated in Fig. 17. According to the BPS, both freshwater withdrawal and consumption are estimated to be reduced 87% by the year 2030, and 99% by 2050, respectively, compared to the 2015 level. In 2050, gas-fired power plants consume 0.0001 km^3 of freshwater, which is expected to constitute for 100% of the countrýs annual freshwater consumption related to the power sector. Opposed to that, the projections of the CPS show a decline of only 38% in freshwater extractions by 2050. In 2050, thermal power plants consume 0.196 km^3 of freshwater, of which 99.7% is allocated for cooling of newly commissioned coal power plants. More information on the current water demand of thermal power plants and its' projected development during 2015–2050 is available in Supplementary Material (Tables S18–S21 and Figs. S15–S18).

3.6.2. Job creation for the Current Policy Scenario and Best Policy Scenario

The annualised direct jobs created in the power sector during the energy transition for the BPS, as well as the CPS were estimated based on the methodology presented by Ram et al. (2017a, 2019) and the assumed employment generation factors can be found in the Supplementary Material (Table S22). Solar PV is observed to be the prime job creator through the transition period, with 67% of the total jobs created by 2050, in the case of BPS as depicted in Fig. 17. Whereas, coal-based power generation creates the most jobs in the CPS, with 45% of the jobs by 2050 as indicated in Fig. 18. Overall, number of direct energy jobs created in the BPS are seen to grow massively from around 210 thousand in 2015 to nearly 408 thousand by 2035, with the massive capacity additions propelled by higher growth rates. Beyond 2035, as growth rates stabilise, jobs created are observed to steadily reduce to over 278 thousand by 2050. On the other hand, jobs created in the CPS remain quite stable with a marginal decrease to around 184 thousand by 2050.

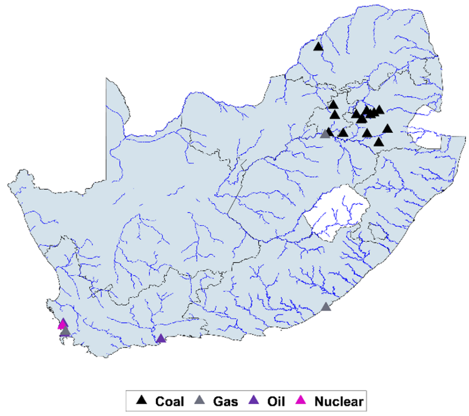

Fig. 16. Active thermal power plants exceeding 50 MW, per fuel type.

Figs. 18 and 19 also indicate the distribution of jobs across the different categories during the transition period in the BPS as well as CPS. In the case of BPS, with ramp up of installations up to 2035, bulk of the jobs are created in the construction and installation of power generation technologies. The electricity demand specific jobs in the BPS increases substantially from 787 jobs/TWh_{el} in 2015 to 1148 jobs/TWh_{el} in 2025 with the rapid ramp up in RE installations. Beyond 2025, it stabilises around 1000 jobs/TWh_{el} and then declines steadily to around 511 jobs/TWh_{el} by 2050, as shown in Fig. 17. Whereas, the electricity demand specific jobs in the case of CPS decline continually from 2020 onwards to 338 jobs/TWh_{el} by 2050, as indicated in Fig. 19. The International Renewable Energy Agency (IRENA) estimated that the RE sector employed nearly 10 million people worldwide in 2016, with 62,000 jobs in Africa. Nearly half of these jobs are in South Africa and a quarter in North Africa (IRENA, 2017).

4. Discussion

Results of this research indicate that transition towards 100% RE-based system is achievable for South Africa. A 100% renewable based electricity is found to be the least cost option, consuming less water and creating more jobs than the current power system, which is mainly

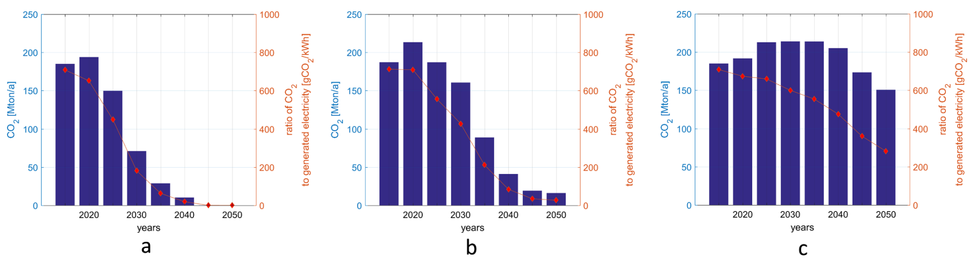

Fig. 15. The total annual GHG emissions and ratio of GHG emissions to electricity generation during the transition for BPS (a), BPSnoCC (b) and CPS (c).

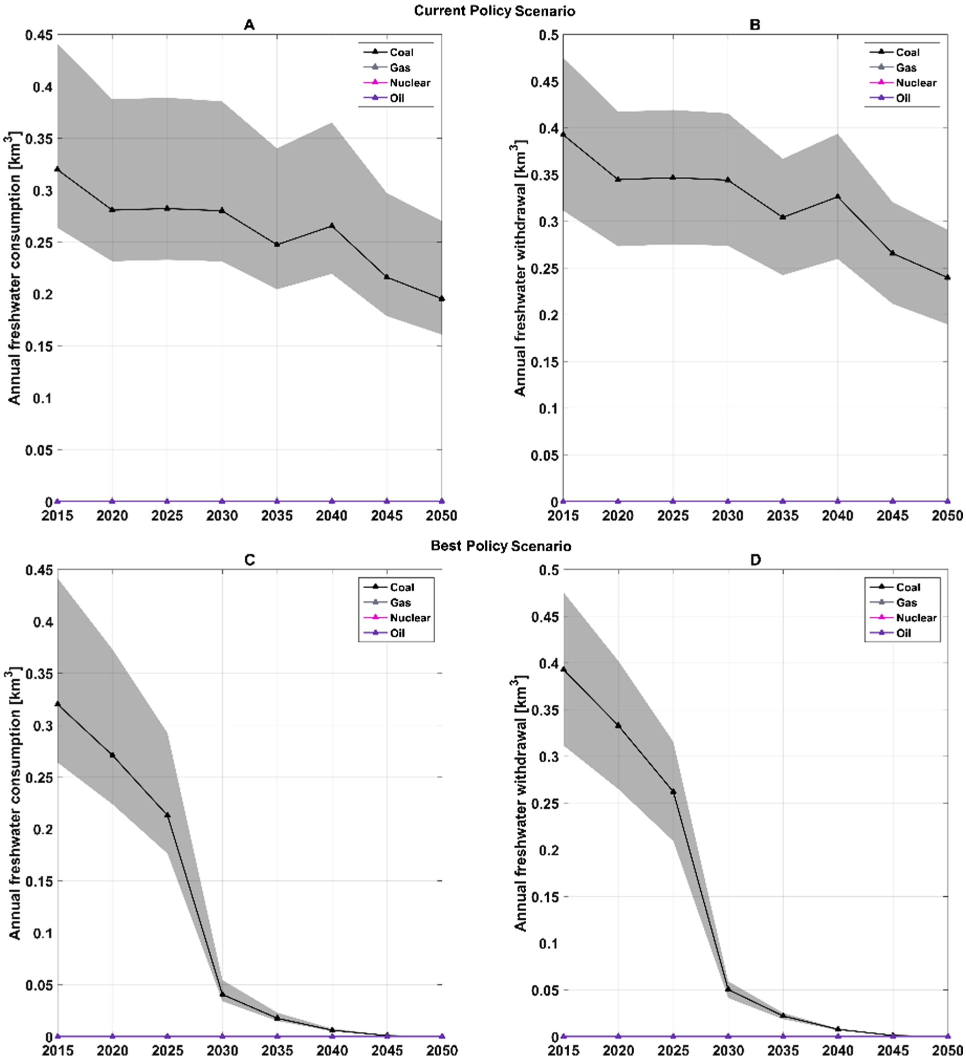

Fig. 17. Development of freshwater consumption and freshwater withdrawal (median values and min-max interval): the CPS (a and b) and the BPS (c and d).

driven by coal-fired power plants. An addition scenario is presented in the Supplementary Material, which describes the integration of the desalination sector to the power sector (BPS-DES). Additional information on the electricity generation profile and energy flow diagrams are provided in the Supplementary Material (Figs. S19–S24).

4.1. Analysis of key differences in Best Policy Scenarios and Current Policy Scenarios in 2050

This section compares the BPSs and the CPSs. Table 3 highlights the key differences in financial outcomes and selected electricity parameter for 2050. This research demonstrates that a fully decarbonised power system is the more cost optimal solution for South Africa by 2050. It reduces GHG emissions by 100% compared to the CPS. The total annualised cost of system in the CPS is 50% higher than in the BPS as show in Fig. 20. Whereas, the total annualised cost of system obtained for 2050 in the CPSnoCC is 20% higher than in BPSnoCC as show in Fig. 20. The total annualised cost of system required in CPSnoCC and BPSnoCC are relatively close until 2035, afterwards a disparity occurs as new investments in nuclear power plants are incurred in the CPSnoCC. Regarding capacity requirements, the BPSs are approximately 59% higher than required in the CPS. This is due to lower FLH of

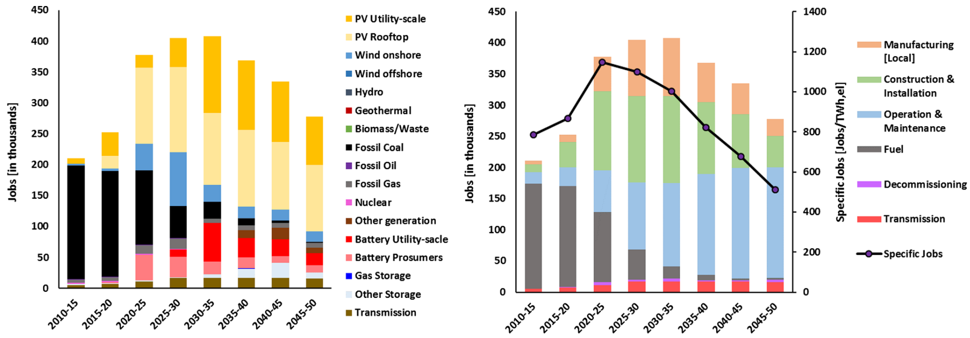

Fig. 18. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in South Africa for the BPS.

RE technologies, particularly solar PV and wind energy that dominate the power system in the BPS. While, the total generation in the BPSs are higher than the CPS by 16%, approximately. Results for the fully renewable end-point scenarios indicate that there is no need for high cost and high risk nuclear energy in the future South African electricity mix.

The LCOE obtained for the BPSs is comparable to Breyer et al. (2018), which shows a global range of 50–70 €/MWh. The annualised cost of system obtained for the year 2050 is 27.5b€, 25.5b€, 55.8b€ and 32.9b€ in the BPS, BPSnoCC, CPS and CPSnoCC, respectively. The financial outcomes of this research show that RE-based systems are economically feasible in South Africa. Most of the cost reduction can be attributed to low cost of solar PV, batteries and wind energy. In addition, RE has no fuel costs, which compensate for the entire system investments in the BPSs. Whereas, investments in fossil power plants in the CPSs might become a burden on the country's economy, as newly built coal or nuclear plants are likely to become stranded assets due to high relative cost, not only for the investment cost, but also the operation cost. In addition, the profitability of fossil fuel based technologies will be undercut by the increasing competitiveness of RE technologies (IEEFA, 2016). The 100% RE-based option for South Africa presented in this study is more cost competitive than the other alternative scenarios, which still have further disadvantages. South Africa is committed to reducing its GHG emissions, in pursuit of this goal, carbon capture and storage (CCS) is considered as part of its climate change mitigation strategy (Beck et al., 2013; Surridge et al., 2009). Energy system options, such as nuclear and fossil-CCS are not cost competitive (Breyer et al., 2018). According to Ram et al. (2017b; 2018), coal-CCS CAPEX are around 3891 €/kW in 2030, while the LCOE is around 105 €/MWh. For gas-CCS, the CAPEX ranges from 1934 €/kW to 2118 €/kW in 2030, the respective LCOE ranges from 94 €/MWh to 130 €/MWh. The LCOE assumed for new technologies in South Africa, shows that the tariffs in the year 2015 for solar PV and wind energy are 38% and 40% lower than LCOE for new baseload coal and nuclear (Wright et al., 2017). Furthermore, based on South Africa's decommission plan, another BPS scenario was simulated with coal and nuclear power plant decommissioning schedule set to 50 and 60 years, respectively. The result shows that by extending the coal and nuclear decommissioning schedule the power system will incur additional cost from 2030 onwards, until around 2045, in the range of 0.02–1.01b€/a (0.1–3.9% of total annualised system cost).

The high costs observed in the CPS, is due to new investments in thermal power plants, in particular nuclear power plants from 2040 onwards. In fact, the relative cost difference may be higher in the CPS than the BPS, if capex assumptions for coal are considered according to IRP 2018 (DOE, 2018). Representatives from South Africa's largest utility mentioned, in early 2018, that nuclear would not be at the top of the agenda and South Africa simply could not afford nuclear (EWN, 2018). In addition, nuclear projects are susceptible to huge cost overruns (Sovacool et al., 2014). Moreover, new investment in coal power plants in South Africa should be carefully considered, as recently added coal-based power plants have already become stranded assets in several countries (Ram et al., 2017b; Farfan and Breyer, 2017; IEEFA, 2016).

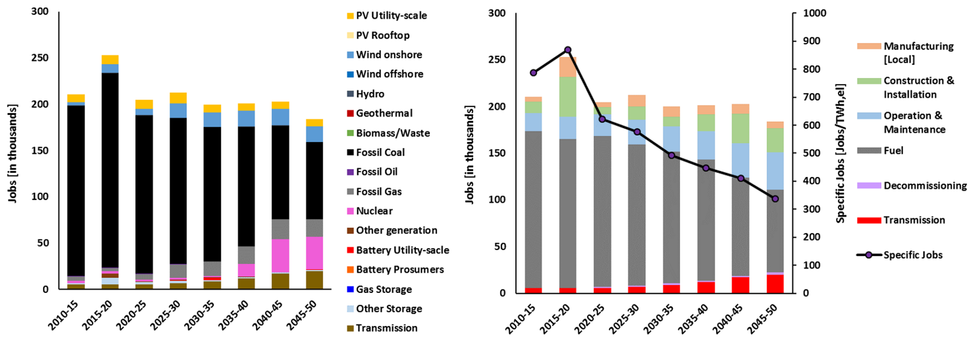

Fig. 19. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in South Africa for the CPS.

