Ayesha Sadiqa

SUSTAINABLE ENERGY TRANSITION FOR PAKISTAN: ASSESSING THE ROLE OF ENERGY, WATER SUPPLY, SOCIAL AND GENDER EQUITY DIMENSIONS

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Abstract

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The main aim of this dissertation is to evaluate the energy, water and social dimensions of a 100% renewable energy system in Pakistan. Techno-economic aspects of the sustainable energy transition are assessed by modelling various scenarios integrating electricity, transport, heating and desalination sectors. Moreover, gender vulnerabilities of low-carbon transitions are mapped by a systematic review of the available literature since gender was under-researched in low-carbon transition studies.

To model Pakistan’s 100% renewable energy pathways, the LUT Energy System Transition Model (LUT-ESTM) is used in this dissertation. LUT-ESTM linearly optimises the target function, i.e., to choose the least annual cost option for the energy system. LUT-ESTM is characterised by its high spatial and temporal resolution, multi-nodal power transmission network, and sector coupling. Pakistan’s energy system is analysed using 5-year intervals from 2015 to 2050. The possibility of a transition to an entirely renewable energy-based system is demonstrated, using the country’s own renewable resources. Examining different flexibility options, such as storage and Power-to-X, is necessary to integrate significant amounts of variable renewable energy in the system.

An energy transition from the present fossil fuel-dependent power and energy system towards 100% renewable energy is achievable by incorporating large shares of solar photovoltaic, accompanied by wind power, hydropower, and modern bioenergy uses. However, obstacles and needs for new flexibility solutions arise with integrating substantial percentages of variable renewable energy into the energy system. As presented in this dissertation, batteries, transmission grids, and Power-to-Gas provide the required flexibility for a 100% renewable energy-based system. This energy transition not only reduces the cost of electricity but also offers other implicit economic, environmental, and societal advantages like decreasing emissions, producing additional jobs, and lowering dependence on fossil fuels. Furthermore, as one of the extremely water-stressed nations in the world that is completely reliant on the availability of fresh groundwater resources and highly inefficient irrigation systems, seawater desalination utilising affordable renewable energy offers a viable solution, solving the nation's present and future water crises.

The outcomes of this dissertation provide scientific knowledge for the discourse on the necessity of a sustainable, clean, and cost-effective energy transition in the country. Therefore, this dissertation will contribute to the body of knowledge that such a transition from the present energy system towards a 100% renewable energy-based system is technically possible and economically competitive. The analysis also provides several insights into the techno-economic viability of a fully sustainable energy system, hoping it will aid researchers and policymakers in Pakistan in addressing issues about the energy system and water scarcity. In addition, it is anticipated that the work on gender vulnerabilities will collectively advance the understanding of the disproportionate distribution of the benefits and challenges connected with low-carbon transitions and their relationship to social and political inequalities for different genders. Developing a fully renewable energy-based energy system would need undivided attention, political willpower, and tight coordination among all the involved parties at the local and national levels.

Keywords: energy transition, renewable energy, energy storage, cost optimisation, energy system flexibility, sector coupling, Power-to-X, monsoon, Pakistan, Gender, vulnerabilities

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Ayesha Sadiqa
October 2023
Lappeenranta, Finland

The thesis is dedicated to all women entrepreneurs, scientist and activists who are leading the fight for global sustainability.

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Publications

List of publications

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

I. Sadiqa, A., Gulagi, A., & Breyer, C. (2018). Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. *Energy, 147*, 518-533.
II. Sadiqa, A., Gulagi, A., Caldera, U., Bogdanov, D., & Breyer, C. (2021). Renewable energy in Pakistan: Paving the way towards a fully renewables-based energy system across the power, heat, transport and desalination sectors by 2050. *IET Renewable Power Generation, 16(1),* 177-197
III. Caldera, U. Sadiqa, A. Gulagi, A. Bogdanov, D. Breyer, C., (2021). Irrigation efficiency and renewable energy powered desalination as key components of Pakistan's water management strategy, *Smart Energy, 4,* 100052.
IV. Sadiqa, A. Sahrakorpi, T. Keppo, I., (2023). Gender vulnerabilities in low-carbon energy transitions: a conceptual review, Environmental Research Letters, 18, 043004.

Author's contribution

Ayesha Sadiqa is the first author and researcher in **Publications I, II and IV**. In **Publication I, II and IV**, Ayesha Sadiqa led and assisted in conceptualising the research, data collection and analysing, investigated, examined the results, and interpreted the conclusion and discussion. Simulation for **Publication I and II** was performed by Ashish Gulagi. In **Publication III**, Upeksha Caldera carried out the simulations and paper writing. Ayesha Sadiqa collected the data, contributed to the paper writing, drew the key conclusions and ensured the framing for Pakistan.

Nomenclature

Abbreviations

A-CAES	Adiabatic compressed air energy storage
b€	Billion Euros
BPS	Best Policy Scenario
Capex	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CSP	Concentrating solar thermal power
DH	District heating
FLH	Full load hours
FPE	Feminist Political Ecology
FT	Fischer-Tropsch
GHG	Greenhouse gases
HPIE	Highest possible irrigation efficiency
HVDC	High-voltage direct current
IEA	International Energy Agency
IEP	Irrigation efficiency push
IH	Individual heating
LCOC	Levelised cost of curtailment
LCOE	Levelised cost of electricity
LCOG	Levelised cost of gas
LCOS	Levelised cost of storage
LCOT	Levelised cost of transmission
LNG	Liquified natural gas
LUT-ESTM	LUT Energy System Transition Model
MED	Multiple Effect Desalination
MSF	Multi-Stage Flash
NTDC	National Transmission and Dispatch Company
OCGT	Open-cycle gas turbine
Opex	Operational expenditure
PHES	Pumped hydro energy storage
PtG	Power-to-Gas
RE	Renewable energy
RFO	Residual fuel oil
RLNG	Regasified liquifies natural gas
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
WACC	Weighted average cost of capital

1 Introduction

1.1 Need for a Sustainable Transition of the Energy System

The imperatives of climate change, energy poverty, security, and sustainability have made adopting renewable energy (RE) technologies an essential solution. In the past decade, policy drivers, technological advancements, and decreasing prices of renewable technologies have moved these technologies to the mainstream. Nearly 80% of the world's population resides in nations that import fossil fuels. Furthermore, technological innovations have made significant progress in electric mobility, storage, and digital technologies.

Climate change also exacerbates social, gender, ethnical, and geographical vulnerabilities. A transition of the global energy system aligned with the Paris Agreement can become a great equaliser of the world. Significant progress has been made during the last few years, but uneven across geographies and communities. Every country possesses RE sources that could offer a way out of this import dependence while driving economic growth and development opportunities. It is a political choice to put policies in place that are aligned with climate change goals and a sustainable development agenda. Fossil fuel investments will only perpetuate uneconomic practices and increase climate change hazards. Over 90% of the emerging solutions to climate change involve renewable technologies through energy efficiency, electrification, green hydrogen, and bioenergy. A transition of the energy system can bring new economic growth prospects, social equity, employment, and energy security. However, such energy transition benefits will be possible only if the transition happens in a just and inclusive manner. Governments must take the lead on goalsetting to align the transition with several Sustainable Development Goals, particularly SDG 3 (good health and well-being), 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry, innovation, and infrastructure), 11 (sustainable cities and communities), 13 (climate actions) and achieve multiple social and economic priorities. The involvement of the private sector, communities, civil society, youth, and women is crucial for the design of a fair and just transition process.

According to the World Bank, South Asia is most vulnerable to climate change. IPCC (Intergovernmental Panel on Climate Change) highlights that Pakistan’s rural and urban areas will face more significant challenges related to climate change in the coming decades. According to IRENA, more than half of the rural population and over 25% of the total population in Pakistan do not have electricity access, while around 20% is not connected to the grid. To achieve the national goals, Pakistan needs to expand RE rapidly, reaching 20% of the installed capacity by 2025 and 30% by 2030. A significant part of Pakistan’s energy generation depends on conventional energy sources. However, conventional electricity generation options are no longer competitive due to the declining cost of renewable technologies.

Moreover, the power system has inefficiencies, high transmission and distribution losses and non-technical losses. To address these issues, new laws and policies in Pakistan have increased the urgency of transitioning to clean energy technology throughout the country's energy sector. Renewable energy sources, including solar, wind, geothermal, hydropower, and biomass, must be integrated into Pakistan's modern energy system.

In the case of Pakistan, solar PV and wind power offer economically and technically feasible solutions with off-grid and on-grid options by paying more attention to rural areas and the energy generation sector. RE provides a significant possibility to secure energy access in rural and scattered communities. However, a system dominated by variable RE (VRE), particularly with high shares of solar PV and wind power, raises the challenge of meeting the demand in hours of low generation. Security of supply of such a system is persistently expressed as a challenge and concern. Various options are available to overcome the variability of the energy system. Existing grid infrastructure and the cost-effectiveness of the overall energy system are the primary factors in selecting a solution for the uncertainty of RE systems. The system's flexibility to accommodate the variability of RE could be achieved by storage, operational practices, demand side flexibility, and other mechanisms. Furthermore, the most obvious and widely publicised barrier to RE is cost, specifically capital costs, or the upfront expense of building and installing solar PV and wind power plants. Considering these projects as risky with low rates of return on their invested capital, the reluctance of banks and financial institutions to finance them has been the major barrier to the expansion of RE in Pakistan. Several reports have evaluated that different nations and areas are capable of making the transition to a completely environmentally friendly energy system.

1.2 Techno-economic and Social Sustainability of the Energy System

Energy policies and practices need to integrate all three dimensions of sustainability to accomplish the global policy objectives of energy security, climate change mitigation, and sustainable economic growth. Sustainability has environmental, social and economic dimensions. (Jeswani et al., 2010; Ness et al., 2007; Oyewo et al., 2021). Each country and region’s economic and social characteristics influence the resilience and sustainability of the energy system and supply chain. The social component of the energy transition has received less research attention than the environmental and financial components (Geels et al., 2017a). All three dimensions of sustainability must be considered in the implementation and planning of RE projects to build a truly sustainable supply chain, implementing generation, consumption and socio-cultural aspects of the region. The problem identified with the fast realisation of the energy projects is an underestimation of the social dimensions of the project. As a result, negative perceptions of RE projects may decrease the ability to mitigate climate change (Asantewaa Owusu & Asumadu-Sarkodie, 2016; Badri Ahmadi et al., 2017).

Negotiations with local communities must be vigorous to successfully transform the existing energy system into affordable and self-sufficient renewable resources. As observed from the issue of the Danish Island of Samsø and the Sarulla geothermal power plant in Indonesia, energy system change was achieved by negotiation and integrating the community and regional stakeholders as strategic and economic partners (Marczinkowski et al., 2019; Pater, 2017). Therefore, planning energy supply networks and policies should prioritise the social dimension. Data based on social dimensions have not been thoroughly examined because of the lack of integration of social factors (Obrecht et al., 2020). Lund et al. (2014) explain that awareness of the choices is the key to achieving a 100% RE system, and this needs the availability of data on various alternatives to stakeholders. According to Henrik (2014), public awareness of the different alternatives is the key enabler for a successful energy transition. Gains, shortcomings and vulnerabilities associated with each alternative solution should be intensively discussed with stakeholders (Gareiou et al., 2021). The energy producers and distributors who affect the implementation of energy policy are not just a few large companies but also the increasing numbers of prosumers and small and mid-size firms (Segreto et al., 2020). This requires additional data sharing, but consequently, it will improve the efficiency and public acceptance of solutions (Lund et al., 2017).