Table 3
Difference in electricity parameters and financial outcomes in 2050 for all scenarios.

		unit	BPS	BPSnoCC	CPS	CPSnoCC
Financial outcome	Total annualised cost of system	[b€]	27.5	25.5	55.8	32.9
	Levelised cost of electricity	[€/MWh_{el}]	50.8	47.1	104.9	62.8
Electricity parameters	Demand	[$TWh_{,el}$]	539.8	539.8	539.8	539.8
	Generation	[$TWh_{,el}$]	648.1	606.2	561.1	561.1
	Installed capacity	[GW]	321.1	294.6	133.5	133.5

The results of the BPSs show that no new coal and nuclear will be required in the least-cost expansion. Furthermore, nuclear energy violates all sustainability criteria that should form a framework for a resilient energy system design (Child et al., 2018).

4.2. Role of RE and storage technologies

The power system optimisation shows solar PV followed by wind energy drive the energy system in the BPS and BPSnoCC. The outstanding role of PV technologies needs to be highlighted in RE dominated scenarios for the case of South Africa. It is least-cost to supply 71–73% of electricity demand from solar PV alone. PV prosumers contribute 22% to the total electricity generation in 2050. Based on living standards measure 7 (LSM7) households and 5 kW household installations, embedded generation residential and commercial PV in South Africa could reach 22.5 GW by 2030 (Tuson, 2014). There are already developed regulations to guide the implementation of small-scale solar PV embedded generation in South Africa (Tuson, 2014). In addition, South Africa is recognised to have a huge solar potential, which is largely untapped. Barasa et al. (2018) reported on the impact of PV prosumers on a 100% RE system for Sub-Saharan Africa for 2030 cost assumptions and concluded that the total system cost increase slightly by 3.4–3.6%, while the electricity costs of the PV prosumers go down, whereas the peak load is reduced by 5.2%, which may lead to cost reductions beyond the scope of that study. PV prosumers installed capacity increases during the transition as the retail electricity prices increase. The growth is propelled by continuous decline in PV battery capex anticipated during the transition. The PV prosumers appear to be an important enabler of the transition. A study estimates the utility-scale solar PV projects to be equivalent to 220 GW using existing environmental impact assessment, while a conservative estimation for rooftop solar PV showed a potential capacity of 72 GW (Knorr et al., 2016). Both the rooftop and utility-scale solar PV showed a conservative potential of about 292 GW. The plausible reason for a high solar PV penetration is due to excellent resource conditions, low seasonal variation unlike other countries where solar PV supply drops in winter months and continuous cost decline of PV (Bischof-Niemz and Creamer, 2018; Breyer et al., 2018). Wind energy is expected to supply 22–28% to the total generation in 2050. However, wind energy contribution remains constant from 2030 onwards, due to further costs decline of solar PV and battery storage. In addition, if the wind capex would decline faster, a higher share of wind power generation could be expected. South Africa has the solar, wind and land resources to technically host a power system led by a mix of RE technologies (Bischof-Niemz and Creamer, 2018). The specific capacity density limited in the LUT Energy System Transition model is 75 MW/km^2 for optimally tilted PV and 8.4 MW/km^2 for onshore wind (Bogdanov and Breyer, 2016). Hence, an area of 3260 and 6180 km^2 is needed for solar PV and wind capacities in 2050 representing just 0.3% and 0.5% of the total land area of South Africa. The results of this study show that solar PV and wind energy will emerge as the backbone of a fully RE-based power system in South Africa, which is comparable to the findings of Barasa et al. (2018) for entire Sub-Saharan Africa (SSA) based on an overnight scenario approach for 2030. They conclude that SSA countries can be powered mainly by solar PV and wind energy. The Greenpeace Advance Energy [R]evolution scenario (Greenpeace, 2011), projects higher annual RE growth rates, thus achieving a renewable electricity share of 94% and RE installed capacity of 114 GW by 2050. According to Greenpeace (2011), solar PV dominates the installed capacity with 40 GW (35%), followed by CSP with 35 GW (31%), and wind energy with 27 GW (24%) by 2050. However, in the generation mix CSP dominates with 259 TWh (54%), complemented by solar PV with 79 TWh (16%) and wind energy with 68 TWh (14%) (Greenpeace, 2011). The Council of Scientific and Industrial Research (CSIR) demonstrates that solar PV, wind and flexible power generators are the cheapest energy mix for South African power system (Wright et al., 2017). The study demonstrates a least cost option for the South African power system with over 70% of RE penetration by 2050, which uses less water and provides a higher number of job opportunities (Wright et al., 2017). According to Wright et al. (2017), solar PV and wind energy dominate the total

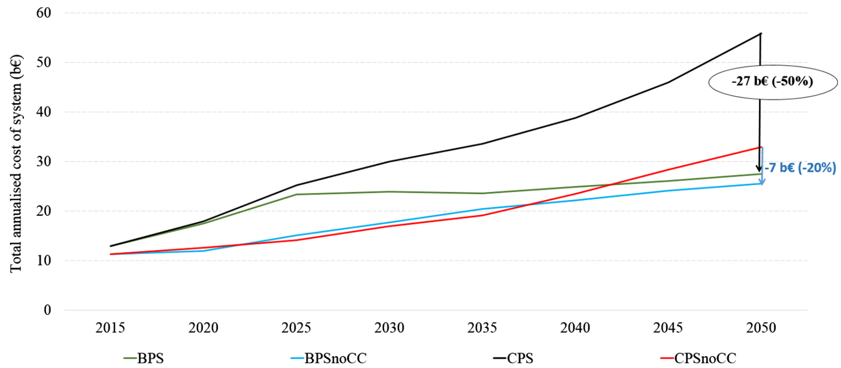

Fig. 20. Comparison of total annualised cost of system for all scenarios in 2050.

installed capacity with 140 GW (45%) and 73 GW (23%), while electricity supplied by solar PV is 213 TWh (36%) and wind is 223 TWh (38%), whereas no CSP generation is expected. The results of the BPSs in this study are comparable to the findings of Wright et al. (2017, 2019). In the CPS, fossil power plants dominate the power system accounting for 72% (383 TWh) of the total electricity generation in 2050. Among the RE technologies, wind energy emerges as a relevant resource in the CPS by 2050, which contributes 114 TWh (21%) of the total electricity generation by 2050. Upon the completion of Inga 3, 2.5 GW of the capacity is expected to be supplied by hydropower transmitted to South Africa. Electricity imports increase from 2030 onwards, in the CPS due to imports from Inga 3. The major risks associated with relying on hydropower imports are delays in the construction of the necessary grid extension as well as the hydropower plant (DOE, 2018). Oyewo et al. (2018) conclude that South Africa and other neighbouring countries can benefit from the Inga hydropower development. While the host country may bear most of the economic burden, not to mention the environmental risks. Results of the BPSs indicate that South Africa could independently meet its electricity demand without any electricity imports.

The results of this research reveal the significant role of PtG for handling high shares of RE, as discussed in (Gulagi et al., 2018; Ram et al., 2017a; Pleßmann et al., 2014; De Boer et al., 2014). The significance of battery storage is noticed from 2025 onwards, particularly in the BPSs. Regarding storage outputs, battery storage dominates due to daily requirements. By 2050, battery total output is 183 TWh (92% of total storage output) and 186 TWh (92%) in BPS and BPSnoCC, respectively. The role of prosumers and utility-scale batteries increased significantly from 2030 onwards. PV-battery hybrid systems emerge as the least cost option in a fully optimised RE system. Further cost reduction of batteries is expected (Schmidt et al., 2017; Kittner et al., 2017), which will increase PV growth (Breyer et al., 2018). Storage requirement is low in the CPS due to the dominance of thermal power plants that run on high FLH. Grid utilisation is very high in the beginning and towards the end of the year, particularly due to balancing demand in power deficit sub-regions in the BPSs. In the CPS, power plants are site specific and transmission grids are frequently utilised to supply electricity across the country. This clearly indicates the advantage of a distributed power system observed in the BPSs, as each region could produce its own electricity and import only when needed. The role of dispatchable gas technology is observed in the BPSs, as it is required to maintain balance between demand and supply in the power system. The role of gas turbines in a fully RE system is discussed in (Greenpeace, 2011). According to Greenpeace (2011), gas turbines installed capacity is 10 GW and generation is 16 TWh. Similarly in the CPS, gas technologies respond in times of high demand. A recent study on energy transition in South Africa concludes that a power grid with high RE penetration, in particular solar PV and wind energy requires flexibility that could be provided by using flexible natural gas fired turbines, if the costs of battery do not decrease (Klein et al., 2018).

4.3. Benefits of 100% RE

Examining the application of a GHG emissions cost during the transition, especially in the BPSs results in a rapid transition and fast GHG emissions reduction in comparison to no GHG emissions cost scenarios. However, the no GHG emissions cost scenarios achieved comparable results in terms of capacity, generation, cost of electricity and GHG emissions trajectory to the BPSs. By 2050, the RE electricity generation reaches 95.6% (579 TWh) in the no GHG emissions cost scenario, while the remaining 4.4% (26.9 TWh) is supplied by coal and gas turbines. The BPSnoCC is about 17% lower in total costs than the BPS, but 7% lower in costs than the CPSnoCC and 42% lower in total GHG emissions for the period 2015 to 2050. This indicates that the South African energy transition is achievable without GHG emissions cost implementation, if least cost options are chosen.

This study presents a pathway to a fossil carbon-free economy for South Africa on an hourly basis in 5-year intervals, which makes this study unique and a first of its kind. From an energy security perspective (Azzuni and Breyer, 2018), analysis of this research reveals that South Africa could achieve a secure power supply without imports. RE development in the country will foster socio-economic development, the results show that the BPS could boost employment prospects in South Africa. The direct energy jobs created in the BPS are seen to grow massively from around 210 thousand in 2015 to nearly 408 thousand by 2035, with the massive capacity additions propelled by higher growth rates. Beyond 2035, as growth rates stabilise jobs created are observed to steadily reduce to over 278 thousand by 2050. Whereas, jobs created in the CPS remain quite stable with a marginal decrease to around 184 thousand by 2050.

The findings of this research align with the perspectives of a recent review on the feasibility of 100% RE systems (Brown et al., 2018). Results of this research clearly show that a fully decarbonised South African power system can be achieved between 2040 and 2050. Deep decarbonisation of South Africa's energy system is technically and economically feasible by 2050. Owing to the low-cost electricity driven by solar PV and wind, South Africa can progressively pursue an electrification-of-almost-everything strategy by coupling the low-cost renewables-led electricity generation to the transport and heat sectors (Bischof-Niemz and Creamer, 2018). This research presents a detailed transition pathway towards a least cost and fully decarbonised power system by 2050, which complies with the Paris Agreement target of limiting temperature rise to 1.5 – 2 °C compared to the pre-industrial age.

5. Conclusion

The modelling outcomes reveal that a fully RE-based system is cost competitive and reliable as observed in the BPSs in comparison to the CPSs. The total system LCOE obtained in the BPSs ranged from 47.1 €/MWh to 50.8 €/MWh and from 62.8 €/MWh to 104.9 €/MWh in the CPSs by 2050. Much of the cost savings can be characterised by realistic ongoing cost decrease of RE technologies expected during the transition, especially high competitiveness of solar PV-battery hybrid systems and wind energy. Solar PV and wind dominate all the BPSs by 2050, solar PV contributes the most (75–79%) and wind energy (11–16%) to the total installed capacities, and (71–73%) and (22–28%) to the total electricity generation, respectively.

Storage technologies, transmission grids and gas power plants provide the required flexibility in a fully RE-based power system. The huge share of solar PV in electricity generation leads to a corresponding share of battery storage due to daily requirements. Gas storage becomes prominent when the RE share reaches 80% around 2035 in the BPS, balancing seasonal variation of wind and solar PV in the system. The existing coal and nuclear plants are expected to be phased out based on their lifetimes. However, new investments in coal and nuclear power plants may become stranded assets, which may be permanently subsidised. In addition, they stand the risk of cost overruns as in the case of Medupi and Kusile coal-fired power projects. Introducing GHG emissions cost would result in a rapid energy transition. Zero GHG emissions energy system is achieved in the BPS by 2050, when the GHG emissions cost is considered. Although, a similar emissions trajectory is observed in the BPSnoCC, but zero GHG emissions could not be achieved by 2050. The results of the BPS without GHG emissions cost indicate that RE electricity generation can reach 95.6%, while coal and gas turbines cover the remaining 4.4% by 2050

Energy policy in South Africa should place solar PV and wind energy at its core. It is clear that these technologies are set to play an active role in South Africa's future energy system as they are the least cost options for electricity supply. A 100% RE-based system is achievable and a real policy option for South Africa. The results of this research clearly show that a fully renewable power system consumes less water and creates more jobs than a fossil dominated system. South Africa's electricity demand can be met sustainably with the country's abundant renewable resources particularly solar and wind. Solar PV-battery hybrid systems and wind energy drive most of the system from 2030 onwards in a fully RE-based system. Further research has to be conducted incorporating additional energy sectors, i.e. transport, heat and industry, for a wider analysis of the South African energy transition in the mid-term future.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2019.09.039.

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Publication VI

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Transition towards decarbonised power systems and its socioeconomic impacts in West Africa

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Transition towards decarbonised power systems and its socio-economic impacts in West Africa

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ABSTRACT

Pathways towards a defossilated sustainable power system for West Africa within the time horizon of 2015–2050 is researched, by applying linear optimisation modelling to determine the cost optimal generation mix to meet the demand based on assumed costs and technologies in 5-year intervals. Six scenarios were developed, which aimed at examining the impact of various policy constraints such as cross-border electricity trade and greenhouse gas emissions costs. Solar PV emerges as the prime source of West Africa's future power system, supplying about 81–85% of the demand in the Best Policy Scenarios for 2050. The resulting optimisation suggests that the costs of electricity could fall from 70 €/MWh in 2015 to 36 €/MWh in 2050 with interconnection, and to 41 €/MWh without interconnection in the Best Policy Scenarios by 2050. Whereas, the levelised cost of electricity without greenhouse emission costs in the Current Policy Scenario is 70 €/MWh. Results of the optimisation indicate that a fully renewables based power system is the least-cost, least-GHG emitting and most job-rich option for West Africa. This study is the first of its kind study for the West African power sector from a long-term perspective.

1. Introduction

Energy crisis and susceptibility to climate change are foreseen to constrain the future human and economic growth of West African (WA) countries [1]. Globally, the need for harmonised efforts to alleviate the danger of climate change and eradicate widespread energy poverty is apparent in the perspectives of the Paris Agreement on climate change and Sustainable Development Goal no 7 (SDG 7) [2]. In WA, a great deal of attention is directed towards the interrelated problems of energy crisis, climate change and energy security, which is characterised by growing demand, poor access to electricity and huge dependence on unsustainable biofuel [3]. In doing so, the Economic Community of West African States (ECOWAS) has adopted measure to streamline renewable energy (RE) and energy efficiency into their energy policies to tackle the predominant energy challenges in the region [4].

ECOWAS is comprised of 15 member states, and is characterised by diverse socio-economic, demographic and cultural backgrounds, each of this factor influence the region's electricity production and consumption [5]. ECOWAS with a growing population above 300 million, accounts for almost one-third of Sub-Saharan Africa's population, occupying an area of over five million square kilometres [6]. The regional gross domestic product (GDP) rebounded, averaging about 2.5% in 2017 from 0.5% in 2016, and is expected to increase to 3.9% in 2019 [7]. In spite of the region's abundant energy potential and progress achieved in the establishment of the regional power pool, the West African Power Pool (WAPP) [8], the region's electricity sector is underpowered with inadequate generation and transmission systems [9], leaving about 175 million people (48%) in the region unelectrified in 2016. Further, the total population relying on biomass for cooking was 263 million (75%) in 2015 [10]. Studies on energy consumption and economic growth nexus conclude that energy is a critical parameter for socio-economic development [11]. The socio-economic development of most WA countries is hampered by its underdeveloped energy sector [12]. Most ECOWAS countries rank among the poorest, having Low Human Development [5]. Access to electricity in the region is at 52%, with shortages of up to 80 h/month and yet electricity prices in WA remain among the costliest in the world, at 0.21 €/kWh, more than twice of the global average [13]. In 2016, the electrification rate was below 40% in 10 of the 15 countries, with Guinea-Bissau, Liberia, Niger and Sierra Leone occupying the

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Abbreviations

A-CAES	adiabatic compressed air energy storage
BPS(s)	Best Policy Scenario(s)
CAPEX	capital expenditures
CCGT	combined cycle gas turbine
CHP	combined heat and power
CPS(s)	Current Policy Scenario(s)
CSP	concentrating solar thermal power
ECOWASS	Economic Community of West African States
GT	gas turbine
GHG	greenhouse gas
HVDC	high voltage direct current
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
LCOC	levelised cost of curtailment
LCOS	levelised cost of storage
LCOE	levelised cost of electricity
LCOT	levelised cost of transmission
OCGT	open cycle gas turbine
OPEX	operational expenditures
PHES	pumped hydro energy storage
PV	photovoltaic
RE	renewable energy
RoR	run-of-river
SNG	synthetic natural gas
SDGs	Sustainable Development Goals
ST	steam turbine
TES	thermal energy storage
VRE	variable renewable energy
WACC	weighted average cost of capital
WA	West Africa
WAPP	West Africa Power Pool

bottom: with 13%, 12%, 11% and 9% respectively [14]. The average annual electricity consumption in WA was about 145 kWh/capita in 2015 [15].

Nonetheless, the electricity supply gap is likely to increase as population, urbanisation and income are expected to rise, driving up electricity demand in the nearest future [9]. Electricity demand in the region is projected to increase fivefold by 2030, to 250 TWh, based on the ECOWAS Master plan [16]. The current grid capacity is not sufficient to cover the demand implying load shedding is becoming more prominent, driving consumers towards large-scale use of costly backup generation [17]. Due to significant under-capacity in electricity generation, some countries in the region such as Benin, Burkina Faso, Niger and Togo rely on electricity imports for a substantial share of their supply. As of 2015, the power generation capacity in the ECOWAS region is about 21 GW, producing about 57 TWh of electricity [15]. As shown in Fig. 1, more than half of the grid-connected capacities in the region are natural gas powered thermal plants, mostly in Nigeria, where it is the main power generation technology [18,19]. Nigeria, Ghana and Côte d'Ivoire account for more than 80% of installed capacity and generation [18]. In addition, the operating capacity is low in comparison to the overall existing capacity in most of the countries in the region.

In order to stem the energy crisis while contributing to the objectives of the Paris Agreement, the ECOWAS region aims to

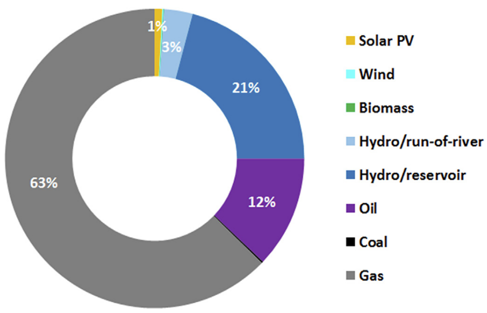

Fig. 1. West Africa power plant installed capacity by 2015 [18].

increase the share of grid-connected RE in the overall generation mix, including large hydropower, to 35% by 2020 and 48% by 2030. In addition, the share of rural population served by decentralised renewable energy systems is expected to reach 22% by 2020 and 25% by 2030 [3]. Over the period 1990–2015, CO_2 emissions in WA have increased by 68% reaching 139 Mt CO_{2eq} [20]. The electricity sector is the focus of many countries, in slowing down GHG emissions, as the sector accounts for one-third of the world's energy-related GHG emissions [21]. Therefore, a transition towards renewable electricity systems is essential, as the current systems dominated by fossil fuels are unsustainable on all accounts of social, economic and environmental criteria [22]. Over the past decades, the global trend in installed RE capacities has grown significantly from 995 GW in 2007–2179 GW at the end of 2017, and is dominated by solar photovoltaics (PV) and wind energy. In Africa, RE installed capacity grew from 23 GW in 2007 to 43 GW at the end of 2017. Much of this growth comes from solar PV (+98%), wind (+90%) and hydropower (+32%) [22]. RE has come to lead the new investments in the global power sector. As a result, the RE cost decline accelerates further, out-competing new built fossil capacities [23]. Solar PV utility-scale global levelised cost of electricity (LCOE) fell by 73% between 2010 and 2017 [24]. For instance, the differential between the LCOE for onshore wind and solar PV in South Africa is now 40% and almost 50% lower in price than newly built coal and nuclear, respectively [25].

The ECOWAS region has huge RE resource potential, widely distributed across the region and could provide low-cost and reliable energy supply [5]. Countless opportunities exist for deploying solar PV, wind energy, hydropower and biomass technologies across the region [5]. Currently, RE generation in WA is dominated by hydropower; and is even the main power source for some countries. Solar PV, wind energy and hydropower are anticipated to experience strong growth in the region's power mix [4]. However, these power sources in WA are governed by the monsoon, which causes seasonal variability [4]. Thus, the need for improved interconnections within the ECOWAS region is essential to achieve the synergetic effects by harnessing locally available RE resources, a solution to the challenges of low access and unreliable electricity supply in the region. Furthermore, the variability of RE supply may not be as significant, when viewed over larger geographic area [26]. Moreover, there is a spatio-temporal complementarity between various resources [27], which result in lower intermittency when examining the entirety of resources contribution, rather than a single resource contribution [26]. Additionally, energy system modelling is essential when assessing the least cost electricity expansion path for developing countries or regions [26]. Recent works have shown the possibility of achieving a fully renewable electricity system, as in the case of Nigeria [19], SSA [26] and global [28]. These studies have shown technical possibility and economic prospects of full defossilisation of the future power system, while considering all sustainability criteria. Both international agendas, the Paris Agreement and SDG 7 can be achieved by the deployment of RE technologies, in tackling the two major challenges of the 21st century; climate alteration and prevalent energy poverty [2]. Energy access is underlined in the SDG 7, while energy transition is highlighted in the Paris Agreement for mitigating climate change [2]. A brief review on RE share in the WA energy system is presented in Table 1.

So far, there is a lack of high temporal and spatial resolution energy transition studies for WA, which considers the impact of high penetration of RE in meeting the growing demand in the region under the operation of the WAPP electricity market. For these reasons, this study extends the investigation begun in Refs. [4,17,26,29–31], for a better understanding of the roles and benefits of flexible electricity generation, interconnected electricity networks and energy storage solutions in the transition towards a fully decarbonised power system and improved energy access for the 15 member states of ECOWAS, within the time horizon of 2015–2050. In addition, this study seeks to determine the least-cost and most-job enriching power system for WA. Furthermore, WA as an electricity island or individual country scenarios are compared towards a least-cost solution for the region. To this end, six scenarios were developed to fully understand the transition pathways for WA, under certain policy constraints, such as cross-border electricity trade and GHG emissions costs. These scenarios could cater, for instance, to policy decisions for decarbonising the WA electricity system within the time horizon of 2015–2050. The research investigates cost optimal generation mix to meet the demand based on assumed costs and technologies in 5-year intervals. The paper is organised as follows: section 2 describes the research methodology. Section 3 presents the result of the optimisation. Implications of the transition is discussed in section 4. Conclusions and policy measures are proposed in section 5.

2. Methodology

The ECOWAS power system optimisation was performed with the LUT Model described in Ref. [28,32]. The employment creation during the transition is analysed based on methodology presented in Ref. [33,34]. Fig. 2 illustrates the geographical scope of this study. West Africa was structured into 20 defined sub-regions based on the existing cooperation.

2.1. Model description

The LUT model a linear optimisation tool, which performs simulations for an entire year on an hourly resolution under certain operational conditions. The key function of optimisation algorithm is to minimise the system cost. To compute the lowest system cost, the model seeks to optimise the sum of installed capacities of each technology, operational expenditures, and costs of generation ramping. The WA power sector transition is simulated in 5-year time intervals under certain constraints. The model's main inputs and outputs are provided in Fig. 3. The model detail description can be found in Ref. [28].

In addition, the energy system takes into account electricity distributed generation by prosumers. The prosumer consumption is categorised as follows; residential, commercial and industrial. The prosumer sector is optimised exogenously on hourly resolution, the self-consumption model describes the optimal PV and storage (mainly battery) system size for the potential prosumers. The key function for self-consumers algorithm is to minimise cost of electricity consumed, estimated as the summation of prosumer generation, cost of grid electricity consumed and annual costs. Excess prosumer generation is sold to the grid at 0.02 €/kWh by prosumers, when their own demand is satisfied, but not more than 50% of total self-generation.

The model operates under two essential constraints:

1. The RE capacity share increase cannot exceed 4% per year (3% per year from 2015 to 2020), in order to avoid disruptions.
2. From 2015 onwards, no new conventional power plants would be installed, except gas turbines due to their lower carbon emissions, higher efficiency, and their ability to use sustainable synthetic biomethane and natural gas in the later phase. The current fossil-fueled plants are decommissioned based on their technical lifetimes [35].

2.2. Applied technologies

The ECOWAS power system is modelled with various technologies as show in Fig. 4, which include electricity generation, storage, and transmission. Existing transmission grid capacity was taken from Ref. [17], losses in transmission and distribution are considered during transition simulation [36]. Fig. 4 illustrates the LUT model components.

2.3. Technical and financial assumptions

The technical and financial assumptions introduced to the model are provided in the Supplementary Material (Tables S1–S4).

Table 1
Review on the share of renewable energy in West Africa.

Study	Year	Remark
IEA [17]	2014	The New Policies Scenario assumes RE installed capacity of 43 GW (38%) and fossil power plant of 70 GW (62%) by 2040. Gas dominates the installed capacity with 50 GW (44%), followed by hydropower with 24 GW (21%). Gas and hydropower contribute 249 TWh (53%) and 100 TWh (21%), respectively, of the total electricity generation at 474 TWh by 2040.
IRENA [29]	2015	RE installed capacity is 32 GW, and hydropower tops with about 22 GW by 2030 for the power sector. Hydropower dominates with 82 TWh for the total RE generation at 116 TWh (52%).
IRENA [30]	2018	This study reveals a growing share of RE in WA by 2030 under three scenarios. Depending on the scenario analysed, solar PV in the region ranges from 8.2 GW to 21.5 GW by 2030. While hydropower ranges from 11.4 GW to 11.5 GW, and wind energy remains constant at 1.6 GW for all scenarios. The remaining capacity is mainly supplied by gas in the range of 30 GW–36 GW by 2030.
Adeoye and Spataru [31]	2018	The study compares the baseline scenario of the 2025 power system with the renewable energy scenario of high penetration of solar PV. In the baseline scenario, gas-fired power plants contributes 55% of electric power generated, 27% from hydropower, 9% from coal and 8% from diesel. Under the renewable scenario, gas power plants account for 37% of electricity supply, 28% comes from solar PV, 25% from hydropower and 3% from diesel.

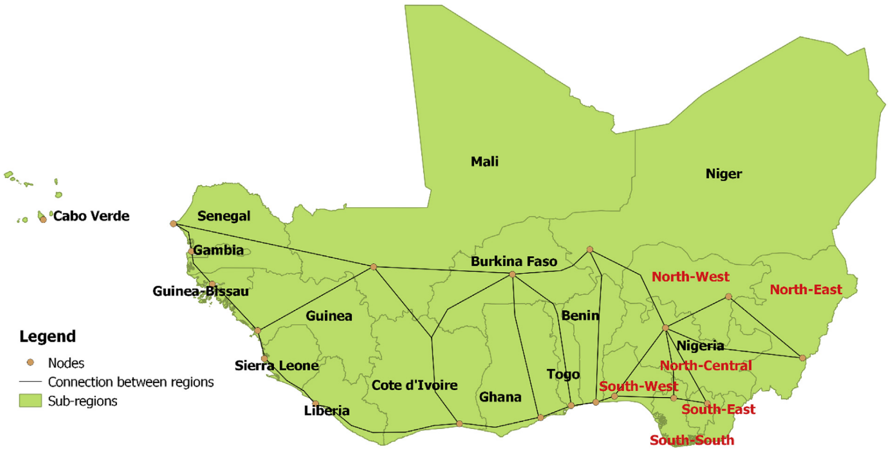

Fig. 2. The different sub-regions of West Africa.

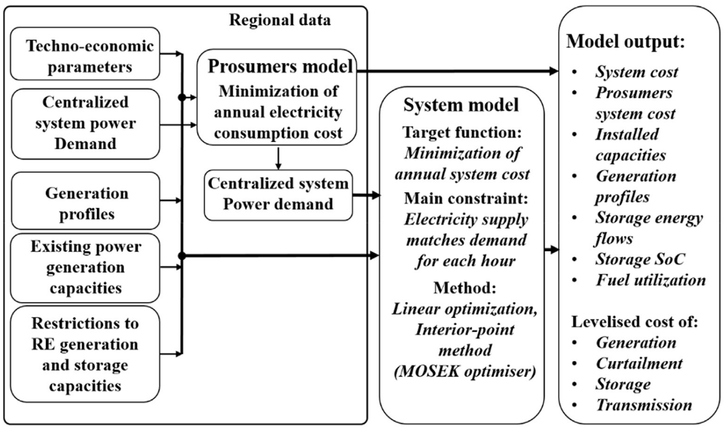

Fig. 3. Schematic of the LUT model [28].

In all the scenarios examined, a 7% weighted average cost of capital (WACC) was assumed, whereas 4% WACC is set residential PV self-consumption. A lower WACC is assumed for the PV self-consumption, as financial return expectations are lower. The residential, commercial and industrial consumers electricity prices were estimated till 2050 based on methodology described in Ref. [38,39]. The cost of electricity for each country in the region are provided in the Supplementary Material (Table S5).

The RE technologies upper limits were estimated based on methodology described in Ref. [32], existing installed capacities until 2015 are taken from Ref. [35] and set as lower limit. Absolute numbers of the upper and lower limit of all technologies are provided in the Supplementary Material (Tables S6 and S7). The required power capacities during transition for WA are provided in the Supplementary Material (Tables S8–S12).