1.3 Motivation and Key Research Questions

This dissertation aims to stimulate, develop and investigate comprehensive energy transition pathways for Pakistan's low-cost, sustainable and reliable energy supply. Moreover, social and gender dimensions of the energy transition are investigated. This dissertation provides a detailed insight into Pakistan’s energy transition to a 100% RE system, including the power, heat, transport, and desalination sectors. There aren't many high-resolution spatial and temporal RE transition studies for Pakistan. This dissertation examines how using a high share of renewable energy will help Pakistan's electricity market operation satisfy the region's growing demand. To address these issues, this dissertation investigates how and why flexible electricity production, transport, and storage options might help shape the energy sector from 2015-2050. The core questions driving this research are: Is a completely renewables-based electricity supply technically viable for Pakistan? How much a fully renewable electricity and power system would cost? Would such a system ensure the security of supply in terms of availability, affordability, and independence? How heat and transport sectors could be fully renewables-based in the system and how much it would cost? To answer the research questions, this dissertation evaluates the technological transition in the country by exploring different renewable resources like solar, wind, hydro, geothermal, and biomass with various storage options. It also considers how this energy transition could be implemented from a technical and financial point of view that not only the demand for power and storage could be met by available resources, but it is also the least cost option for Pakistan (**Publication I-II**).

Pakistan's energy system relies heavily on desalination due to the country's high saltwater content. It has been stated that the country is one of the top 10 most water-stressed nations (ANI, 2023). This dissertation analyses the feasibility of using renewable energy RE-based water desalination technologies and an enhanced irrigation system to address the nation's water shortage problem (**Publication III**). The main questions leading this research are: What is the possibility of using RE-based seawater desalination and improved irrigation systems to address water stress issues in the country? Is it technically and economically possible? And how much such a system will cost? Efficient, low-cost and sustainable options were explored to address the looming water stress and demand-supply gap in Pakistan that are aligned with the climate mitigation goals of the country.

Beyond the energy transition's financial and technological analyses, social and gender vulnerabilities related to low-carbon energy transitions were also mapped using the conceptual literature review method. The gender dimension of energy transitions is an under-researched area in literature. The aim is to fill the gap in the literature and provide policymakers with insight into potential risks that could emerge or be strengthened by the low-carbon energy transitions. **Publication IV** explores the gender implications of low-carbon energy transitions in literature and links them with low-carbon modelling pathways. The goal is to identify and map gender-related vulnerabilities nationally and internationally. It also aims to document the parameters and factors that could lead to these vulnerabilities and risks. Furthermore, **Publication IV** also explores the drivers (increase in price, land use change, gender-neutral policies) in low-carbon transition that could lead to gendered vulnerabilities (livelihood change, water regime change, loss of jobs, etc.). The overarching question is how incorporating low-carbon technology into existing energy infrastructure affects women and men differently?

1.4 Scope of the Research

The main scope of the dissertation is to model a 100% RE system for Pakistan involving the power, heat, transport, and desalination sectors. The sub-objectives of this dissertation have been further broken down to address the key research questions posed in the previous section:

1. This dissertation contributes to whether 100% RE systems are feasible in Pakistan. It offers a thorough roadmap for the change in the energy sector. The literature that examines energy transition routes toward 100% RE for all energy sectors in an hourly resolution is quite scarce in South Asia (Gulagi et al., 2017, 2020, 2021, 2022). This dissertation includes power, heat, transport, and desalination sectors that haven't been resolved hourly for 100% RE for Pakistan. In the power, heat, transport, and desalination sectors, this dissertation seeks to create techno-economic scenarios for Pakistan that are cost-optimised and lead to a 100% RE system by 2050. A low-cost option for the nation is an energy system entirely based on renewable resources. In **Publications I-III**, various sources of system flexibility are investigated. These elements include storage, distribution network connectivity, variable renewable energy, flexible generators, and curtailment.

2. Additionally, this dissertation shows the significance of seawater desalination in solving the impending water scarcity in Pakistan. Pakistan's predicted increased

energy needs due to desalination had not been considered or studied in other energy transition studies. According to studies, by 2047, Pakistan’s demand for freshwater will exceed its local water supplies (Kamal et al., 2012; Shannon, 2013). **Publication III** of this research assesses the potential for using enhanced irrigation systems and seawater desalination based on RE to alleviate Pakistan's water shortage. **Publication III** also examines how improving irrigation infrastructure and utilising large amounts of solar PV and affordable electricity generation potential will help Pakistan address its future water crisis. Seawater reverse osmosis (SWRO) desalination plants could be utilised with rapidly falling battery storage costs to guarantee that potable water is given to all sectors in Pakistan at reasonable prices.

3. Energy transitions are both techno-economic, deeply gendered, and socio-political phenomena (Lawhon & Murphy, 2011). Despite the evidence on links between gender, energy and society, research and literature on gendered implications of low-carbon energy transitions are emerging very slowly. Moreover, modelling approaches and studies provide a valuable understanding of the attributes and nature of low-carbon transitions but have important limitations (Geels et al., 2017b). Such studies involve a limited number of actors and stakeholders, while energy transitions involve a more comprehensive range of actors. Energy transitions are not linear and about market diffusion of new technologies but also changing practices, cultural debates, and broader political struggles (Farla et al., 2012). **Publication IV** explored the current understanding of the academic literature on gender and low-carbon transitions.

1.5 The Scientific Impact of the Research

The primary contribution of this dissertation is to offer a detailed understanding and future scenarios and to expand the dialogue on the RE transition in Pakistan. Alternative energy transition strategies that are both environmentally friendly and inexpensive are discussed, hoping they may encourage lawmakers and policymakers in Pakistan to defossilise the country's energy system by 2050.

Only a few studies are available that simulate Pakistan's energy system with a significant share of RE. The modelling of the energy system and scenario analysis are two areas where this dissertation contributes to and enhances scientific understanding. Understanding future energy systems' underlying structure and dynamics is essential, especially when integrating vast amounts of VRE sources in power generation. To shed light on the best resource combinations in line with sustainability and climate change objectives, a nationwide techno-economic analysis of the transition was carried out.

This dissertation is the first to incorporate significant amounts of RE at an hourly resolution to construct techno-economic scenarios for the energy system. According to the dissertation, gradually transitioning Pakistan's energy system to one powered by solar PV, supported by wind power and other RE alternatives, provides the most environmentally friendly, cost-effective, water-efficient, and least greenhouse gas GHG emitting option. This dissertation outlines the operation, time, and investment requirements for Pakistan. These details are important for determining investment goals for politicians and planners of the energy system.

Moreover, according to WWF-Pakistan (Kamal et al., 2012), Pakistan is approaching a critical point of water scarcity, with per capita water availability falling to 1,090 m^3. The main causes of the current water shortage are population growth, insufficient water allocation, low irrigation efficiency, and low water usage efficiency. **Publication III** examines more effective irrigation techniques and RE-based desalination as additional strategies for resolving Pakistan's water crisis. **Publication III** applies the techniques and ideas discussed by Caldera and Breyer (2020) within a global context to Pakistan. Thus, this dissertation provides Pakistan with a roadmap for managing the nation's future water demand through increased irrigation efficiency and supplementing the country's limited water supply with affordable, RE-powered desalination facilities.

Furthermore, gender vulnerabilities of low-carbon transitions were explored in current academic literature. The objectives of **Publication IV** are three-fold: to identify the actors and parameters that could lead to potential gendered risks in the future in low-carbon transitions and identify the gaps in existing academic literature, to inform government and decision makers, and to reduce environmental and sustainability risks. **Publication IV** aims to contribute to the literature on dispossessions, geography, and political ecology through a conceptual review approach. It is aimed to show that decarbonisation pathways must make an effort to become more reliable, fair, and inclusive.

1.6 Structure of the Dissertation

The dissertation is structured as follows:

Chapter 1: presents the need for and importance of RE systems in Pakistan and highlights the importance of three dimensions of sustainability. It also emphasises the overall demand for sustainable energy transition globally and in Pakistan. It also contextualises this dissertation's objectives, scope, contribution and scientific relevance.

Chapter 2: provides insight into the current energy situation, poverty, and access to electricity. It further shows the importance of RE in addressing these issues in the country. It links the techno-economic and social aspects of the energy transition.

Chapter 3: presents the methodologies used in this dissertation. It provides insight into introducing the LUT Energy System Transition Model modelling tool. It describes the different model features, setup, applied technologies and input data collection. It also describes the review methodology used for **Publication IV.**

Chapter 4: presents the key results of the publications included in this dissertation.

Chapter 5: discusses the results and policy implications of the energy transition in Pakistan.

Chapter 6: presents the conclusions of this dissertation.

The four original **Publications I-IV** comprise this dissertation, and a list of references is included.

2 Techno-economic and Social Aspects of Sustainable Energy Transition in Pakistan

2.1 Current electricity generation mix and future trends

Pakistan’s energy sector heavily relies on imported fuels, which constitute a large part of the country’s energy mix. About 64% of the total electricity mix comes from imported oil and gas, with 27% hydropower and 7% nuclear power, while RE contributes 2% (NTDC, 2021). Figure 2.1 shows installed capacity in 2020-21 by fuel. Hydropower has the largest share, followed by regasified liquified natural gas (RLNG) and residual fuel oil (RFO). Population and industrial growth have increased the demand for sustainable and cost-effective energy systems, but fossil fuel dependence is increasing the economic pressure while contributing to climate change. The primary issues in Pakistan’s energy system could be attributed to governance inadequacies that resulted in the difference in demand and supply of energy, and fiscal sustainability has become a challenge due to the increase in energy payments. The crisis has developed over the years from persistent power supply shortages to one where there is excess installed capacity but not enough cash flow in the system to run it (JICA, 2016; NEPRA, 2022). Figures 2.2, 2.3 and 2.4 represent the total energy supply, total energy consumption by sectors and energy consumption by source, respectively, from 1990 to 2020.

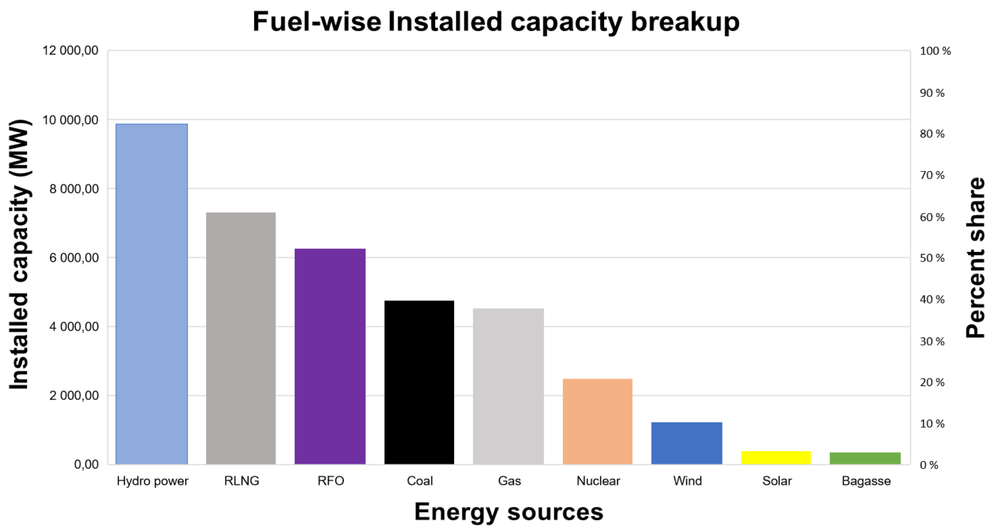

Figure 2.1: Fuel-wise installed capacity breakup 2020-21 (Finance Division, 2021).