2.4. Renewable resources potential

The wind energy, optimally tilted PV and solar CSP generation profiles, were estimated based on the methodology described in Ref. [32], and PV single-axis tracking according to Ref. [40], based on resource data of NASA [41,42] reprocessed by the German Aerospace Centre [43]. The hydropower generation profiles are estimated using daily resolved water flow data for the year 2005 [44]. The computed Full load hourly (FLH) for all resources can be found in the Supplementary Material (Tables S13–S17). Fig. 5 shows the annual FLH of various resources for entire WA. Biomass and waste potentials are provided in Ref. [45] and are classified according to Ref. [32]. Biomass costs are estimated using data from Ref. [46,47]. A gate fee of 50 €/ton was assumed for solid waste in 2015, which gradually increases up to 100 €/ton in 2050.

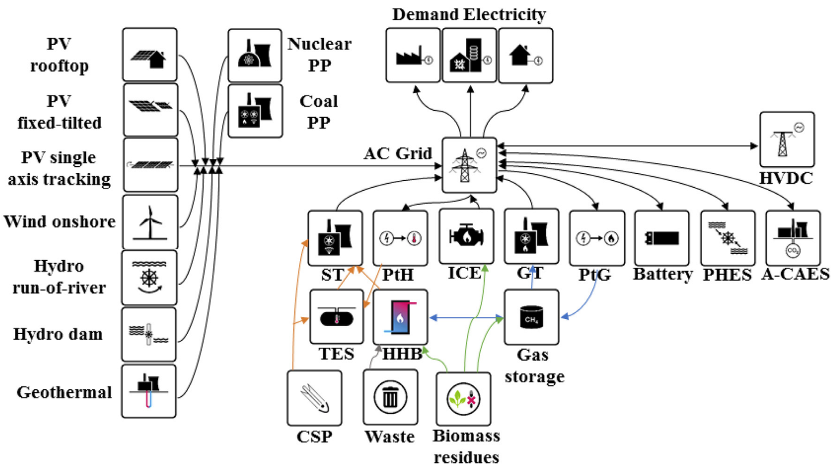

Fig. 4. Components of the LUT model [37]. Abbreviations not introduced elsewhere include PP - power plant, ST - steam turbines, PHES – pumped hydro energy storage, HHB – hot heat burner, ICE – internal combustion engine, PtH – power-to-heat, GT - gas turbines, PtG - power-to-gas, CSP – concentrated solar thermal power, A-CAES – adiabatic compressed air energy storage, TES – thermal-energy-storage.

2.5. Development of electricity demand

The WA electricity demand for the power sector is estimated to increase from 60 TWh in 2015 to about 667 TWh in 2050 [17], and absolute numbers are provided in the Supplementary Material (Table S5). Fig. 6 shows the aggregated load curve for WA. A regional compound average annual growth rate of about 7% in electricity demand drives the transition. The electricity demand is driven mainly by Nigeria, Ghana and Côte d'Ivoire, together they account for about 80% of the regional demand by 2050. The hourly load demand profiles are estimated based according to Refs. [48].

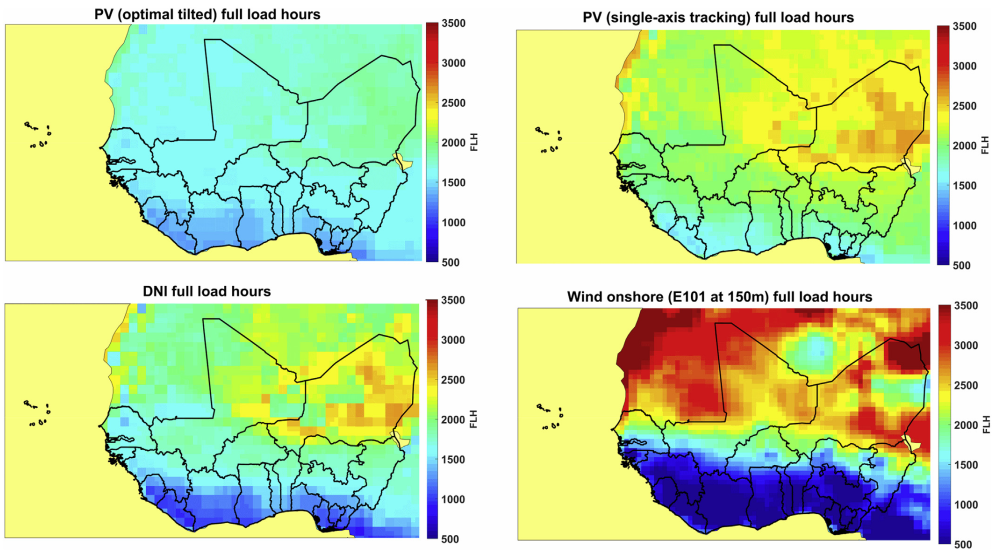

Fig. 5. Maps of West Africa showing annual full load hours for optimally tilted (top left) and PV single-axis tracking (top right), CSP solar field (bottom left), and wind (bottom right).

2.6. Scenario descriptions

In this study, six scenarios were studied for WA power system analyses, which are briefly described in Table 2.

3. Results

3.1. Electricity installed capacity and generation mix

Investments in power generation capacities are needed in WA, due to under-capacity power supply and rapid increase in electricity demand across the region. The installed capacities during the transition for all technologies under various scenarios are shown in Fig. 7 and absolute numbers are provided in the Supplementary Material (Tables S8–12). Table 3 presents the electricity installed capacity by technology for all scenarios in 2050. The respective power generation capacities in the BPSs is visualised first as shown in Fig. 7(a–d). Across the BPSs, solar PV dominates the installed capacities by 2050, with 284 GW in BPS-A, 284 GW in BPSnoCC-A, 328 GW in BPS-C, and 316 GW in BPSnoCC-C. Besides solar PV, a diverse technology mix can be observed in Fig. 7(a–d). Wind energy appears to be relevant in the BPSs across the area (BPS-A and BPSnoCC-A), while gas-based technologies contribution appears to be higher in the BPSs across the countries (BPS–C and BPSnoCC-C). The installed capacities in the CPSs are shown in Fig. 7(e–f). Gas turbines and hydropower dominates the installed capacities during the transition in the CPSs, followed by nuclear and coal, while the remaining capacities come from solar PV, wind energy and bioenergy. In 2050, gas turbine and hydropower installed capacities reach 72 GW and 28 GW, respectively, in the CPSs.

Fig. 8 shows the generation mix under various scenarios during the transition. Electricity generation increases for all scenarios to meet the demand over the transition in WA. In 2050, solar PV tops the generation mix in the BPSs, complemented by hydropower, bioenergy and wind energy as shown in Fig. 8(a–d). Solar PV contributes about 589 TWh in BPS-A, 590 TWh in BPSnoCC-A, 644 TWh in BPS-C and 619 TWh in BPSnoCC-C of the total electricity generation in 2050. Whereas, gas turbine dominates the power supply in the CPSs, followed by hydropower, coal and nuclear. By 2050, gas turbines account for 60% (407 TWh) of the generation and hydropower for 18% (120 TWh). Additional graphical results on the generation mix under various scenarios are available in the Supplementary Material (Fig. S1).

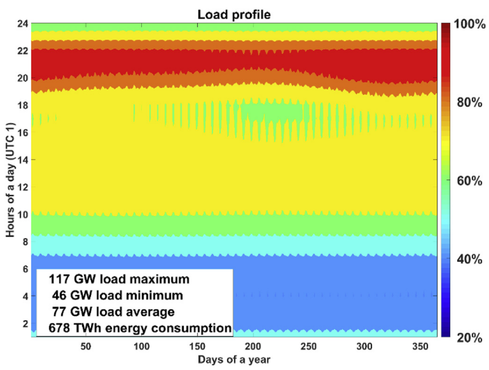

Fig. 6. Aggregated load curve for West Africa for 2050.

Fig. 9 presents the sub-regional capacities projection for 2050. Solar PV capacities are observed in all sub-regions due to very good solar irradiation across WA as shown in Fig. 9 (top) for the BPS-A. Wind capacities are predominant in Niger and Mali. Hybrid PV-battery systems dominate the power system by 2050. Batteries emerge as the major supporting storage technology for PV. Fig. 9 (bottom) shows the capacity outlook in the CPS-A, which is dominated by gas turbines and hydropower. Nigeria with 53 GW (42%) and 93 GW (29%) dominates the total installed capacity in the CPS-A and BPS-A, respectively. Gas-fired power plants (32%) and hydropower (53%) together make up 85% of the WA planned capacities in the pipeline [30]. Fossil gas is expected to be supplied via the Western African Gas Pipeline to coastal countries: Benin, Ghana, Togo, with extension to Côte d'Ivoire. Additional graphical results on regional capacity and generation outlook can be found in the Supplementary Material (Figs. S2 and S3).

3.2. System flexibility

This section analyses the system flexibility, a vital precondition for the grid integration of high shares of power feed-in from variable renewable electricity (VRE), particularly in BPSs. Solar PV, wind energy and hydropower potential in WA is influenced by the monsoon, which causes seasonal variability. The sources of operational flexibility examined in this research include storage technologies, transmission grid, flexible generators (gas turbines), but also dispatchable RE (hydro reservoir, bioenergy) and generation curtailment. These flexibility components act on different timescales.

3.2.1. Storage need and utilisation

Electrical energy storage units are observed to be valuable in providing flexibility to the power system, particularly in the BPSs due to high penetration of RE as shown in Fig. 10(a–d), visualising the electricity throughput. The residual load demand covered by storage units is 259 TWh (36%) in BPS-A, 256 TWh (35%) in BPSnoCC-A, 333 TWh (44%) in BPS-C and 266 TWh (37%) in BPSnoCC-C by 2050. Contrarily, storage units output in the CPSs is about 20 TWh (3%). Battery storage emerges as the key element of the storage units in terms of output, particularly in the BPSs throughout the transition due to daily charge and discharge. Thermal energy storage (TES) and gas storage outputs appear to be relevant in the BPSs across the countries from 2035 to 2045, respectively. Whereas in the CPSs, TES dominates storage output until 2045, due to CSP installed capacities. Absolute storage throughput numbers under various scenarios examined are provided in the Supplementary Material (Tables S19–S23). Table 4 presents the storage capacity by technology for all scenarios in 2050. Fig. 11 shows the required storage capacities under various scenarios. In terms of storage capacities requirement, gas storage dominates in the BPSs throughout the transition, followed by TES in the CPSs until 2045. The installed storage capacities are lower in the BPSs across the area in comparison to the BPSs across the countries as shown in Fig. 11. While the lower installed capacities of storage technologies in the CPSs due to increasing share of dispatchable thermal generators and hydropower.

3.2.2. Cross-border electricity trade flow

Asides from the role of energy storage units in balancing the temporal mismatch between generation and demand, the transmission network provides further flexibility to the power system. It further helps in balancing large regional differences of generation and demand, and offers strong spatial interconnections. The overall grid utilisation profile depicts the electricity generation and demand pattern under various scenarios, as shown in Fig. 12. Grid

Table 2
Description of the scenarios examined for the ECOWAS power sector transition.

Name	Description
Best Policy Scenario – Country wide (BPS–C)	Carbon emissions costs are applied to forbid new investment in fossil-fueled plants and 100% RE is achieved by 2050. In this scenario, no interconnection exist among the 15 member states. Within countries, applied for Nigeria, interconnections are free for optimisation.
Best Policy Scenario – Country wide (BPSnoCC-C)	This scenario is similar to the above. However, no GHG emissions costs are assumed.
Best Policy Scenario – Area wide (BPS–A)	This scenario is similar to the BPS-C. However, interconnection among member states is assumed with GHG emissions costs.
Best Policy Scenario no GHG cost – Area wide (BPSnoCC–A)	This scenario is similar to the BPS-A. However, no GHG emissions costs are assumed.
Current Policy Scenario – Area wide (CPS–A)	This scenario is designed according to ECOWAS RE targets [3]. The RE capacities were provided until 2030. From 2030 onwards capacity for various technologies are extrapolated until 2050. All sub-regions are interconnected. Coal, gas turbines, internal combustion engines and nuclear power plants supply the rest of the capacities required to meet the demand.
Current Policy Scenario no GHG cost – Area wide (CPSnoCC–A)	The Current Policy Scenario is simulated without GHG emissions costs.

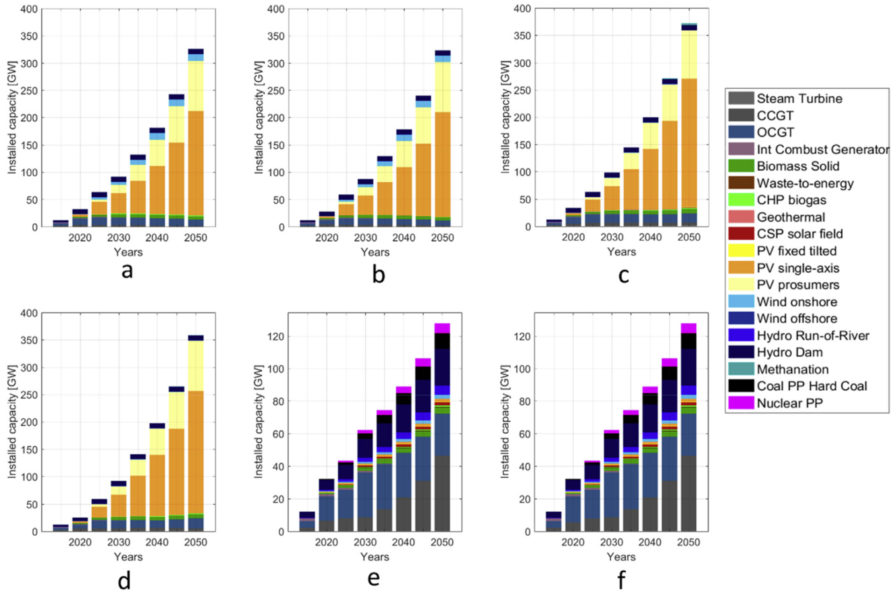

Fig. 7. Installed generation capacities for BPS-A (a), BPSnoCC-A (b), BPS-C (c), BPSnoCC-C (d), CPS-A (e) and CPSnoCC-A (f) from 2015 to 2050.

utilisation appears to be positively related to solar PV generation from around 9.00 to 18.00 per day in the BPS-A, as shown in Fig. 12 (left). Whereas, grid utilisation appears to be more vibrant during the times of higher electricity demand from around 20.00 to 22.00 in the CPS-A, as shown in Fig. 12 (right). As evident in Fig. 13, the 20 sub-regions can be classified as, exporting and importing sub-regions. The annual grid utilisation in the BPS-A is visualised first in Fig. 13 (top). In the BPS-A there are three main exporting sub-regions as shown in Fig. 13 (top); namely, Niger, Mali and NIG-NW. Niger and Mali are net exporters of solar and wind electricity, as a result of high resource potential due to diminishing monsoon influence. While, NIG-NW is a net exporter of solar electricity. Countries with good hydropower potential serve as balancing regions, which include Nigeria (NIG-NE) and Guinea. In the CPS-A, the major exporters are Guinea, Nigeria, Niger and Liberia as shown in Fig. 13 (bottom). The total grid transmission is 298 TWh in the BPS-A, representing 45% of the total electricity demand, and is 39 TWh in the CPS-A, representing 6% of the total electricity demand. The annual grid utilisation increased significantly in the BPS-A by a factor of 7.6 in comparison to CPS-A. Gambia, Sierra Leone and Guinea Bissau did not experience any changes in terms of the amount of electricity imported in the BPS-A and CPS-A. Mali changed from being an importer in the CPS-A to an exporting country in the BPS-A. Electricity imports increased significantly in most of the sub-regions of Nigeria, except NIG-NW, which emerges to be an exporting sub-region in the BPS-A, while NIG-NE maintains status quo in the BPS-A and CPS-A.

Fig. 14 shows the cross-border electricity trade directions and amounts (in TWh) among the sub-regions in the BPS-A and CPS-A. The thickness of the flow illustrates the amount of electricity

Table 3
Electricity installed capacity by technology for all scenarios in 2050.

Generation technology	Unit	BPS-A	BPSnoCC-A	BPS-C	BPSnoCC-C	CPS-A	CPSnoCC-A
PV prosumers	[GW]	92	92	92	92	0	0
PV single-axis tracking	[GW]	192	192	235	223	2	2
PV optimally tilted	[GW]	0	0	1	0	0	0
Wind energy	[GW]	12	12	0	0	2	2
Geothermal power	[GW]	0	0	1	0	0	0
CSP	[GW]	0	0	0	0	2	2
Hydropower	[GW]	10	10	10	10	28	28
Biomass PP	[GW]	5	5	8	7	4	4
Waste PP	[GW]	0	0	0	0	0	0
Biogas PP	[GW]	2	0	2	2	1	1
Biogas Digester	[GW]	1	1	1	1	1	1
Biogas Upgrade	[GW]	1	1	1	1	1	1
CCGT	[GW]	1	2	5	4	46	46
OCGT	[GW]	12	9	17	19	26	26
Steam Turbine	[GW]	0	0	2	1	0	0
Coal PP	[GW]	0	0	0	0	10	10
Oil PP	[GW]	0	0	0	0	0	0
Nuclear PP	[GW]	0	0	0	0	6	6

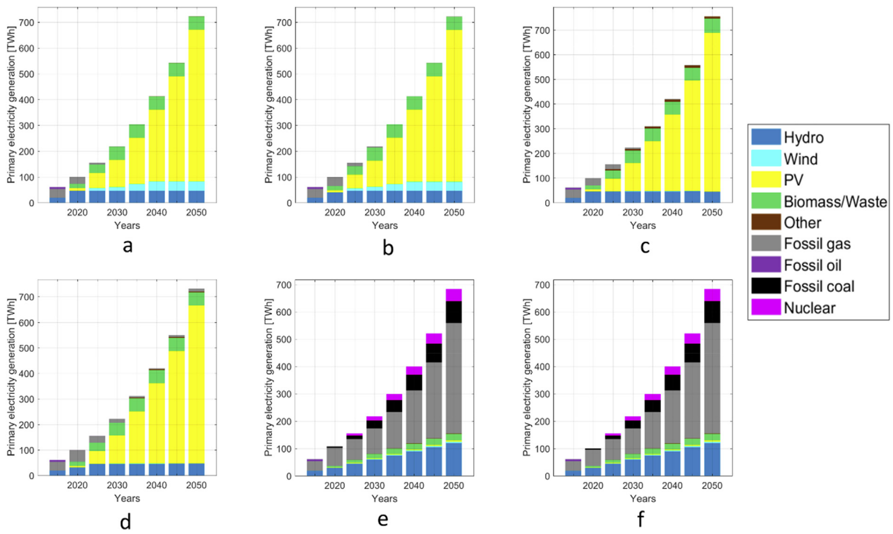

Fig. 8. Electricity generation mix for BPS-A (a), BPSnoCC-A (b), BPS-C (c), BPSnoCC-C (d), CPS-A (e) and CPSnoCC-A (f) from 2015 to 2050.

transferred between the regions in TWh. Niger dominates the net electricity trade with 204 TWh (68%), followed by 54 TWh (18%) for Mali and 34 TWh (11%) for NIG-NW in BPS-A. Whereas, Guinea dominates the electricity trade in the CPS-A with 12 TWh (31%). Benin and NIG-NC emerge as the main transit conduit in the regional electricity trade in the BPS-A, including Gambia and Guinea Bissau in the CPS-A as shown in Fig. 14 (bottom). The regional electricity trade depicts the role of grid interconnections, particularly in scenario with high shares of RE, in comparison to the one dominated by thermal dispatchable generators.

3.2.3. Role of gas turbines

The fleet of VRE generators are accompanied by flexible power plants. Gas turbines are found to be dynamic fast-responding dispatchable generators, covering some fraction of the residual load demand based on different timescales from days to weeks, particularly in the BPSs. The average FLH declined from 5470 in 2015 to 191 in 2050 for BPS-A, to 275 in BPSnoCC-A, to 417 in BPS-C and to 601 in BPSnoCC-C. This document a drastic shift in the role of gas turbines, from bulk electricity generation to peak electricity generation for the most challenging seasons of the year. By 2050, gas turbine generation is 2.5 TWh in BPS-A, 3.1 TWh in BPSnoCC-A, 9.0 TWh in BPS-C and 14.0 TWh in BPSnoCC-C. The installed gas turbine capacities are 12.9 GW, 11.4 GW, 21.7 GW and 23.3 GW BPS-A, BPSnoCC-A, BPS-C and BPSnoCC-C, respectively, by 2050. Whereas in the CPSs, the CCGT operates as baseload generators and OCGT is utilised in meeting peak loads during the night. Fig. 15 illustrates the gas turbine (CCGT and OCGT) utilisation for BPS-A, BPS-C and CPS-A by 2050. Gas turbines are most utilised during the monsoon period in BPSs as shown in Fig. 15 (a-b, d-e).

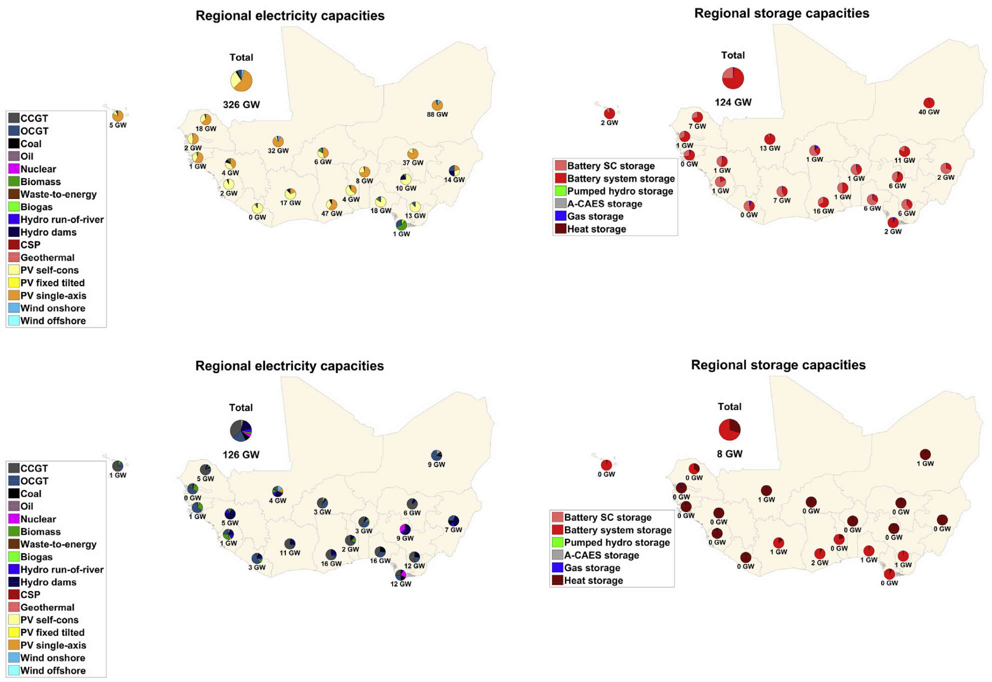

Fig. 9. Overview of the generation mix (left) and energy storage (right) for the BPS-A (top) and CPS-A (bottom).

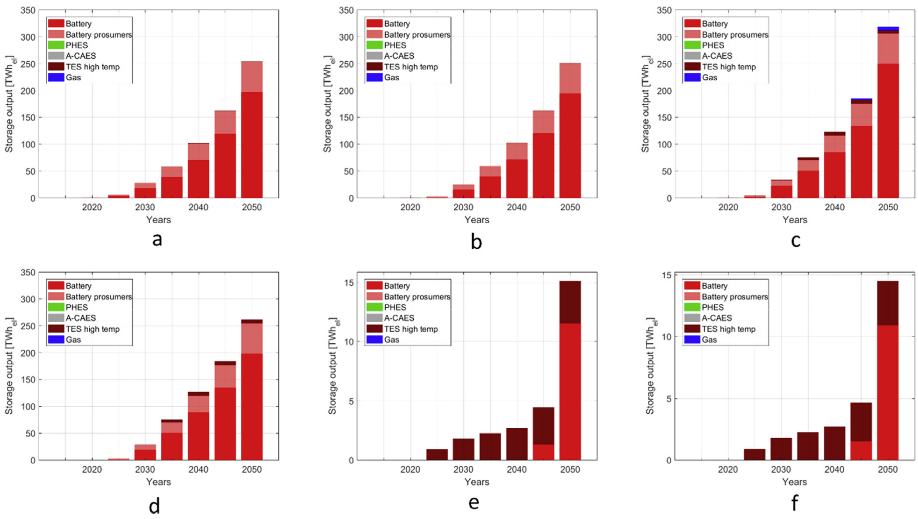

Fig. 10. Storage throughput for BPS-A (a), BPSnoCC-A (b), BPS-C (c), BPSnoCC-C (d), CPS-A (e) and CPSnoCC-A (f) from 2015 to 2050.

Table 4
Storage capacity by technology for all scenarios in 2050.

Storage technology	Unit	BPS-A	BPSnoCC-A	BPS-C	BPSnoCC-C	CPS-A	CPSnoCC-A
Battery total	[GWh]	735	737	840	800	33	31
PHS storage	[GWh]	0	0	0	0	0	0
TES storage	[GWh]	5	3	164	49	19	19
A-CAES storage	[GWh]	0	0	7	11	0	0
Gas storage	[GWh]	2403	1738	9359	1630	8	9

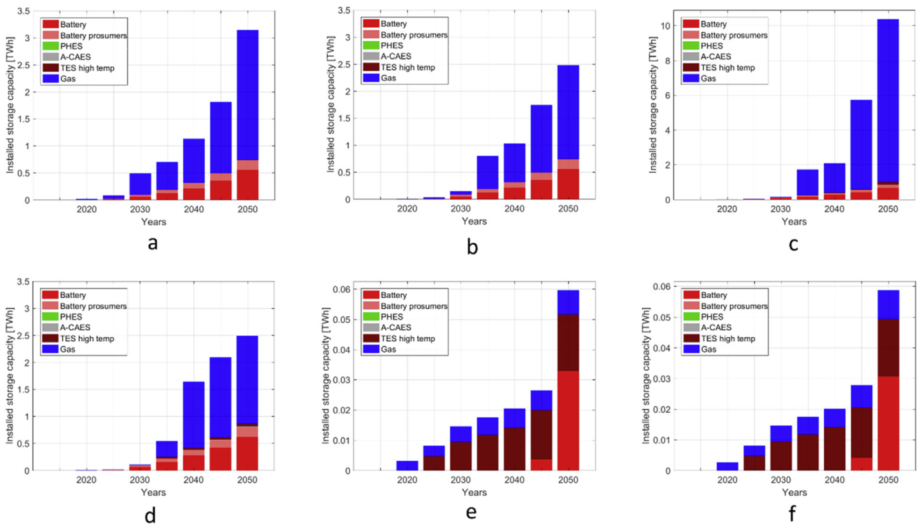

Fig. 11. Installed storage capacities for BPS-A (a), BPSnoCC-A (b), BPS-C (c), BPSnoCC-C (d), CPS-A (e) and CPSnoCC-A (f) from 2015 to 2050.

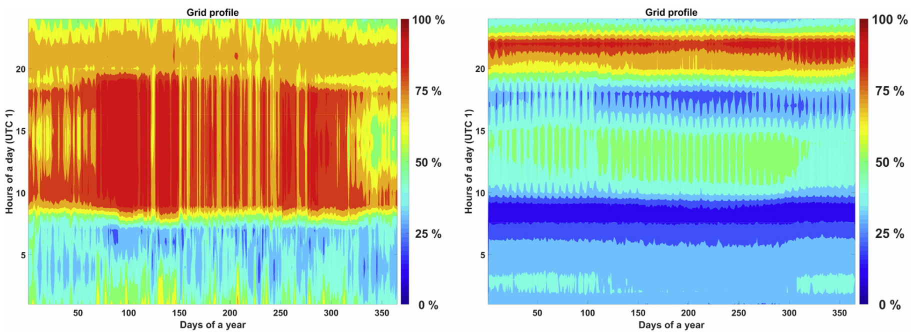

Fig. 12. Grid utilisation profiles for BPS-A (left) and CPS-A (right) in 2050.

Additionally, gas turbines are flexible power plants because their power output can be modulated sufficiently fast when needed and the robustness of their market power setup.