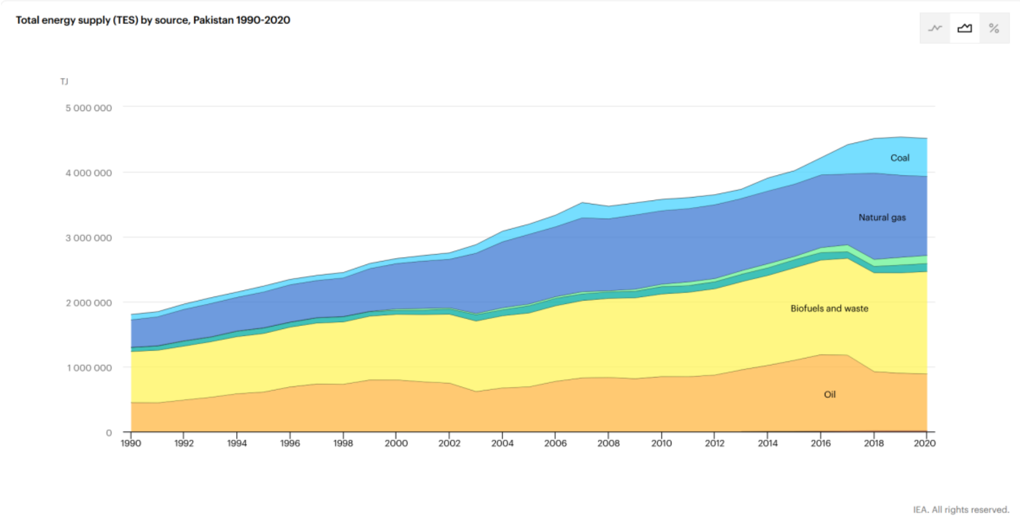

Figure 2.2: Total energy supply by energy sources in Pakistan from 1990 to 2020 (IEA, 2022).

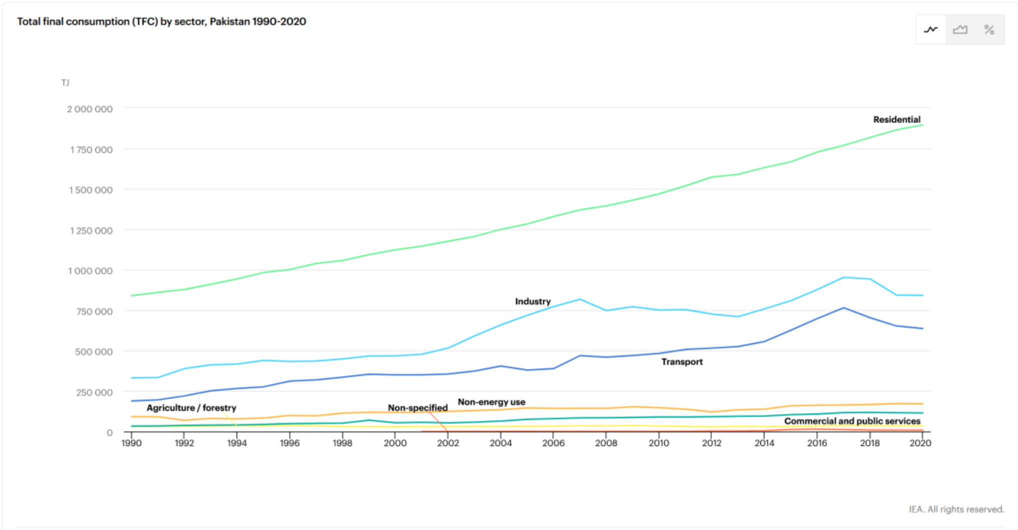

Figure 2.3: Total energy consumption by sectors in Pakistan from 1990 to 2020 (IEA, 2022).

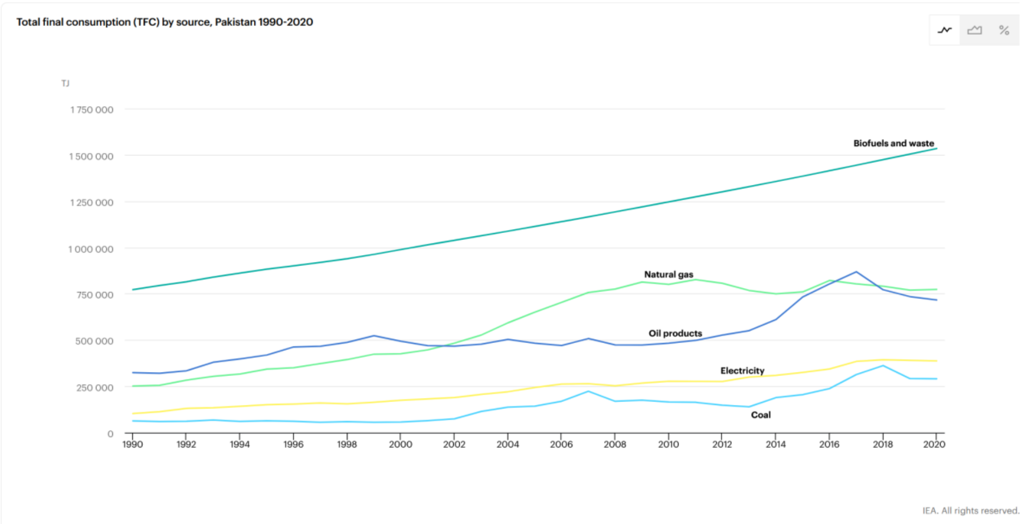

Figure 2.4: Total energy consumption by energy sources in Pakistan from 1990 to 2020 (IEA, 2022).

Figures 2.5 and 2.6 show the generation of electricity by sources and consumption of electricity by sectors, respectively, for 1990 to 2020.

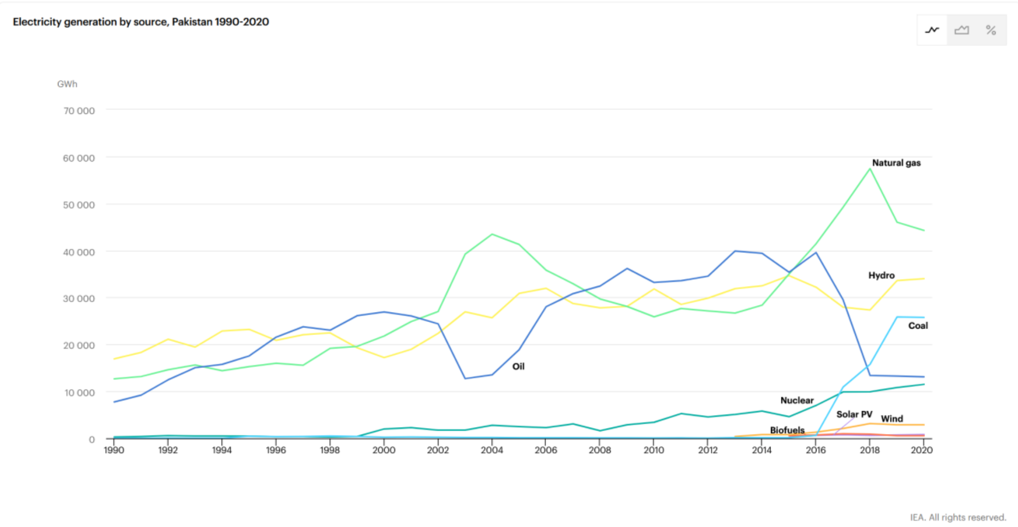

Figure 2.5: Electricity generation by source in Pakistan from 1990 to 2020 (IEA, 2022).

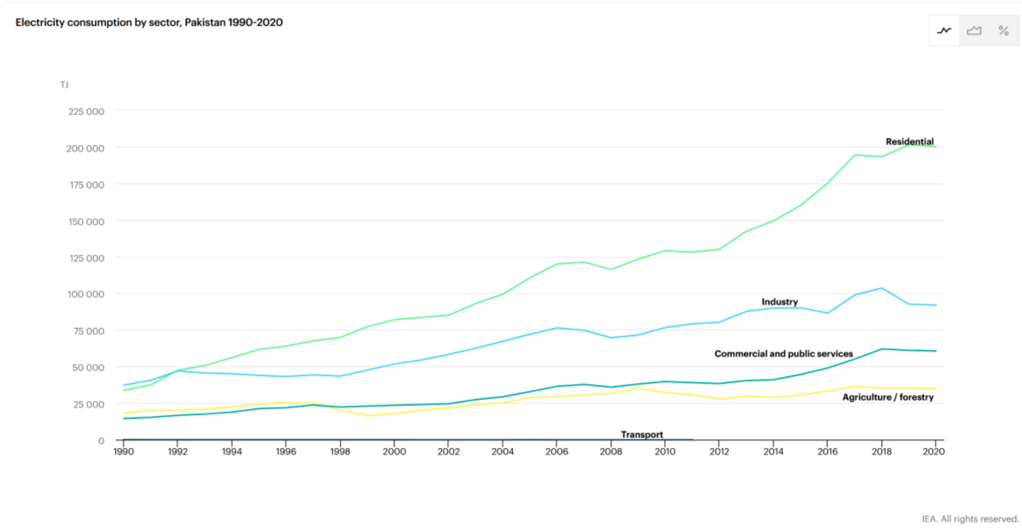

Figure 2.6: Electricity consumption by sectors in Pakistan from 1990 to 2000 (IEA, 2022).

During the 2010s, the dependence on natural gas declined because of shrinking gas reserves in the country and the introduction of LNG. The government is taking measures to gradually increase the share of low-carbon and RE technologies (wind power and solar PV). Upgrading the energy infrastructure to RE technologies is crucial for achieving Sustainable Development Goal 7 and climate mitigation goals, which means investing in RE, particularly solar PV and wind power (AEDB, 2019). In 2006, Pakistan issued its first policy measures for the development of renewables-based power generation (MoWP, 2006).

In 2019, Pakistan formulated a RE policy to support the conductive environment for RE development in the country's power sector (AEDB, 2019). The policy envisioned includes 20% of technologies to total generation and 30% by 2030. The policy covered all RE sources such as solar, wind, geothermal, biomass, hydrogen technology and all the hybrids of renewable technologies. Moreover, the country aims to include 30% of the total generation from hydropower by 2030. Another study by the National Transmission & Despatch Company (NTDC) (2021) presents the electricity demand forecast and capacity expansion plan from 2021 to 2030. The demand forecast has been presented in three demand scenarios: base case, low demand and high demand. Under the high demand, the scenario is forecasted at 195,244 GWh in 2030. The study underwent meaningful criticism since the total share from renewables technologies was only 12% by 2030, and a large share was by committed projects. An earlier report by NTDC (2021) projected the demand forecast from 2015 to 2040.

Estimates show that oil-based power plants account for 65% of all GHG emissions from the power production industry, while gas-based plants account for 32% (Munawer, 2018). The capacity expansion plan by the NTDC (2021) is expected to increase the amount of coal power in the mix by almost 30,000 MW by 2040. This will result in enhanced power capability for the nation and substantial carbon emissions simultaneously. The significant emissions from coal burning and its susceptibility to air pollution are well recognised. It depends on the type of coal utilised and the method employed to produce the energy. Pakistan already has poor air quality. Therefore, utilising coal with a high sulphur level will have major negative health effects and life-threatening consequences (Munawer, 2018).