3.2.4. Generation curtailment

Curtailment is a flexibility option, which can be low cost in highly renewable energy systems, compared to other flexibility options [49]. In addition, sudden and unexpected power imbalance in the system is controlled by partial generation curtailment. VRE generation and curtailment under various scenarios are shown in Fig. 16. Fig. 16 (right) further shows the curtailed generation potential corresponding to VRE generation. The curtailed generation potential increases throughout the transition in BPSs, with the exception of the CPSs. It can be observed that generation

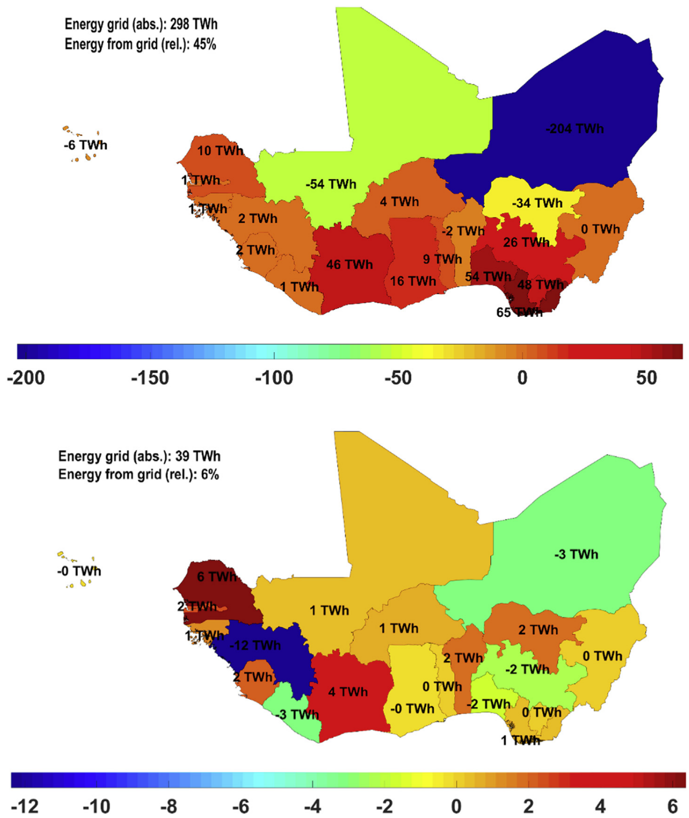

Fig. 13. Absolute annual grid utilisation in the BPS-A (top) and CPS-A (bottom) for the ECOWAS region in 2050. Net annual exports is represented by negative values, while the positive values represent the net annual imports.

curtailment is higher in the BPSs across the countries than in BPSs across the area. The high diversity of the region's power mix balances the regional electricity generation and contributes to low curtailment in the BPSs across the area. By 2050, generation curtailment is 27 TWh (4.1%) in BPS–A, 28 TWh (4.1%) in BPSnoCC–A, 41 TWh (6.1%) in BPS–C, 39 TWh (5.8%) in BPSnoCC–C and 3 TWh (0.5%) in CPSs.

3.3. Energy flow overview

Fig. 17 illustrates the energy flows for 2015 and the BPS in 2050. It shows the generation, end use and efficiency of each energy conversion process. The produced heat and losses in the system consist of the difference between the primary power generation and final demand. In 2015, electric power generation is provided mainly by gas turbines and hydropower, while RE generation, particularly solar PV, dominate in 2050.

3.4. Financial implications of the energy transition

Fig. 18 illustrates the LCOE under various scenarios during the transition. The LCOE in the BPSs is visualised first as shown in Fig. 18(a–d). The LCOE decline from about 70 €/MWh in 2015 to 36 €/MWh in BPS-A, to 41 €/MWh in BPS-C by 2050. Whereas, LCOE declines from 68 €/MWh in 2015 to 36 €/MWh in BPSnoCC-A and to 39 €/MWh in BPSnoCC-C by 2050. Lower LCOE over time during the transition in BPSs signifies the cost competitiveness of RE technologies during the transition. Fig. 18(e–f) depicts the LCOE in the CPSs. The LCOE increased significantly from about 70 €/MWh in 2015 and to 116 €/MWh in CPS-C by 2050, while the LCOE increased slightly from 68 €/MWh in 2015 to 70 €/MWh in CPSnoCC by 2050. Fuel costs and GHG emissions costs contribute to the high LCOE in the CPSs. Additional results on costs are provided in the Supplementary Material (Table S18 and Figs. S4–S6).

3.5. Socio-economic prospects of the energy transition

3.5.1. Jobs in the West African power sector

Figs. 19 and 20 depict the direct energy jobs created in the WA power sector during the transition period for the BPS and CPS. The annualised jobs created in the BPS and CPS were estimated based on the methodology presented in Ref. [33,34] and the assumed

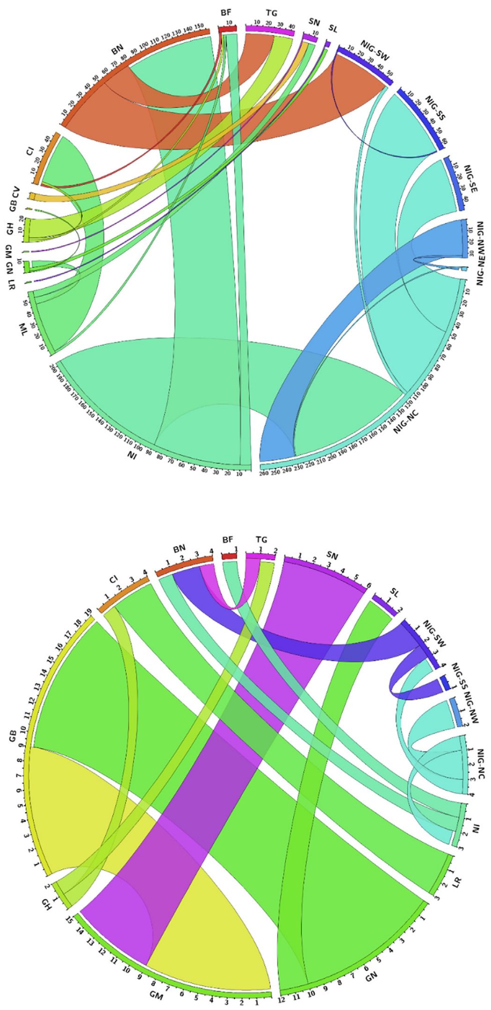

Fig. 14. Regional grid exchange within West Africa in the BPS-A (top) and CPS-A (bottom) in 2050.

employment generation factors are presented in the Supplementary Material (Table 24). About 440 thousand direct energy jobs were created in the BPS and solar PV emerges as the prime job creator with 68% of the total jobs created by 2050, as shown in Fig. 19. Whereas, fossil gas based power generation creates more jobs in the CPS, with 45% of the jobs by 2050, as shown in Fig. 20. Batteries mainly drive jobs created by storage technologies from 2025 onwards, which increases to 44 thousand by 2030 and further increases to 76 thousand by 2050 in the BPS. Overall, number of direct energy jobs created in the BPS appears to grow massively from around 20 thousand in 2015 to about 440 thousand in 2050. Similarly, jobs created in the CPS increase from around 20 thousand in 2015 to about 183 thousand by 2050.

Furthermore, the distribution of jobs by categories during the transition in the BPS and CPS is indicated in Figs. 19 and 20. In the BPS, construction and installation of renewable energy technologies create the bulk of the jobs, enabling the rapid ramp-up of capacity until 2025. The sector creates about 82 thousand jobs by 2050. Furthermore, manufacturing jobs have a relatively low share until 2020, due to higher share of imports (mainly PV, hydropower, bioenergy and fossil gas). From 2025 onwards, a higher share of local manufacturing jobs is observed, as domestic production capabilities are assumed to be increased until 2050. The operation and maintenance jobs appear to take the lead from 2035 onwards and become the main job sector by 2050 with 41% of the total jobs. On the contrary, in the CPS, fuel jobs dominate during the transition. Fuel jobs dominate with a share of 56%, followed by operation and maintenance with 25% while manufacturing, construction and installation jobs are 16% by 2050.

The least-cost option becomes the cornerstone for a vibrant and job-intensive policy option for WA, centred on decarbonisation of its power sector. The electricity demand specific jobs in the BPS increases significantly from 321 jobs/TWh_{el} in 2015 to 1238 jobs/TWh_{el} in 2025 with the rapid ramp-up in RE installations. Beyond 2015, it declines steadily to around 662 jobs/TWh_{el} in 2050 as shown in Fig. 19. Whereas, the electricity demand specifics jobs in the CPS increased from 321 jobs/TWh_{el} in 2015 to 506 jobs/TWh_{el} in 2020, and further declines to 274 jobs/TWh_{el} in 2050.

3.5.2. Greenhouse gas emissions trajectory under various transition scenarios

The GHG emissions trajectory under various scenarios are depicted in Fig. 21. The defossilisation of the WA power system appears to be rapid in the BPSs area in comparison to the BPSs country as illustrated in Fig. 21(a–d). With GHG emissions costs, emissions decline rapidly after 2025 as fossil natural gas plants are replaced with RE capacities as observed in BPS-A and BPS-C. Without GHG emissions costs, the BPSnoCC-A shows similar emission pattern with BPS-A, whereas the BPSnoCC-C deviates the emission pattern observed in BPS-C. In the CPSs, the GHG emissions increased throughout the transition as depicted in Fig. 21(e–f).

4. Discussion

This work investigates the least-cost electricity expansion option for WA, under certain policy constraints. The BPSs results show that deep-decarbonised pathways are cheaper than fossil-based CPSs. Such a system complies with the objectives set out in the Paris Agreement, in comparison to CPSs. This power system is achievable with the abundant and diverse RE resources in WA, but requires a strong political will.

4.1. Solar PV plus battery: the new workhorses of the West African power system

Solar PV emerges as the new workhorse of the WA power system in renewables-led electricity generation. A mix of RE technologies, as observed in the BPSs can substitute the current heavy dependence on gas-fired electricity. The power system optimisation results show that it is least-costing to supply 81%–85% of the electricity demand in WA from solar PV under the BPSs by 2050. In this cost-optimal expansion path, about 284–328 GW solar PV installed capacities are operational by 2050. Solar PV technologies supply 589–644 TWh in the BPSs. PV prosumers contribute 20% to the total electricity generation in 2050. The plausible reasons for a high share of PV in WA power system includes the following, the

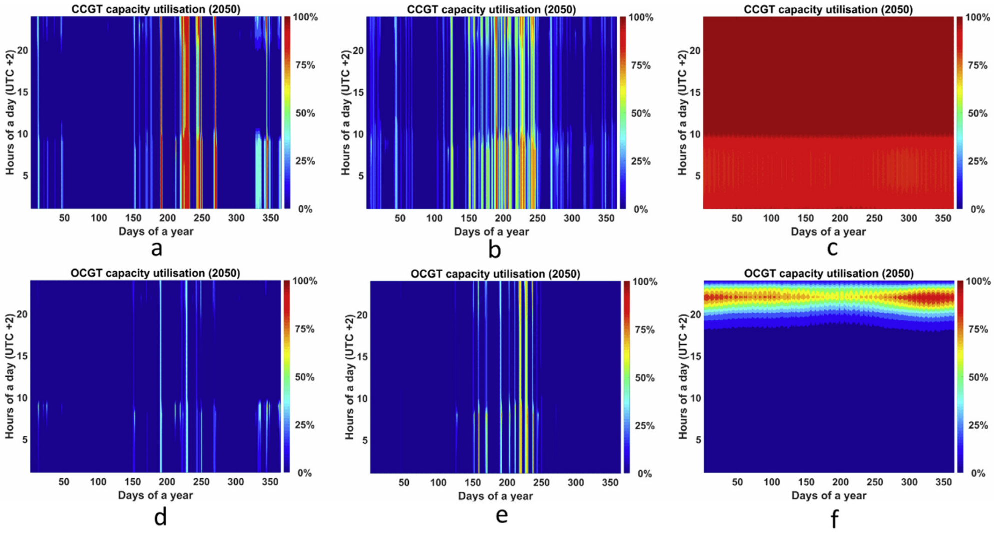

Fig. 15. Combined cycle gas turbine capacity utilisation for BPS-A (a), BPS-C (b), CPS-A (c). Open cycle gas turbine capacity utilisation BPS-A (d), BPS-C (e), and CPS-C (f) in 2050.

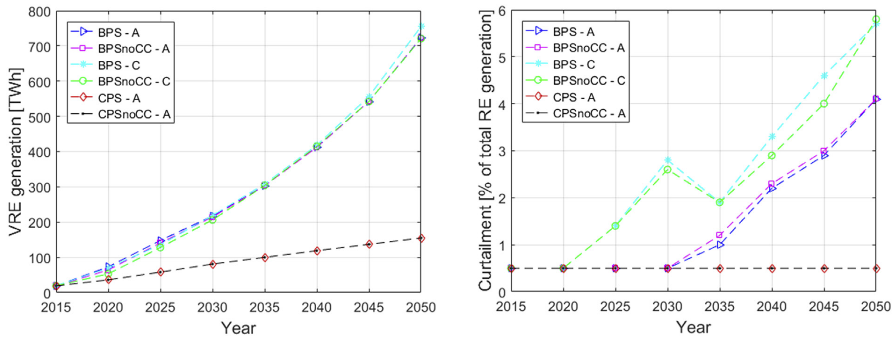

Fig. 16. Variable RE generation (left) and curtailment of generation potential (right) in TWh under various scenarios during the transition.

steep fall in solar PV and battery costs [37], excellent resource conditions and fast growing electricity demand in WA. The PV-battery combination drives most of the system from 2030 onwards. Batteries emerge as the main supporting technology for PV, battery capacities ranged from 735 GWh to 840 GWh in the BPSs. The solar resource potential increases northward due to diminishing monsoon influence. Likewise, highest wind potential is found towards the north/north-west. These factors contribute to high solar PV and wind energy installed capacities in Niger and Mali. WA has the solar and land resources to technically host a power system led by a mix of RE technologies. However, assessments of solar PV and wind power mixes for WA are rare [4]. The required land area for solar PV and wind installation is estimated based on the specified capacity density assumed in the model, which is 8.4 MW/km^2 and 75 MW/km^2 for onshore wind and optimally tilted PV respectively [32]. Therefore, an area of 1454 km^2 and 3784 and is needed for wind and solar PV capacities by 2050, representing just 0.03% and 0.07% of the total land area of WA. The results of this research reveal that solar PV will emerge as the backbone of WA power system, which is similar to the results of Oyewo et al. [19] for Nigeria. They conclude that solar PV will contribute significantly to Nigeria's future power system and it is comparable to any other developing countries with similar climates. Adeoye and Spataru [31] show that the high integration of solar PV plants will reduce the supply-demand gap and load shedding in the WA by 2025. According to Ref. [31], 71 GW of solar PV plants is assumed to be installed and in operation across WA. The BPSs results are also similar to results of Barasa et al. [26] for entire Sub-Saharan Africa (SSA) based on an overnight scenario approach for 2030 conditions, they conclude that countries in SSA