World Bank (ESMAP, 2019b) presents the solar resource assessment undertaken by the World Bank in Pakistan (Figure 2.7).The yearly sum of global horizontal irradiation is in the range of 1600 to 2200 kWh/m^2. This translates to a specific yearly PV electricity output in the range of 1400 kWh/kWp to 1900 kWh/kWp. Khatri et al. (2022) estimated the technical potential of solar PV to be 3000 TWh/year. The article estimates the photovoltaic (PV) potential and suitability factors for land use and for the availability of rooftop areas, defined basic technical assumptions and calculated the technical potential of PV electricity generation in the country for grid connected systems and off-grid solar PV systems. The authors estimate that Pakistan has a potential of 1600 GW for ground-mounted and rooftop grid connected systems and 208 MW for off-grid PV systems.

A GIS wind speed map at the elevation of 100 m, along with wind measurement stations, is shown in Figure 2.8. It is evident from the figure that Sindh and Baluchistan have a high wind potential as compared to that of other provinces. The theoretical wind power potential as studied by the NREL report, is 346 GW (Farooq & Tayyab, 2014). The World Bank has published wind resource maps (Figure 2.8) using satellite data and ground-based measurement data, showing observed theoretical wind potentials at the elevation of 100 m is 486 W/m^2. Khatri et al. (2022) estimated the technical potential of wind energy to be 725 TWh/year by using the Levenberg–Marquardt algorithm (LMA) optimisation method with NREL's SAM model. The geographical potential of the coastal areas of Pakistan, estimated by Harijan (2008), is 22,700 km^2 (approximately 190 GW of wind power), with a suitability factor of 0.38 and a total area of 59,500 km^2 for wind power installation that translates into approximately 500 GW of wind power (Bogdanov & Breyer, 2016).

Based on the water resource potential, Pakistan's total hydropower potential has been estimated to reach more than 40 GW that has not been harnessed (NTDC, 2021). For mini hydropower plants with capacities below 100 kW each and mini-hydropower plants with capacities of 100–500 kW each, a potential of 300 MW and more than 400 MW, respectively, has been estimated in northern areas of Pakistan. The Generation Capacity Expansion Plan (IGCEP) 2021-2030 envisages an addition of 13,148 MW hydropower capacity at the national level by 2030, more than the already installed hydropower capacity in the country (NTDC, 2021). The existing hydropower generation capacity reached a total of 9,873 MW in the year 2021, contributing about 29% to the overall power mix of 34,501 MW in the year 2021 (Siddiqui, 2022) and a share of 25% in the electricity generation of the same year.

Iqbal et al. (2018) claim that the residue of the major crops, including cotton stalks, wheat straw, rice straw, sugarcane trash, and corn stalk, amounting to 25.3 million tonnes, has a power generation potential of 689 TWh annually. Animal dung also offers promising potential for power generation. Pakistan has the potential to generate 7223.3 TWh of electricity per year from animal manure (Arshad et al., 2022). The municipal solid waste potential for electricity generation by biochemical and thermochemical conversion is 216 kWh/ton and 552 kWh/ton that translates into 5.5-14 TWh of power generation annually (Irfan et al., 2020). Although there are numerous hot springs with temperatures ranging from 30 to 170 ^{0}C in various parts of Pakistan (Younas et al., 2016), for example, in the vicinity of Karachi and in the Pakistani part of the Himalayas, but there has been no attempt to make use of geothermal energy in Pakistan yet. In the Himalayan region of the northern part of Pakistan, more than 600 surface indications of geothermal energy resources have been reported, with an estimated potential of 800 MW (Gondal et al., 2017).

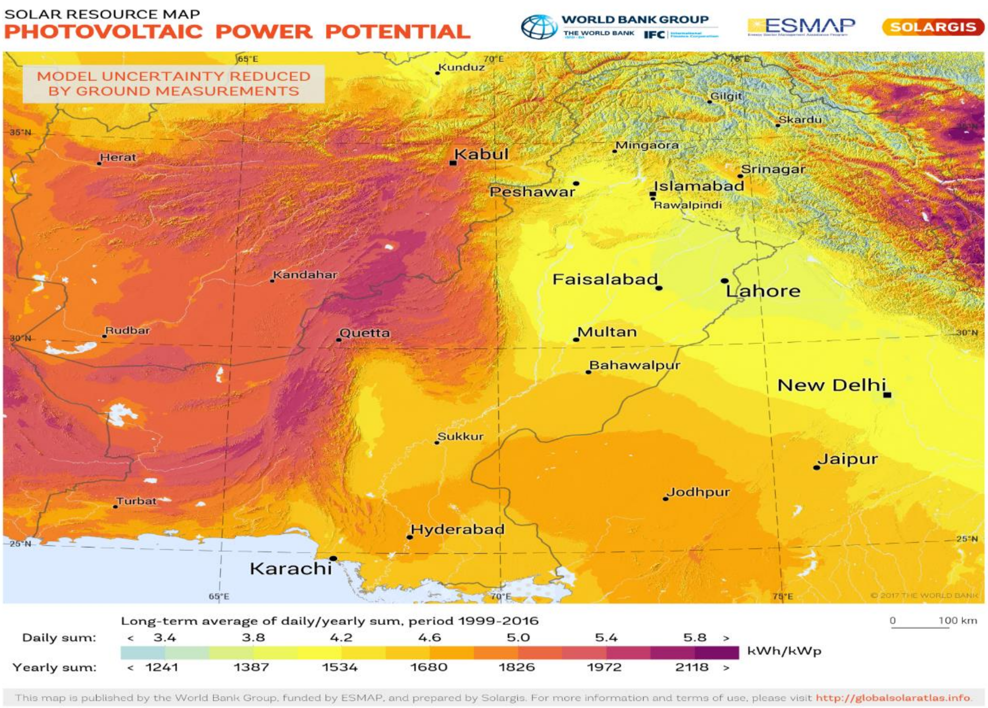

Figure 2.7: Photovoltaic power potential of Pakistan (ESMAP, 2019b).

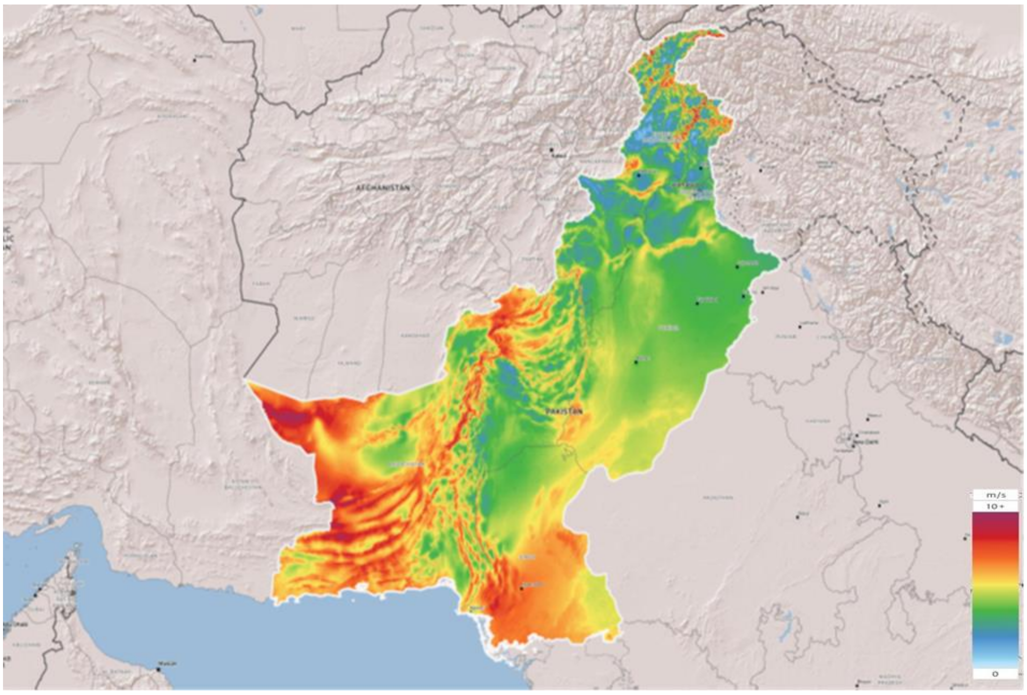

Figure 2.8: Pakistan’s mean wind speed (100 m) map (ESMAP, 2019a).

2.2 Energy Access and Poverty

Access to clean, affordable and reliable energy is the 7th goal of the UN’s Sustainable Development Goals because energy is a crucial element in the well-being and development of society (UN, 2016). Nevertheless, energy poverty has grown in many countries due to rising energy costs, volatility, the elimination of subsidies, limited access to modern fuel, and financial pressure on people. Despite being a global problem, energy poverty is more common in poorer nations. United Nations’ sustainable development goals emphasise the importance of energy access and alleviating energy poverty. Energy poverty has recently gained much attention in the literature; however, the definition of poverty lacks consensus because of its complexity and multidimensionality (Foster *et al.*, 2000). According to a report by Samad and Zhang (2018), Pakistan has made remarkable progress in connecting rural areas to the national grid in the last few decades. In Pakistan, almost 54 million people received electricity services for the first time from 1990 to 2010 (IEA et al., 2022). Figure 2.9 shows the proportion of the population with electricity access from 2000 to 2050 (IEA, 2022). But only 74% of the population has grid electricity, with grid access to 90% of the population in urban areas and 63% in rural areas in 2016 (IRENA, 2021b).

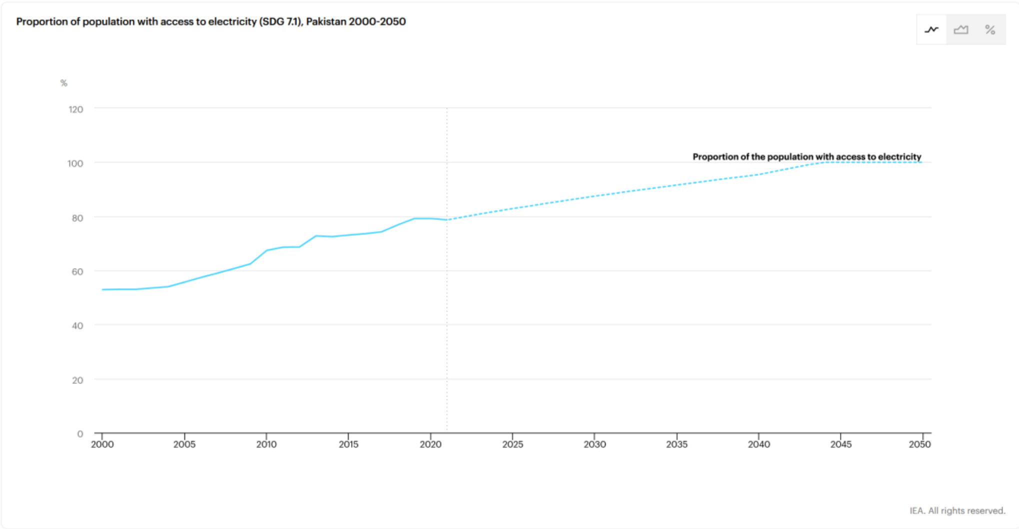

Figure 2.9: Proportion of population with electricity access in Pakistan from 2000 to 2050 (IEA, 2022).

Pakistan is heavily dependent on imported fuels to fulfil its energy needs. This dependence on foreign energy resources has been the primary contributor to raising foreign debt (circular debt) for many years (Nicholas, 2021). In Pakistan, circular debt is a public debt, which is a cascade of unpaid government subsidies, which results in the accumulation of debt on distribution companies. When this happens, the distribution companies cannot pay independent power producers, who in turn, are unable to pay fuel providing companies, thus creating the debt effect as prevalent in the country (WB, 2021). The allocation of a significant portion of national income to import fuels and debt servicing harms the socioeconomic development of Pakistan (Azam et al., 2020). This dimension of energy poverty also reveals how dependence on foreign energy reserves can drain economic resources and worsen the country's poverty (Shahid et al., 2021). Energy poverty is a barrier to education and women's empowerment and can adversely impact the health and well-being of the members of the households. Access to cleaner energy resources improves the environment, well-being, and health, particularly for female household members (Nakata & Kanagawa, 2006). Premature infant mortality and a wide variety of respiratory disorders in women are directly attributable to the lack of access to affordable electricity. The lack of access to clean electricity results in the burning of conventional fuels and coal inside the households, that is the primary source of indoor pollution (Day, Walker, and Simcock, 2016). In Pakistan, around 90% of homes in rural areas and 13% of homes in urban areas rely on solid fuels for cooking. When burned in an open fire, these fuels release toxins and contaminants that harm human health (Naz, Page, and Agho, 2017). Energy poverty has a gendered dimension. Among 1.3 billion people who do not have access to electricity, 70% are women. A more holistic approach in research and policymaking on energy poverty is required to involve women in the supply of clean energy to empower women, improve their health, and improve their capacity for climate adaptation and mitigation (Pavithra, 2021).

2.3 The Potential of Renewable Energy in Changing the Energy Sector

To meet the goals set by the Paris Agreement and Sustainable Development Goals (Nick, 2003; UN, 2021), a massive and rapid development of solar PV and wind power is required to meet the global energy demand while minimising GHG emissions. Although Pakistan has ambitious plans to reduce emissions and add renewable electricity generation, experts believe the country needs a better policy design (Liu, 2022). There is a strong national and provincial debate to develop domestic coal in Pakistan, support local economic development, and increase energy security, even though the economics do not encourage such a strategy. The cost of variable renewable energy (VRE) is reducing and coal is no longer a cost competitive option for electricity generation. Pakistan stopped approving new coal power plants in December 2020 as part of efforts to counteract climate change, but construction of the already permitted plants will continue (Bhandary & Gallagher, 2022; Valentina, 2020). The development of new clean coal technologies is attempting to address the problem of air pollution and GHG emissions so that coal resources might be utilised in the future without the harmful consequences of air pollution and global warming. Much of the challenge is in commercialising the technology so that coal use would remain economically competitive despite the cost of achieving low and eventually near-zero emissions (Medunic et al., 2018). Clean coal technologies are facing criticism for not only being energy and cost-intensive but also not being clean (CER, 2019).

Supporting a transition from domestic coal and reducing reliance on hydropower and thermal power projects can increase the addition of cheaper and reliable renewables by directing the finances towards RE development. RE is out-competing other energy generation technologies on price, and RE projects have much faster construction times. As evidenced by project delays in Pakistan, large hydro and nuclear power projects run over time, adding to already very high project costs (Batool & Abbas, 2017). With renewable technology getting cheaper, coal and LNG-fired power plants increase the country’s reliance on expensive and imported fuels, risks locking Pakistan into decades of outdated technology. Increased utilisation of abundant solar and wind resources can bring several benefits, including increased energy security, diversification of energy sources, and reduced electricity generation costs (Nicholas & Buckley, 2018).

2.3.1 Challenges and limitations

Pakistan aims to respond to the threat posed by climate change by adopting sustainable and RE options. Pakistan issued a detailed RE policy in 2019, aiming for the addition of the share of RE in electricity generation by 2025 to 20 % and increasing the share to 30 % by 2030 (AEDB, 2019). In 2006, the first RE strategy was developed. However, only

430 MW and 1235.20 MW of solar PV and wind power were added, respectively. High costs, a lack of institutional coordination, and subsidies were the key obstacles that contributed to policy failure (MoWP, 2006). The inability of Pakistan's renewable energy (RE) policy to effectively address some crucial issues has resulted in several challenges in implementing the policy, as acknowledged by the policy framework itself. While the ARE (Alternative and Renewable Energy) policy (2019) includes alternative energy sources such as solar PV, offshore and onshore wind power, geothermal, hydrogen, and synthetic gas, it does not cover nuclear and hydro power. The challenges related to both small and large-scale RE schemes are described below:

1. **Lack of incentives:** The lack of incentives in the alternative and renewable energy (ARE) policy (2019) is a considerable shift from the early policy framework, where different incentives were offered to on-grid RE projects. The modifications in the Generation and Distribution Act regulation and other administrative actions show Pakistan's tendency toward more competitive marketplaces. Nevertheless, the current strategy does not provide enough incentives to draw potential investment. (Mittha, 2021).

2. **Outdated grid infrastructure and transmission and distribution losses:** Although the government has undertaken a significant and difficult push to create RE infrastructure, Pakistan's national grid is currently not in good shape (Bhatti, 2015). Due to the variability and intermittency of RE sources, it has not been revamped technologically to absorb RE better. It hasn't been technologically upgraded to better absorb RE because of the erratic and intermittent nature of RE sources. A significant amount of Pakistan's industry relies on captive units because of the country's substantial grid losses. A captive generation plant is a power plant set by a person, company, or entity to generate electricity primarily for their own purpose. Additionally, Pakistan has had major power outages nationwide due to fragile distribution infrastructure. It is crucial to expand and upgrade the power grid to be able to use high-quality solar and wind resources, which are often located far from the existing transmission networks (WB, 2020). Theoretically, a power system can manage any variability by adding a storage system. Yet, everything has a price, and in Pakistan, investments in the power generation sector far outweigh those in the transmission and distribution sector.

3. **Baseload power**: The idea of baseload power and the intermittent nature of RE sources have always made it difficult for RE to integrate more quickly into Pakistan's energy grid. The belief is that building an efficient energy storage system is challenging, expensive, and hinders the development of a RE-based power system (Mittha, 2021). This dissertation's **publications I** and **II** discuss the storage system of Pakistan's power and energy system, which relies entirely on renewable energy.

4. **Cost of energy:** One of the main drivers of its limited expansion in Pakistan appears to be the competitiveness of RE sources with conventional power generators.

Although the cost of renewable energy has significantly fallen over the past ten years, Pakistan’s energy system has been set up so that expenses are constantly increasing; the biggest macroeconomic difficulty can be attributed to the growth of power circular debt. The high cost of power generation, tariff anomalies, and a substantial discrepancy between cost-recovery and notified pricing are some of the fundamental underpinnings of the circular debt buildup. The COVID-19 pandemic has also significantly depleted the nation’s financial resources. The estimated loss of Pakistan was around 384 million USD (Finance Division, 2021). Despite being less than the expected value, the stimulus was also not aligned with a green recovery (Sward, 2022).

5. **Data unavailability**: To ensure the successful implementation of wind and solar PV-generating installations, ground data must be covered for at least one year. However, only a few feasibility assessments have been conducted for such projects. For example, Pakistan has constructed over 40 wind masts to gather data, while other studies have demonstrated wind and solar energy's theoretical and technological potential on different sites (WB, 2020). Obtaining technical data about renewable technology is becoming a significant obstacle in developing renewable energy (RE) projects, as there is currently a lack of information available. The lack of technologies refers to the detailed RE resource assessment, data banks, minimum standards in terms of durability, reliability, and performance (Solangi et al., 2021).

6. **Low market penetration**: Compared to other conventional technologies, renewable energy technologies have a relatively weak market hold and poor penetration rates in Pakistan. The lack of progress in this regard can also be attributed to the general public's lack of awareness and misconceptions regarding the economic competitiveness of renewable energy sources compared to conventional electricity generators. The lack of developed infrastructure prevents the spread of renewable energy technologies. Awareness initiatives should be undertaken to inform society about the advantages of renewable technology (Malik, Qasim, and Saeed, 2018).

7. **Cooperation between different institutions**: The lack of progress in the renewable energy sector can be attributed to several factors, including limited incentives and regulatory frameworks to encourage local industry involvement, inadequate organisational coordination, mutual communication, and interaction between different government institutes, organisations, ministries, and creditors. Additionally, the cost of importing solar panels has recently increased, and there are lengthy procedures for awarding licenses and implementing net metering, with little cooperation from government organisations. Moreover, there is a shortage of technical training facilities and a competent workforce to construct, commission, and maintain renewable energy plants. Furthermore, there is a lack of national support for technology transfer channels and rules, and academic institutions do not have testing and certification labs for research and development purposes (Zhang et al., 2023).

8. **Human resources development:** The ARE policy (AEDB, 2019) also requires the alternative energy development board to set up training and research related to the RE system. The Pakistan Council of RE Technologies has also established a legislative organisation to conduct research and develop RE sources. Nevertheless, there is no publicly accessible information in Pakistan on measures for training human resources and skills for renewable sectors.

2.3.2 Energy security

Energy security is a multi-dimensional concept that includes political, economic, and geopolitical aspects of the region or country. For Pakistan, energy security means an adequate supply of energy, a reliable supply, and an affordable price. Heavy dependence on imported fuels exposes the economy to international price changes and puts the economy under pressure through inflation (Malik et al., 2020). Pakistan needs to increase its share of renewables in the energy mix, as it has already started reducing its reliance on imported fuels. A study by Azzuni *et al.* (2020) performed a security analysis of a 100% RE system in the case of Jordan. It was concluded that a fully renewable system would enhance energy security's five dimensions (availability, cost, health, environment and employment). A 100% RE system in Pakistan can offer cost-effective, reliable, and sustainable energy with improved employment and financial opportunities. Energy security also has very strong gender aspects. RE interventions can have significant gender benefits, which can be realised via careful design and targeting of interventions based on a context-specific understanding of energy scarcity and household decision-making, in particular, how women's preferences, the opportunity cost of time, and welfare are reflected in household energy decisions.

2.4 Role of Renewable Energy in the Defossilisation of the Heating And Transport Sectors

2.4.1 Overview of fuels used in heating and transport sectors:

There is a severe lack of literature and data about the heating industry in Pakistan. Rural and low-income communities often satisfy their heating needs via biomass fuels like firewood, agricultural wastes, and animal dung (Wakeel, Chen, and Jahangir, 2016). In 2015, biomass was responsible for 27% of the world's energy supply, with firewood and agricultural waste accounting for approximately 50% and 34%, respectively (Wakeel, Chen, and Jahangir, 2016). The health of women and children is adversely impacted by using raw wood as an energy source because of its inefficiency, danger, and risk (Fatmi et al., 2010). The industrial sector accounts for 20% of the total Gross Domestic Product (GDP) and utilises 38% of the total energy consumed in Pakistan. There will be an increase in energy consumption in the industrial sector (Hafiz, Sultan, and Rana, 2017). Most industries utilise natural gas for their heating needs. While previously coal was only used for power generation in the wood and cement industries, this is slowly changing (ADB, 2021a, 2021b). The cement and brick kiln industries are also major consumers of coal. In 2021, over 64% of the locally mined coal will be used in the cement sector, while approximately 40% will be used in brick kilns (Butt et al., 2021).

In 2016–2017, the transport sector contributed about 13% of the country's GDP, with road transportation accounting for more than 62% of the entire contribution. (Karandaaz Pakistan, 2018). Almost 90% of the total number of transported tonne kilometres (t-km) are made up of road freight (Karandaaz Pakistan, 2018). In the last few years, road passenger transportation has grown 3.4% annually, while rail passenger transportation growth has been very low (1% annually) (Karandaaz Pakistan, 2018). The International Air Transport Association (IATA) predicts that domestic air travel in Pakistan will increase by 9.5% yearly over the next few decades, twice as fast as the global average (InterVISTAS, 2015). Pakistan's transport policy, National Electric Vehicles Policy (NEVP), issued by the Ministry of Climate Change (2019), targeted electric vehicle (EV) sales as a percentage of total vehicle sales to reach 30% by 2030 and 90% by 2040.