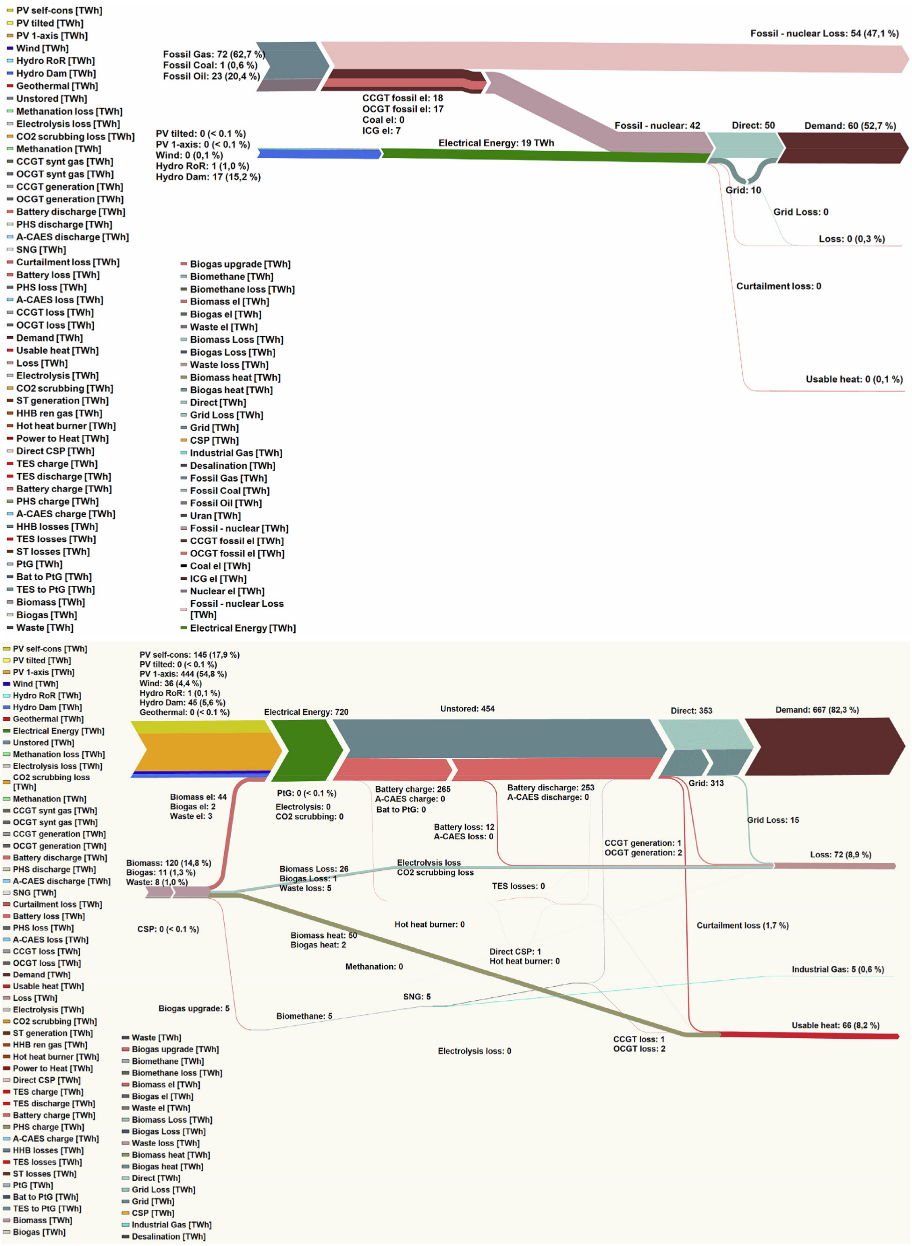

Fig. 17. Energy flows of the system for 2015 (top) and BPS in 2050 (bottom).

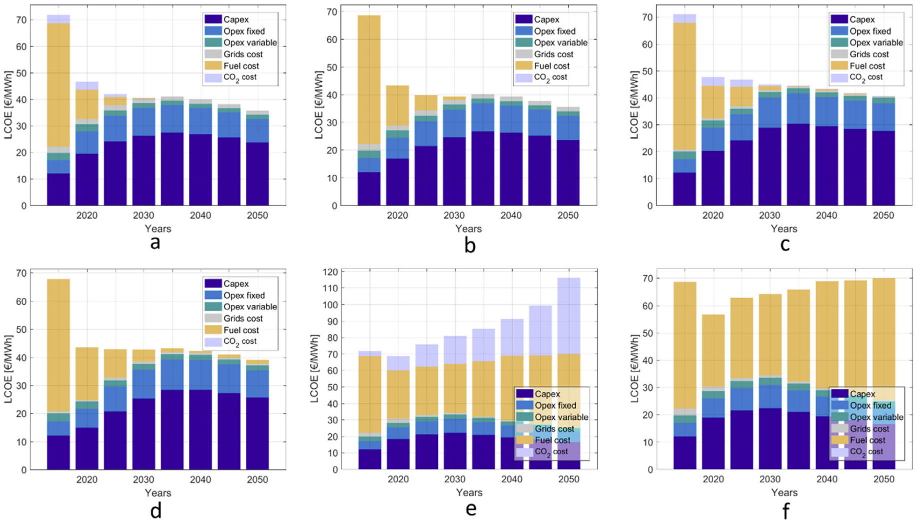

Fig. 18. Levelised cost of electricity for BPS-A (a), BPSnoCC-A (b), BPS-C (c), BPSnoCC-C (d), CPS-A (e) and CPSnoCC-A (f) from 2015 to 2050.

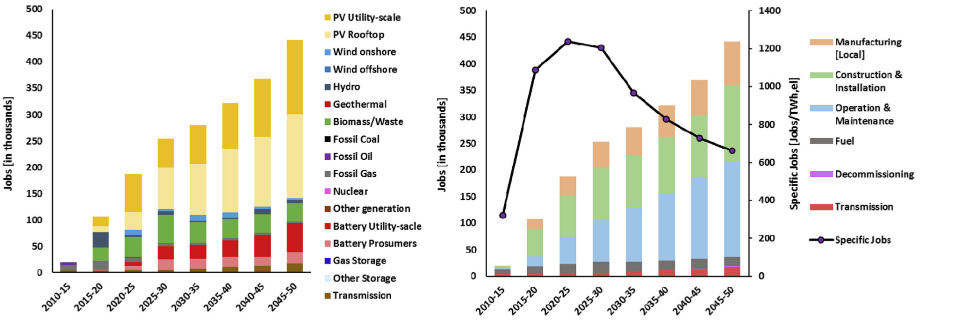

Fig. 19. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in West Africa for the BPS.

can be powered majorly by wind energy and solar PV. A recent study by IRENA [30], shows that the grid connected solar PV market would be over 20 GW by 2030, compared to just over 8 GW in their Reference Scenario (RS). The IRENA National targets scenario achieved a share of 37% RE. According to Ref. [30], solar PV installed capacity is 21.5 GW, wind is 1.6 GW and hydropower is 11.5 GW by 2030, the remaining generation capacity supplied by fossil generators is dominated by gas turbines with about 30 GW. In the CPSs, fossil-based thermal generators and hydropower dominate the power system accounting for 532 TWh (78%) and 120 TWh (18%) respectively by 2050. The results of the CPSs are comparable to the New Policy Scenario (NPS) of the IEA [17]. According to Ref. [17], fossil-based thermal generators dominate with 323 TWh (68%) of which, gas supply is 249 TWh (53%), followed by hydropower with 100 TWh (21%), bioenergy with 12 TWh (3%), solar PV with 17 TWh (4%) and other renewables with 21 TWh (4%). Similarly, gas and hydropower are expected to roughly triple in the IRENA Reference Scenario by 2030 to 32 GW and 11.5 GW, respectively [30]. It is worth mentioning that despite the huge potential for CSP as alternative technology to harness the Sun's energy in WA, future costs appear to be a bottleneck for CSP development. CSP installed capacities ranged from 0.1 to 1 GW, the highest installed capacities occur in the CPSs and lowest in the BPS across the countries, whereas no CSP is installed in the BPS across the area. Overall, the ECOWAS Renewable Energy Policy (EREP) targets for grid-connected capacity for solar PV, wind energy and CSP by 2030, in WA is very low at 1 GW for each [3]. It is obvious that solar PV and wind energy will be very relevant in a least-cost expansion for WA future power sector, while policies to facilitate their deployment are exigent.

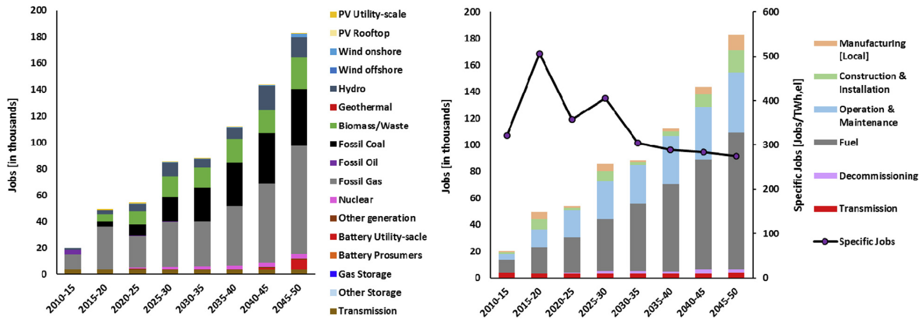

Fig. 20. Jobs created by the various power generation and storage technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in West Africa for the CPS.

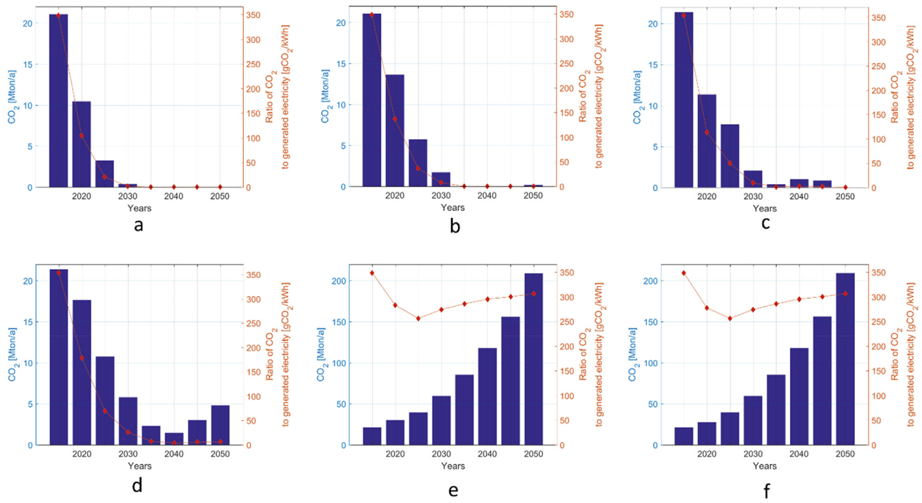

Fig. 21. GHG emissions trajectories for BPS-A (a), BPSnoCC-A (b), BPS-C (c), BPSnoCC-C (d), CPS-A (e) and CPSnoCC-A (f) from 2015 to 2050.

4.2. Flexibility requirement

Flexibility is harnessed from dispatchable renewables (mainly biomass and hydropower), transmission grid, curtailment and storage technologies, which facilitates the high shares of solar PV as seen in the BPSs. The relevance of storage technologies appears to be more vibrant in the BPSs, due to increasing shares of solar PV in the national power systems. Power grids dominated by solar PV are typically characterised by high storage needs [27]. In the BPSs, the relevance of storage technologies, particularly battery storage, increases over time. The PV-battery hybrid system appears to be a least-cost option for the WA power system by 2050, which is similar to the results of Oyewo et al. [27] for the Nigerian power system. Similar results have been obtained for the competitiveness of hybrid PV-battery plants for the case of Morocco [50]. In addition, battery cost has declined over the years, and further cost reduction is expected [51,52]. In terms of storage capacities requirement, gas storage leads in all the BPSs followed by battery storage. However, battery storage dominates when storage throughputs are considered, due to daily requirement in the absence of solar PV. Several studies have shown a need for storage, once the share of RE power generation reaches approximately 50% [28,32,37,49]. Consequently, with a share of 80% RE, seasonal storage is required [32]. The long term and seasonal storage is compensated by TES, adiabatic compressed air energy storage (A-CAES) and power-to-gas (PtG). Seasonal storage contribution is not required in the BPS across the area in comparison to BPS across the countries. Rather, bioenergy and hydropower are sufficient in compensating the seasonal variation in the BPS across the area, along with the vital flexibility provided by cross-border interconnections. As a result, only 9.5 GW PtG conversion units are needed in the BPS across the countries, whereas no PtG conversion units are needed in the BPS across the area. This rather rare phenomenon is also observed for Brazil, based on an overnight scenario approach for 2030 [53]. According to Ref. [53], a 100% RE system can be operated with extremely low seasonal storage based on PtG, this special condition is traceable to very high shares of dispatchable hydropower reservoirs and equatorial weather conditions. Hydropower reservoirs could be considered as virtual batteries, if operated in conjunction to solar PV systems [54]. The extraordinary growth of wind energy, plus some PV and bioenergy in Uruguay can be attributed to its massive hydropower, which can cover shortfall in wind, plus cross-border interconnections [55]. Under the right circumstances, as seen in the BPS area, a mix of RE appears to be a good candidate for the WA power sector. The synergies of RE resources limit the need for storage, improve system flexibility, and reduce day-to-day and inter-annual variability of the system as observed in the BPS area.

Furthermore, the flexibility function of the grid appears to be more vibrant in the BPS across the area for counterbalancing the regional power mismatches. Graphical results on grid utilisation are presented in the Supplementary Material (S7). Grids are a very important flexibility option, and their function will be discussed in more detail in the next section. Curtailment is another flexibility option. Curtailment is widely expected to increase with more VRE [49,56,57], as observed in this research. The question, whether to avoid curtailment or not, is debated increasingly [56], based on the perception that curtailment would be a mere waste of energy, despite the reported technical benefits [49]. Conversely, curtailment is another valuable resource, helping to stabilise the grid and improve system flexibility [57]. Avoiding curtailment requires investing in grid interconnection and storage solutions [56]. Contingencies in the power system can be reduced by curtailment of generation, which appears to be higher in the BPS across the countries than in the BPS across the area. The curtailment-storage-penetration nexus in the energy transition is researched in Ref. [49]. A set of two scenarios were examined in Ref. [49], the first scenario anticipates a limit on curtailment, while the other expects an optimal transition with curtailment considered as a technical solution to minimise mismatch in demand and supply. According to Ref. [49], "curtailment in optimally managed energy transition brings techno-economic opportunities to the system, while no curtailment or improper use of curtailment carriers a penalty".

The WA electricity generation depicts a tendency towards flexibility and complementarity as observed particularly in the BPSs. The need for flexibility will continue to increase in systems dominated by RE such as BPSs, as solar PV appears as the default technology choice for low-cost bulk energy in the power sector, in particular in Sun Belt countries [26,28,37,49,50]. Based on the foregoing discussion, gas power plants appear to be a valuable and flexible peaking technology when required, particularly during the monsoon periods. Several studies have identified gas turbines as a flexibility option for systems dominated by high RE shares, instead of coal or nuclear [19,28,57,58]. A recent study concludes that required flexibility could be provided by using flexible natural gas fired turbines, if the costs of battery do not decrease [59]. Furthermore, there are strong signals that electricity will contribute significantly to the future energy system. An electricity-led energy system will reduce primary energy demand and further increase system flexibility by coupling the decarbonised electricity to heat, transport and industrial sectors [25,60]. What is more, PtG and power-to-liquids solutions can be used to supply residual demand for fuels and chemicals that cannot be replaced with electricity directly [25,60].