2.4.2 **Role of RE and future fuels:**

The transition towards a 100% RE system demands a complete defossilisation of the energy system. A study by Mertens *et al.* (2023) explains that it is better to use defossilisation than decarbonisation since carbon will be a crucial part of the future society. A fully renewable energy system can limit global warming in cost-effective and sustainable ways. Recent research has focused on various challenges and opportunities regarding the electrification of transport, power-to-X, hydrogen-to-X, and sector coupling (Breyer et al., 2022; Kondziella & Bruckner, 2016). Hydrogen can be converted to synthetic electricity-based fuels such as e-methane (Blanco & Faaij, 2018), Fischer-Tropsch fuels (Fasihi et al., 2016), e-ammonia (Fasihi et al., 2021), and e-methanol (Lonis et al., 2021), where direct use of hydrogen is not possible. In addition, the heat from geothermal and bioenergy from biomass and organic waste provides primary energy for electricity, heat, and transport use. Highly efficient electricity systems and sector coupling can decrease the primary energy demand of an integrated energy system by 2050 (Brown *et al.*, 2018; Bogdanov, Gulagi *et al.*, 2021). However, some sectors and services, like the steel and chemical industry and long-distance transport (marine and aviation), are challenging to defossilise. Synthetic fuels produced by using renewable electricity could serve as a solution to replace fossil fuels (Bogdanov, Gulagi, et al., 2021; Osorio-Aravena et al., 2021).

2.5 Role of Renewable Energy-Based Sustainable Water Supply and its Impact on Food Security

Pakistan is a semiarid and primarily agricultural economy. It is facing declining quality and availability of water, water pollution, and environmental insecurity in general. Water scarcity, floods, drought, governance, and operational failures foster domestic discord. According to a study by Ritchie and Roser (2017), this agricultural nation is estimated to decline from water-stressed to scarce water by 2030. Therefore, understanding water availability, distributional mechanism, demand, and unpredictability is crucial to understand resource management challenges and security issues that arise (Shannon, 2013).

Water scarcity and security issues are closely linked to the agricultural sector. However, the sector has grown in the last few decades but is riffed with mismanagement and inefficiency. Declining water availability requires changes in the types of crops grown and more effective irrigation practices that save water while improving the water quality (Qureshi, 2020). Around 80% of farmed land in Pakistan is irrigated, whereas around 33% of the land is impacted by waterlogging and soil salinity (Aslam et al., 2015; Qureshi et al., 2008). This decrease in water quality leads to significant declines in yields. More sustainable and economical irrigation practices must be implemented to solve these issues. As a result of Pakistan's expanding commercial agricultural practices, a rise in urban and peri-urban resettlements may be observed as small farmers are evicted from their land. About half of the rural population subsists mostly on irrigated agriculture, although over 40% of the rural population lives below the poverty line (Qureshi, 2020; Qureshi et al., 2008). The relationship between water and food security is complex, and climate change may lead to changes. Pressure on water security may be increased by changes to the water delivery system, which calls for better disaster risk management and infrastructure (Mallapaty, 2022).

Pakistan’s water policy (Ministry of Water Resources, 2018), which focuses more on supply-side interventions, lacks a comprehensive approach. Water institutions favour megaprojects reflected in the government’s main policy documents and the projects portfolio (WWF, 2023). This approach only masks the problem of water mismanagement and inefficiency. Around one-third of Pakistan's delivered water is lost due to water losses from watercourses and between canal heads and watercourses, with an additional 25% lost within farms. Nevertheless, only 45% of arable land is being farmed at any moment due to the inefficient management and distribution of irrigated water. The country now has one of the lowest production rates in the world per unit of water due to these problems, even though it uses 97% of its allocated water supplies (PIDE, 2022).

2.6 The Need for Integrating Techno-Economic and Social Dimensions of Energy Systems for a Just and Clean Energy Transition

The low-carbon energy transition is critical for mitigating future climate change impacts. However, there is evidence that such transitions can generate new social justice challenges and vulnerabilities while failing to address the existing drivers of inequality in the energy market and larger socio-economy (Sovacool et al., 2019; (Stock & Birkenholtz, 2020). Every energy transition has winners and losers regarding social justice, economics, and community cohesion. The ongoing energy transition will be no different, given the complex and interconnecting patterns of power and practices that influence the actors and key stakeholders involved (Lennon, Dunphy, and Sanvicente, 2019).

Effective climate change mitigation requires massive changes in power, industry, transport, heating, agriculture, and other sectors. Techno-economic energy studies and modelling approaches overwhelmingly dominate academia and policy debates and give valuable insight into the attributes and nature of low-carbon energy transitions but have numerous crucial limitations (Geels et al., 2017a; Krumm et al., 2022; Lieu et al., 2020a). Such studies generally represent a limited number of actors (firms, consumers, policymakers). At the same time, energy transitions involve a wider range of actors, such as civil society groups, media, ministries, communities, local authorities, politicians, and advisory bodies (Geels et al., 2017b; Paltsev, 2017). These groups' actions are determined not only by an implicit cost-benefit assessment but also by beliefs, unequal assets, conflicting values, and complex public relations. Energy transitions are not linear about market diffusion of new technologies but also changing practices, cultural debates, and wider political struggles. Transitions are not linear and unidirectional but disruptive, contested, and non-linear processes (Anderson & Peters, 2016; Farla et al., 2012).

Introducing low-carbon technologies does not guarantee poverty alleviation and equal access to resources for all genders (Johnson et al., 2019). At the same time, literature recorded the positive impacts of the energy transition, such as job creation, access to new electricity and energy sources (clean heating and cooking technologies), and improved access to educational opportunities for women (Botta, 2019; Green & Gambhir, 2020). A transition to low-carbon energy sources holds several benefits but can also enhance vulnerabilities. Carley et al. (2018) mentioned that “some individuals and communities are more vulnerable to possible adverse effects than others.” Castellanos et al. (2015) analysed the employment opportunities, but these jobs were mostly attributed to biofuel plantations. Upon closer examination, in many cases, biofuel plantation holds positive and negative consequences (Castellanos and Jansen, 2015; Dompreh, Asare and Gasparatos, 2021). Numerous studies cite that the host of injustices extends beyond land use, unemployment, and financing (Fernández-Baldor et al., 2015; Stock & Birkenholtz, 2020; Wiese, 2020). A range of economic, social, and political vulnerabilities in low-carbon energy transitions are due to gender inequalities and power structure (Boyd, 2010; Gay-Antaki, 2016).

The energy vulnerability concept is gaining attention from academia, business, and the international community. It is widely accepted that we must minimise vulnerability to fossil fuel consumption's interconnected environmental and socio-economic risks. Such a challenge requires unified efforts toward low-carbon energy transitions and decarbonisation (Geels et al., 2017b). However, the goal of reducing carbon emissions is often treated as a technical task that can be modelled and controlled by science and policy. Recently, there has been increasing recognition that the decarbonisation challenge is inherently intertwined with the social realm, politics, economics, experiences and practices, culture, and geography (Sovacool *et al.*, 2019).

2.6.1 Linkage and Importance of considering gender

Energy transitions are both techno-economic, deeply gendered, and socio-political phenomena (Lawhon & Murphy, 2011). Dedicated studies and literature on the gendered implications of low-carbon energy transitions are only beginning to appear despite the evidence for linkages between gender, energy, and society. Moreover, modelling methods and studies shed light on the characteristics and behaviour of low-carbon transitions but also have significant shortcomings (Geels et al., 2017b). Such studies involve a limited number of actors and stakeholders, while energy transitions involve a wider range of actors. Energy transitions involve shifting habits, cultural discussions, and broader political conflicts in addition to the market adoption of new technology (Farla et al., 2012), all of which will impact the transition's direction and rate. **Publication IV** explored the current state of knowledge in academic research on the implications of low-carbon transitions on gender.

In sustainability discourse, gender is a cross-cutting theme. International organisations (IRENA, 2019b; UN, 2016) encourage the incorporation of gender equality in climate change mitigation priorities. Still, the gender perspective is strikingly absent in carbon mitigation policies and practices (Lieu *et al.*, 2020). Gender equality is essential in energy markets due to the skewed gender dynamics of land, resource, and property ownership, which disproportionately benefit males in developing countries (Denton, 2002). However, studies on gender and sustainable development indicate that many forest conservation projects ignore women’s marginalisation in land and resource access, excluding them from policies and practices (Resurreccion and Elmhirst, 2012). Yet, studies on women and sustainable development have shown that many forest conservation programs ignore women's need for equal access to land and resources (Rocheleau et al., 1996). Hence, gender is a useful analytical classification for examining power interactions. According to Fernández-Baldor et al. (2015), women are disproportionately impacted by environmental degradation due to their caregiving and providing responsibilities, which place them at a disadvantage compared to men when it comes to accessing economic resources, education, paid employment, and land (Jassal, 2016; Lieu *et al.*, 2020b; Wiese, 2020).

2.6.2 Future directions

A study by Johnson *et al.* (2020) indicated no solely positive or negative results from using low-carbon energy systems. These technologies cannot be separated from the political and social environment in which they were created. Existing political power dynamics and underlying socioeconomic and geographical inequities may contribute to the varying outcomes. The energy transition is multifaceted, and technological advancements are essential to its success. In addition to distributing benefits and vulnerabilities, political, social, economic, and cultural factors play a significant role in the energy transition process and manifest themselves in various ways (Johnson *et al.*, 2020).

The gender perspective in energy policy and decision-making underlines the absence of gendered and diverse voices in energy transitions. This narrative sustains the technical cultures that the energy sector preceded, translating energy transition discourses almost exclusively into technical terms, keeping the domain of specialist knowledge in the hands of male technical professionals while eliminating all social and gender discourse. Using a gender lens can force energy experts to consider why women must have the power to influence the decision making processes.

Nevertheless, some efforts have been attempted to widen the discussion to include both women and men. Also, it creates spaces for different narratives to potentially include minority groups (Lieu et al., 2020a). However, the inclusion of gender in energy policies is fairly limited to domestic areas. The issue with this concept is that when women’s roles and activities are narrowly defined in the domestic realm, policies only focus on that area, and a broad range of interests are left unexplored. As a study points out (Gay-Antaki, 2016), women took extra responsibility to participate in carbon projects because of the financial gains presented by these projects or an opportunity to leave home. The under-recognition of women’s roles restricted the benefits of the energy transition.

Ambitious initiatives must be undertaken not only by governments and investors but also by the international research community. It is crucial to delve deeper into the gender dimensions of energy transitions in future studies, with a significant commitment from researchers. The main challenge lies in the current scarcity of empirical evidence on how low-carbon solutions impact men and women differently, which highlights the need for thorough empirical research in this area. Future studies should include gender-specific data on time usage, income-generating opportunities, and pre-existing conditions (such as land ownership) while examining changes throughout the project. Apart from integrating gender perspectives, empirical research and case studies must also account for intersectionality by considering various factors, such as age, marital status, geographical location, and ethnicity. These factors may influence whether local communities benefit from low-carbon energy transitions and whether certain individuals or groups are more likely to gain advantages than others.

3 Research Methodology

3.1 Overview of the LUT Energy System Transition Model

The LUT Energy System Transition Model (LUT-ESTM) optimised energy system scenarios for Pakistan, including power, heat, transport, and seawater desalination. The optimisation was conducted under specific conditions and constraints for each hour throughout the year. The main goal of the model is cost reduction through energy system optimisation. To guarantee the best supply and demand balance and the lowest operational costs for the system, the model develops the scenarios using optimisation for the energy system and simulates operation at each hour. The sum of various costs, including energy conversion generation ramping and installation costs, are considered to optimise the cost of the whole energy system based on assumptions in techno-economics and technologies. The assumptions were made about future technological development, use of different technologies, economic development, price changes, changes in consumer behaviour, etc. The energy system simulation was implemented in 5-year steps from 2015-2050. LUT-ESTM has been presented in various articles (Bogdanov, Toktarova and Breyer, 2019; Bogdanov *et al.*, 2021; 2021).

3.1.1 Model setup and main target function

The LUT-ESTM is a linear optimisation model designed to create a 100% renewable energy-based system by optimising system parameters under constraints. The main constraint for the optimisation is that the generation from all technologies must meet the demand for power for every hour of the application year, and the optimisation target is to have the least annual cost of the power or energy system. Matching supply from all technologies with demand from all sectors is a general restriction for the complete energy system model. The model's hourly precision lengthens the calculation time, but it also ensures that the overall supply in an area always covers the local demand and allows for a more accurate system description that considers the synergy effects of various system components. The model uses hourly resolution, which ensures that demand and supply are constantly balanced within a region for every hour of the set year. This level of resolution allows for a more accurate system description, including the combined effects of different elements or sectors (sector coupling) in an energy system.

The LUT-ESTM is compiled in the Matlab environment in a LP file format; therefore, it is readable by most standard solvers. The optimisation is accomplished in a third-party solver. The main option is MOSEK ver. 8, but other solvers (e.g., Gurobi, CPLEX, etc.) can also be used. After the simulation, results are processed for analyses and graphs preparation. Figure 3.1 portrays a simplified modelling procedure, from data collection to results.

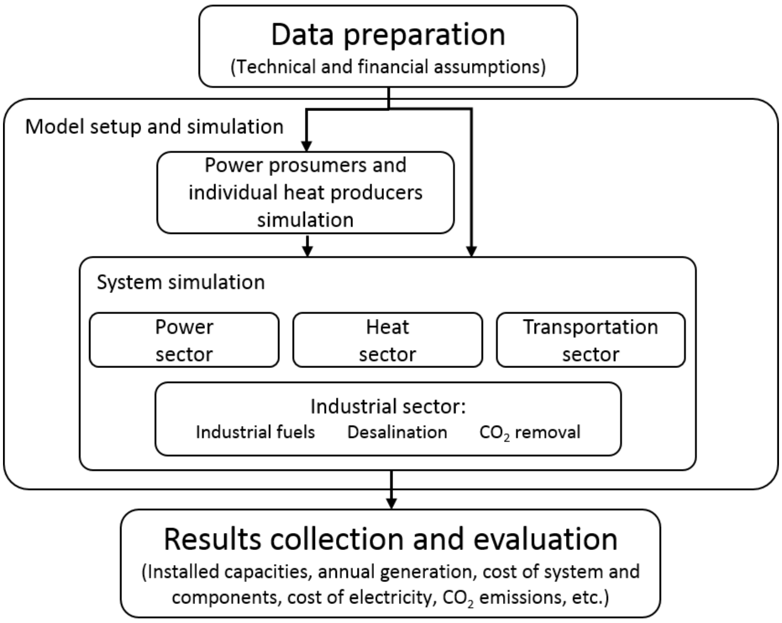

Figure 3.1: The overall structure of the modelling procedure (Bogdanov et al., 2021).

Furthermore, in addition to optimising system parameters and sector coupling, LUT-ESTM also considers residential, commercial, and industrial power prosumers. Prosumers are individuals who can both consume and produce electricity. With LUT-ESTM, prosumers can install solar PV systems, including rooftop and battery systems, and sell unused electricity back to the grid. PV prosumers install the capacity of rooftop PV systems and batteries according to their individual needs. The target function for prosumers in LUT-ESTM is to reduce the cost of energy used. LUT-ESTM includes optimisation of PV self-consumption, annual cost, and grid electricity usage to minimise consumed electricity costs. Prosumers in the model can sell their excess electricity to the grid at a rate of 2 €ct/kWh but must satisfy their own demand first.
Additionally, the model optimises individual heating systems and power prosumers in hourly resolution to minimise the cost of consumed electricity, including electricity generation and electricity from the grid. Once prosumer demand is satisfied, excess energy generated is sold to the grid and deducted from the annual cost (Bogdanov & Breyer, 2016). The model works under the following certain constraints:

1. After the starting period (2015 in this dissertation), no new coal, nuclear and oil-based power and heat generation capacities could be added. In the best policy scenario (BPS), only gas turbines can be added as a transition fuel, with the potential to switch to synthetic gas and biomethane later during the transition period. It is worth noting that this condition can be modified for other types of scenarios.

2. Hydropower plants are refurbished every 35 years and are usually not decommissioned based on empirical observations (Farfan & Breyer, 2017).

3. Based on empirical observations (Farfan & Breyer, 2017), renewable capacity share increase cannot be more than 4% (percentage increase) per year (3% per year from 2015 to 2020) to prevent system disruptions.

4. There is a limit on the share of electricity generated by PV prosumers, set at 20% of the total power sector demand. Additionally, only half of the total prosumer electricity generation can be supplied to the grid for a small financial benefit. The model uses a stepwise progression approach to control the addition of prosumer-generated electricity, starting with a maximum of 3% and increasing to 6%, 9%, 15%, 18%, and finally 20% in subsequent periods. It is important to note that these conditions can be adjusted to match other scenario types.

5. To regulate the biomass and waste resources, accessible bioenergy capacity addition is set to 33% by 2020, 66% by 2025, and 100% by 2030. This constraint limits bioenergy technologies from being installed too quickly.

3.2 Model Design

This dissertation used the LUT-ESTM model to optimise the energy system, including the power, heat, transport, and desalination sectors. The target function was to minimise the total annualised cost of the system calculated as the addition of capital and operational expenses, including costs of ramping for all the considered technologies in modelling as given in (1). The main objective of this dissertation was to demonstrate the BPS for achieving a sustainable energy system by 2050 using local renewable resources.

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

Abbreviations: sub-regions (*r*, *reg*), generation, storage and transmission technologies (*t*, *tech*), capital expenditures for technology *t* ($CAPEX_t$), capital recovery factor for technology *t* (crf_t), fixed operational expenditures for technology *t* ($OPEXfix_t$), variable operational expenditures technology *t* ($OPEXvar_t$), installed capacity in the region *r* of technology *t* ($instCap_{t,r}$), annual generation by technology *t* in region *r* ($E_{gen,t,r}$), cost of ramping of technology t ($rampCost_t$) and the sum of power ramping values during the year for the technology t in the region r ($totRamp_{t,r}$).

The prosumers of the power and heat system are realised in an independent sub-model with a slightly different target function. The target function for the prosumers is given in (2). The prosumer system is optimised independently for each sub-region (2 sub-regions in **Publication I-II** and 12 sub-regions in **Publication III**), even if interconnected. The optimisation goal includes the costs of prosumer power generation and storage, individual heating equipment, the electricity required from the distribution grid, and the cost of fuels for boilers. The income from electricity feed-in to the distribution grid is subtracted from the total annual cost.

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

Abbreviations: generations and storage technologies *(t, tech)*, capital expenditures for technology t ($CAPEX_t$), capital recovery factor for technology t (crf_t), fixed operational expenditures for technology t ($OPEXfix_t$), variable operational expenditures for technology t ($OPEXvar_t$), installed capacity of technology t ($instCap_t$), annual generation of technology t ($E_{gen,t}$), retail price of electricity *(elCost)*, feed-in price of electricity *(elFeedin)*, an annual amount of electricity required from the grid (E_{grid}), curtailed excess energy (E_{curt}).

The main energy balance constraint for the power sector matches the power generation and demand for every hour of the applied year, as shown in (3). For every hour of the year, the total generation within a sub-region and electricity import must cover the local electricity demand.

$$\forall h \in [1,8760] \sum_{t}^{tech} E_{gen,t} + \sum_{r}^{reg} E_{imp,r} + \sum_{t}^{stor} E_{stor,disch} = E_{demand} + \sum_{r}^{reg} E_{exp,r} + \sum_{t}^{stor} E_{stor,ch} + E_{curt} + E_{other} \quad (3)$$

Abbreviations: hours (h), technology (t), all modelled power generation technologies ($tech$), sub-region (r), all sub-regions (reg), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies ($stor$), electricity from discharging storage ($E_{stor,disch}$), electricity demand (E_{demand}), electricity exported (E_{exp}), electricity for charging storage ($E_{stor,\,ch}$), electricity consumed by other sectors (heat, transport, industry) (E_{other}), curtailed excess energy (E_{curt}).

The heat sector energy balance is primarily defined by two equations for high-temperature industrial heat demand, high and medium-temperature industrial heat demand, and centralised heat demand. High-temperature heat can only be produced by fuel-based boilers, as given in (4). Medium-temperature heat can also be generated by electrical heating. It can be stored in high-temperature heat storage and used to produce electricity with steam turbines, as given in (5). Heat pumps, electric heating rods, and waste heat from other technologies can also provide low-temperature heat.

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

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

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

For other sectors except for the power sector, a general energy balance constraint is given in Equation 6

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

Abbreviations: hours (h), technology (t), all modeled power generation technologies ($tech$), energy generated (E_{gen}), storage technologies ($stor$), energy from discharging storage ($E_{stordisch}$), energy demand (E_{demand}), electricity energy for charging storage (E_{storch}), electricity consumed by heating (E_{other}), excess energy (E_{curt}).

Transportation demand is expressed in (metric) tonne kilometres (t-km) and passenger kilometres (p-km). Electricity and fuel consumption for each transport mode is calculated based on the transportation demand for this transport mode, the share of the vehicles driven with that specific fuel and the specific energy consumption of that transport type for the given fuel (Eq. 7-12). Power and fuel consumption for a given mix of transportation means is included in the power and fuels (H_2, diesel, jet fuel, LNG, liquid hydrogen) balance equations on the demand side.

$$\forall h \in [1,8760]\; ElCons_{h,t} = TranspDem_{h,t} \cdot Share_{El} \cdot EffEL_t \qquad (7)$$

$$\sum HyCons_{h,t} = \sum TranspDem_{h,t} \cdot Share_{Hy} \cdot EffHy_t \qquad (8)$$

$$\sum DieselCons_{h,t} = \sum TranspDem_{h,t} \cdot Share_{Diesel} \cdot EffDi_t \qquad (9)$$

$$\sum JetFuelCons_{h,t} = \sum TranspDem_{h,t} \cdot Share_{JetFuel} \cdot EffJF_t \qquad (10)$$

$$\sum LNGCons_{h,t} = \sum TranspDem_{h,t} \cdot Share_{LNG} \cdot EffLNG_t \qquad (11)$$

$$\sum LHyCons_{h,t} = \sum TranspDem_{h,t} \cdot Share_{LHy} \cdot EffLHy_t \qquad (12)$$

Abbreviations: hour *(h)*, transport type *(t)*, electricity consumption *(ElCons)*, hydrogen consumption *(HyCons)*, diesel consumption *(DieselCons)*, jet fuel consumption *(JetFuelCons)*, LNG consumption *(LNGCons)*, liquified hydrogen consumption *(LHyCons)*, transportation demand for transport technology *t* and hour *h* *(TransportDemh,t)*, installed energy capacity of the storage *(instCapEnstor)*, installed power capacity of the storage *(instCapIntstor)*, share of vehicles driven by specific fuel

(Share), specific energy consumption of the specific fuel by the transport type *t (Eff)*. Transport types *(t)* are light-duty vehicles (LDV), buses, 2-3 wheeled transport (2/3W), medium-duty vehicles (MDV), heavy-duty vehicles (HDV), passenger and freight rail, marine, and aviation transport.