4.3. Benefits of cross-border electricity trade

The interconnection of sub-regions in WA offers multiple benefits. Broad cost saving opportunities and increased flexibility in the power system is achieved due to grid interconnections between sub-regions of WA. The transmission network facilitates the exploitation of best RE production sites and smoothens out day-to-day variability. The transmission interconnections have the potential to reduce the LCOE, total system cost, installed capacities, storage requirements and curtailment in a highly renewable WA power system, as observed in the BPS across the area. With GHG emissions costs, the LCOE drops to 40.6 €/MWh in the BPS across the countries and to 35.7 €/MWh in the BPS across the area by 2050. Without GHG emissions costs, LCOE decreases to 39.0 €/MWh in the BPS across the countries and to 35.5 €/MWh in the BPS across the area. Likewise, the total annualised cost of system is 27.2 b€ in the BPS across the countries and it is 23.9 b€ in the BPS across the area with GHG emissions costs. Without GHG emissions costs, the total annualised cost of system is 26.1 b€ in the BPS across the countries and it is 23.8 b€ in the BPS across the area. This implies annual cost savings of 9% or 2.3 b€/a in the BPS across the area without GHG emissions costs, and is 12% or 3.3 b€/a with GHG emissions costs. This result requires special highlighting: the BPS across the area with and without GHG emissions costs lead practically identical energy system solutions. Table 5 highlights the key differences in financial outcomes and selected electricity parameters for 2050. It can be seen that the system costs are more or less the same as shown in Table 5 for the BPSs, which implies that with or without GHG emissions costs, the WA power sector can reach 100% RE as the least cost solution. What is more, the BPSs without GHG emissions costs leads to 98% and 99% RE generation in the area and country scenarios, respectively.

With transmission and GHG emissions costs, the BPS across the area shows approximately 12% less installed capacities (327.9 GW vs 370.8 GW), 70% less storage capacity (3.1 TWh vs 10.4 TWh) and 22% less storage output (259.2 TWh vs 332.9 TWh) than the BPS across the countries. Likewise, with transmission and no GHG emissions costs, the BPS across the area shows a reduction of about 10% of installed capacities (325.2 GW vs 360.5 GW), 11% less energy storage capacity (2.4 TWh vs 2.7 TWh) and 4% less storage output (256.2 TWh vs 266.5 TWh) compared to the BPS across the countries. Faster defossilisation of the power system can be achieved as observed in the BPS across the area in comparison to the BPS across the countries. The remaining cumulative GHG emissions are approximately 37% lower (75 $MtCO_{2eq}$ vs 119 $MtCO_{2eq}$) in the BPS across the area with GHG emissions costs, without GHG emissions costs it is about 51% lower (109 $MtCO_{2eq}$ vs 221 $MtCO_{2eq}$) both compared to the BPS across the countries and aggregated from 2018 to 2050.

Investments in the transmission and distribution (T&D) infrastructure are vital for any emerging power grid system, such as WA. For instance, to facilitate the export of wind production from Niger and Mali as observed in the BPS across the area from 2025 onwards, the development of the North-core interconnection linking Niger, Nigeria, Benin and Burkina Faso is significant. According to IRENA [30], the development of nearly all cross-border transmission projects between WA countries currently in the pipeline appear to be beneficial. The World Bank (WB) estimates the economic benefits of the WAPP at 5–8 bUSD per year. Through the International Development Association (IDA), 750 mUSD of current WB support is directed towards the completion of the primary interconnections in WA. About 4000 km of grid lines are currently under development, all to be completed in the early 2020s [13]. According to the IEA NPS [17], the cumulative investment in T&D lines for the WA power sector is 229.3 bUSD from 2014 until 2040.

4.4. Off-grid electrification

The development of T&D infrastructure is recognised as a solution to the challenges of low access and unstable power

Table 5
Differences in key energy system parameters and financial results in 2050 under various scenarios.

	unit	BPS-A	BPSnoCC-A	BPS-C	BPSnoCC-C	CPS-A	CPSnoCC-A
Total annual levelised cost	[b€]	23.9	23.8	27.2	26.1	78.9	47.5
Levelised cost of electricity	[€/MWh,el]	35.7	35.5	40.6	39.0	116.2	70.0
Generation	[TWh,el]	723.2	722.7	754.7	732.5	683.4	
Installed capacity	[GW]	327.9	325.2	370.8	360.5	129.7	
Storage capacity	[TWh,el]	3.1	2.5	10.4	2.7	0.06	0.06
Curtailment	[%]	4.1	4.1	6.1	5.8	0.5	

supply in the region [17]. According to Ref. [17], most of the investments in electrification expansion in SSA go towards on-grid access, new T&D lines account for more than half of the investments. WA accounts for the largest share of the investments with around 75 bUSD (37%). Bertheau et al. [61] investigate the impacts of grid expansion in SSA, using geospatial methods. The results shows that around 190 million West Africans lack access to electricity. The first scenarios based on exsisting grid indicates 17% mini-grids, 43% grid extension and 40% solar home systems (SHSs). Whereas the planned grid scenario outcome indicates 12% mini-grids, 58% grid extension and 30% SHSs, hence more by grid extensions. Another research on electrification planning in SSA by 2030 [62], shows an investment need between a low of 19.3 bUSD (20% grid expansion, 0% mini-grid and 80% SHS) and a high of 370.6 bUSD (78% grid expansion, 16% mini-grid and 6% SHS) to provide universal access in WA [62]. The grid extension approach appears to dominate in all electrification expansion scenarios [61,62]. However, this approach may not eradicate energy poverty in regions like WA, due to complexity of rural settlements, poorly developed infrastructure and costs of grid extension [63]. Thus, off-grid solutions like mini-grids and especially SHS provide a least cost and potentially very fast applicable solutions for achieving rural electrification [63,64]. A recent study analysed the complete implications of mini-grid/off-grid electrification plans with a solar PV plus battery storage technology option for Nigeria [65]. According to Ref. [65], a 233 cluster covering 7.2 million people requiring 3280 MW solar PV and 7518 MWh battery capacities was derived as the best location for mini-grids auctions in Nigeria, while LCOE ranged from low 0.18 USD/kWh in the North to a high 0.25 USD/kWh in Southern Nigeria.

4.5. Benefits of a 100% RE system

The modelling outcomes show that a 100% RE system is the least-cost, least-GHG-emitting and most job-rich option for the WA power system, as observed in the BPSs. The PV-battery hybrid system appears as the backbone of the least-cost generation mix by 2050. The LCOE obtained for the BPSs is comparable to Barasa et al. [26], which shows a range of 35.2–47.6 €/MWh for SSA. The annualised cost of the system obtained for the year 2050 is 23.9 b€, 23.8 b€, 27.2 b€, 26.1 b€, 78.9 b€ and 47.5 b€ in the BPS-A, BPSnoCC-A, BPS-C, BPSnoCC-C, CPS-A and CPSnoCC-A, respectively. With GHG emissions costs, the total annualised cost is 70% higher in CPS than in the BPS, and is 50% higher without GHG emissions costs. The cost reduction effect observed in this study matches the experience of the energy transition in Uruguay. Uruguay made dramatic shifts to about 95% electricity from RE in the past 10 years, while reducing costs, building on its existing hydropower and new RE mainly wind energy, with some solar PV and bioenergy [66]. The results of this research show that the RE-based system is not only technically feasible, but also economically viable in WA. Such a finding is characteristic for 100% RE systems all around the world as highlighted by Brown et al. [67]. Most of the cost reductions in the BPSs can be attributed to low costs of RE technologies particularly solar PV and batteries. The costs of investments in RE technologies in the BPSs are offset by savings in fuel costs from displaced fossil-based generators, which is similar to the finding of Adeoye and Spataru [68], for WA region based on overnight approach for the year 2030. However, investments in fossil-based generators, as observed in the CPSs, will continue to be a burden on the WA's economy. The high costs in the CPSs are due to new investments in thermal generators, which are finally run on high full load hours that lead to enormous fuel costs. Furthermore, investments in fossil technologies are prone to cost overruns and schedule spills [69], they violate all sustainable criteria discussed in Ref. [70] and are likely to become stranded assets [35].

Beyond the robust techno-economic analysis of WA power systems, the LUT model also computes the emissions trajectory under various scenarios. The emissions pattern depicts the trajectory of RE deployment under various scenarios. In the BPSs, zero emission is achieved by 2050, however, the BPS across the area shows a rapid decarbonisation. Consequently, GHG emissions in the CPSs increased to about 60 $MtCO_{2eq}$ in 2030, which is comparable to the findings in Refs. [30], which shows a range of 70–80 $MtCO_{2eq}$ in 2030. By 2050, GHG emissions in the CPSs are about 209 $MtCO_{2eq}$. Investigating the impact of GHG emissions costs throughout the transition, the BPSs achieved a rapid decline in GHG emission in comparison to applying no GHG emissions costs. Without GHG emissions costs, the RE electricity generation reaches 99.9% (722.2 TWh) in the BPS across the area by 2050, while the remaining 0.1% (0.5 TWh) is supplied by gas turbines using fossil gas. Conversely, the RE generation in the BPS across the countries reaches 98.4% (721.0 TWh), while the remaining 1.6% (11.5 TWh) is supplied by gas turbines using fossil gas.

The energy transition is expected to lead the creation of new jobs, transformation or substitution of existing jobs and elimination of certain jobs, either as a complete phase out or at least a significant reduction without direct replacement [25]. The RE development in WA will facilitate socio-economic development, particularly job creation. Employment creation under various scenarios is examined in this research. The BPSs will create more jobs in comparison to the CPSs. Opponents of renewable energy often question if the sector can ever realistically create the numbers of jobs as a system based on large-scale fossil generators [25]. The results of this study show that RE dominated scenarios create more than twice the jobs compared to fossil-based scenarios. A 100% RE system would employ 440 thousand people in WA and solar PV emerges as the major job creating industry, employing about 300 thousand in 2050. A study found that replacing the millions of kerosene lamps, candles and flashlights with modern solar lighting technologies for people living off-grid could create 500 thousand new light-related jobs in the ECOWAS region [71]. Several studies [25,34,71] indicate that a shift in the energy landscape from fossil to RE technologies creates more jobs, which is comparable to the findings of this research.

4.6. Impact of changing parameters on results

Our findings indicate the significance of PV technologies and batteries as vital for the transition, due to anticipated decline in CAPEX. However, it is worth mentioning that changing cost parameters would influence technology deployment, as it appears that the costs and share of installed capacities of technologies are directly related, which is a predominant aspect of cost optimal future energy systems. Latest insights of Vartiainen et al. [72] indicate that the applied PV and battery CAPEX assumptions are rather conservative.

It should be noted that a uniform WACC of 7% is applied across the region, which is in line with leading international reports such as of IEA [73], IRENA [24] and journal publications [74–76]. However, Egli et al. [77] argue that uniform cost of capital (CoC) may result in distorted results and policies. It is worth mentioning that there are no better methods on offer to estimate future CoC values, uniform CoC remains the most ideal solution available. According to Bogdanov et al. [78] "proper choice of CoC assumption has a strong impact on the results of any energy system analysis and its uncertainty has to be considered in an analysis of the results". Further, not all countries in WA fulfil the WACC assumption today; some uncertainty is induced by the WACC assumption. However, economic development in WA will lead to a more stable and lower WACC during the transition.

5. Conclusions and policy implications

The modelling outcomes show two distinctive features for the WA power system: expansion and transition. This study foresees transition of the WA power sector in exploiting the region's abundant RE resources, which includes solar PV, wind energy, biomass and hydropower. Solar PV emerges as the new bulk electricity provider of the WA power sector as illustrated in the BPSs. Solar PV dominates in all the BPSs by 2050, and contributes the most (87–89%) to the total installed capacities and (81–85%) overall generation mix, respectively. In WA a 100% RE-based power system can run with low seasonal storage based on PtG conversion as observed in the BPS across the countries, whereas seasonal PtG storage is not required in the BPS across the area. Dispatchable RE hydropower reservoirs and bioenergy maintain a vital functionality in balancing seasonal variations in the WA power system. The solar PV, wind energy, hydropower and bioenergy synergies lead to a substantial reduction in storage requirements. The risk of day-to-day variability and capacity requirements reduce with higher transmission interconnection among the sub-regions, leading to increased system flexibility, broad cost savings and rapid defossilisation.

This study shows the need for substantial power generation capacity expansion due to under-capacity and growing demand in WA. Electricity demand grows 10 times by 2050 in comparison to 2015, while the installed capacity ranges from about 325 to 370 GW in the BPSs, and is about 130 GW in the CPSs. The capacity requirements are about 3 times higher in the BPSs than in the CPSs. This is due to RE technologies running on low FLH, particularly solar PV, while total electricity generation in the BPSs is around 6% higher than in CPSs. What is more, there are on-going plans to construct new fossil-based power plants in WA. These power plants are susceptible to cost overruns and schedule spills. In addition, the discoveries of new fossil fuels might pose a challenge to RE development in the region. However, this research presents a critical dimension of the transition for WA, which has to do with the cost-competitiveness of RE technologies as observed in the BPSs in comparison to the CPSs. Aside, the monumental and mounting costs of fossil-based technologies in the CPSs, such power systems violate sustainability principles that form the basis of a resilient power system. What is more, the BPSs without GHG emissions costs lead to 99.9% renewable in the BPS across the area and 98% in the BPS across the countries, while the remaining generation is covered by fossil fuel-fired gas turbines. This indicates pure market economics, even if the massive cost for GHG emissions cost would be allocated fully as subsidies for the fossil system by neglecting any price for the massive climate change costs. It will be imprudent for WA countries to invest in new fossil technologies, particularly coal power plants, but also nuclear. The fleets of RE technologies are accompanied by flexible gas turbines in the BPSs, however with fast declining full load hours. No new coal and nuclear power plant capacities are built in the least-cost expansion pathways for WA.

The ECOWAS energy policy should place solar PV at its core. Hybrid solar PV-battery power systems appear the least-cost solution for the region. A strong transmission grid infrastructure can enable substantial wind electricity generation from Niger and Mali, which can further reduce the entire energy system LCOE of WA. This research shows that a fully renewable electricity system is technically feasible and economically viable. A 100% RE system is a most efficient, least-cost, least GHG emission and most job-rich option for WA and is compatible with the Paris Agreement and the Sustainable Development Goals of the United Nations. This kind of power system is achievable with the vast RE resources of WA and it represents a real policy option for the region. It is noteworthy that a substantial roll-out of RE capacities in the BPSs does not require any subsidies at all. It is a least-cost option for the WA power system without subsidies. Consequently, subsidies might be unavoidable if a policy-driven deviation from this techno-economic least-cost option is pursued. A well-designed policy framework that limit new investments in conventional power plants, comprehensive energy market reforms and ambitious RE targets with a long-term perspective is needful in WA. Additionally, supportive policies that will strengthen cross-border electricity trade are vital for the WAPP. Further research has to be carried out incorporating additional energy sectors, i.e. heat, transport, industry and desalination, for broader analyses and to better understand the benefits of sector coupling for developing regions like WA.

Credit author statement

Ayobami Solomon Oyewo carried out main parts of the research and writing the manuscript. Arman Aghahosseini contributed to the research development. Manish Ram contributed to the research development. Christian Breyer framed the research questions and scope of the work, checked the results, facilitated discussions, and reviewed the manuscript.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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