This section discusses the energy balance constraints for the power, heat, and transport sectors. The industrial sector in this dissertation includes industrial fuels production, desalination, while the electricity demand is part of the power sector, and industrial process heat is part of the heat sector.

3.3 Portfolio of Modelled Technologies

Various technologies have been integrated into the LUT-ESTM that could be classified into five main categories: electricity generation (renewables, nuclear, fossil), heat generation (renewables and fossil), energy and heat storage, power transmission and sector coupling technologies.

Figure 3 is the graphic representation of the LUT-ESTM and all the power sector technologies considered for energy transition modelling (Gulagi *et al.*, 2021).

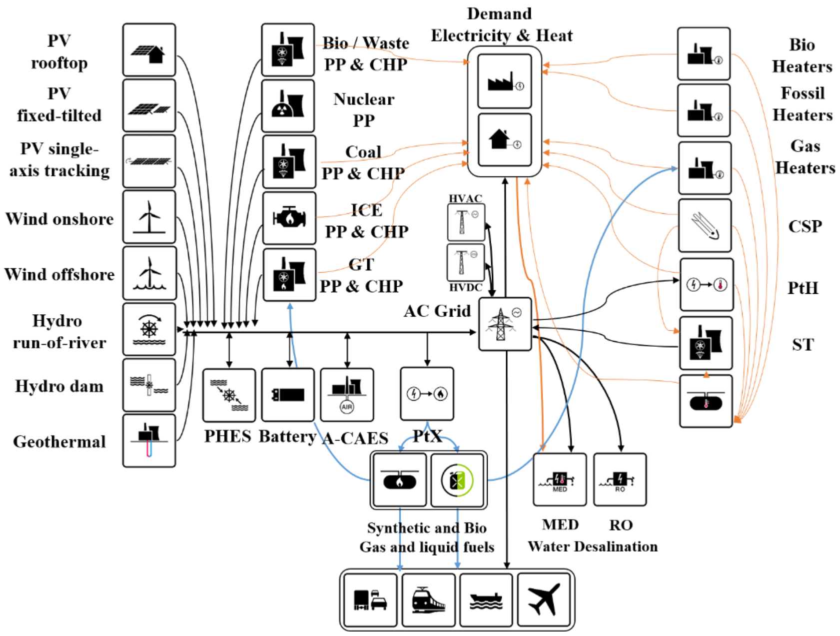

Figure 3.2: Schematic of the LUT Energy System Transition Model for the coupled power and heat sectors (Bogdanov, Ram, et al., 2021).

1. **Electricity generation technologies**: 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 coalfired power plants, oil-based internal combustion engines (ICE), open cycle gas turbines (OCGT), combined cycle gas turbines (CCGT) and nuclear power plants.

2. **Heat generation technologies**: Renewable technologies are CSP, solar thermal water heaters (individuals), geothermal district heaters, and bioenergy (solid biomass, biogas district heat, and individual boilers). Fossil fuels-based heat generation technologies are coal-based heating (district), oil-based (district and individual scale) boilers, gas-based district and individual scale boilers.

3. **Storage technologies:** Li-ion batteries and pumped hydro energy storage (PHES) are utilised for short-term energy storage. For high and medium temperature heat, adiabatic compressed air energy storage (A-CAES) (Aghahosseini & Breyer, 2018) and thermal energy storage (TES) are employed. Additionally, power-to-X technologies, including power-to-heat and power-to-hydrogen, are used in various applications (Fasihi & Breyer, 2020).

4. **Electricity transmission:** The current power grid and its future expansion, along with their influence on total electricity transmission and distribution losses (Sadovskaia et al., 2019), are considered in the energy transition pathway. Different regions in Pakistan are interconnected via direct high-voltage (HVDC) or high-voltage alternating (HVAC) power lines. These connections offer the required flexibility for the spatial distribution of renewable-based electricity, especially during the monsoon season, while also lowering overall national system costs. This is explained in **Publication I and II**.

5. **Sector coupling technologies:** The technologies used for sector coupling include electrolysers, methanation, Fischer-Tropsch (FT) units, SWRO desalination plants, steam turbines, direct electric heaters, and heat pumps for district heating and individual use. These technologies enable converting energy from one sector into useful products for another, improving the overall energy system's efficiency, flexibility, and cost-effectiveness. Please refer to the source material for a more detailed description of these sector coupling technologies (Bogdanov, Ram, et al., 2021). Figure 6 shows the energy generation, storage and bridging technologies that comprise the version of LUT-ESTM used for **Publication III**.

Figure 3.3 represents the different fuel types and modes of transportation: road, rail, marine and aviation. Figure 3.4 is a simplified representation of industrial fuel production, and Figure 3.5 shows the structure for seawater desalination.

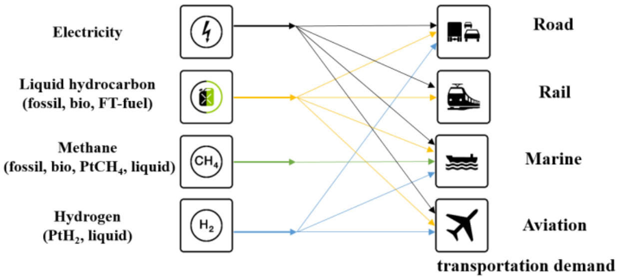

Figure 3.3: Diagram showing different fuels and transport modes (Bogdanov, Farfan, et al., 2019).

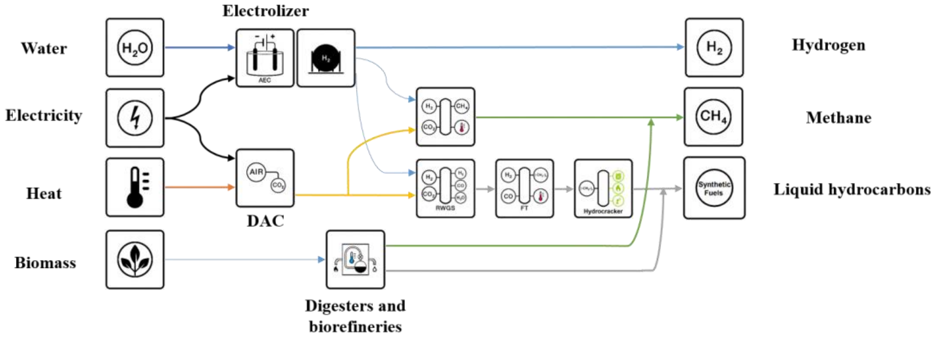

Figure 3.4: Simplified diagram of industrial fuel production (Bogdanov, Farfan, et al., 2019).

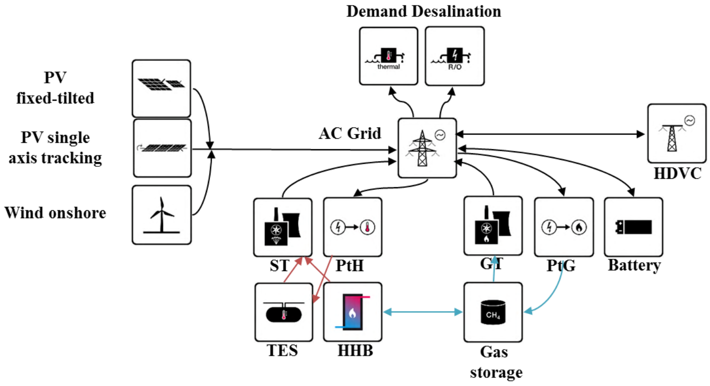

Figure 3.5: Simplified overview of the desalination sector (Caldera & Breyer, 2020).

To fulfil the growing demand for desalination, LUT-ESTM utilises multiple-effect desalination (MED) stand-alone and SWRO plants. These technologies are preferred due to their lower electricity and thermal demand. Excess heat from gas turbines and PtG units is used to install MED stand-alone plants during the transition. The model optimises the water production from MED stand-alone plants based on the availability of heat and the cost of heat generation. After 2015, multi-stage flash stand-alone plants were not installed as they require higher thermal consumption than MED stand-alone plants. The lifetime of the plants determines the phase-out of multi-stage flash and MED cogeneration plants.

3.4 Main Assumptions and Input Data for Modelling

LUT-ESTM ensures high precision computation and reliable results. The costs of the entire system are calculated as a sum of the annualised capital expenditures, including the weighted average cost of capital (WACC), operational expenditures (including ramping costs), fuel costs and the cost of GHG emissions for all available technologies.

1. **Technical and financial assumptions:** The costs and technical parameters used in modelling all technologies are based on literature and are presented in the main manuscript or supplementary material of each publication included in this dissertation. In cases where country-specific cost estimates were not available, a global average financial projection was used. A weighted average cost of capital (WACC) of 7% is generally used for all renewable energy (RE) technologies. In comparison, a WACC of 4% is considered for residential PV rooftop prosumers due to their lower risk and lower financial return expectations (Bogdanov, Child, et al., 2019).

2. **Renewable resource potential:** To model the energy system, the LUT-ESTM used hourly capacity factor profiles for a full year of solar PV, wind power, and hydropower. The solar PV was broken down into optimally tilted PV, single-axis north-south tracking PV, and solar PV rooftop. For countries in the South Asian region, only onshore wind was considered due to a lack of offshore wind profile data. The raw data is for 2005 from NASA databases (Stackhouse and Whitlock, 2008; 2009), reprocessed by the German Aerospace Center (Stetter, 2012) and having a resolution of 0.45°×0.45°. This data is further processed to calculate hourly capacity factor profiles described in Bogdanov and Breyer (2016) and Afanasyeva et al. (2018). This dissertation does not reflect on the increasing efficiency of solar PV systems on land area demand during the transition. However, it would positively affect the country's densely populated areas (Gulagi et al., 2017, 2021). In addition, monthly resolved river flow data for 2005 is used to prepare hydropower capacity factor profiles as a normalised sum of the river flow throughout the country (Verzano, 2009).

3. **Demand:** The electricity demand and demand projection data are obtained from various local and international sources (such as the World Bank and the Asian

Development Bank) and are described in the relevant publications used in this dissertation. The electricity demand is segmented into three categories: residential, commercial, and industrial. The hourly load profile for each sub-region is determined by calculating the proportion of the total demand in the country using synthetic load data (Toktarova et al., 2019). The hourly electricity demand projection is based on the method described by Toktarova *et al.* (2019). For **Publication III**, the data for different crop areas and respective irrigation beneficial efficiencies are obtained from Jägermeyr *et al.* (2015) as a global dataset in a gridded scale of 0.5º x 0.5º. The datasets are employed to derive beneficial irrigation efficiencies for Pakistan's rice, wheat, and maize crops (Caldera & Breyer, 2019).

3.5 Conceptual Review for Mapping the Gender Vulnerabilities in Low-Carbon Transitions

This part of the dissertation explores academic literature on the differentiated impacts of low-carbon energy transitions on gender using a systematic review method. For the literature search mainly, Scopus was used. Other databases (Google Scholar, Web of Science) were also searched, but these databases produced the same results as Scopus. Search strings are developed by using a combination of the different terms related to (1) low-carbon energy, (2) transitions and (3) gender. The search was limited to the English language and peer-reviewed literature. After removing duplicates and non-peer-reviewed articles, a screening process was conducted according to the review criteria described in **Publication IV**. The research in not limited to studies in Pakistan because of the limited availability of the studies. It covered all the articles that appear in search databases.

The literature reviewed is mainly case studies, but literature on policies and strategies is also included. The articles that mention the gender impacts in the text specifically or connected to economic and social class, displacement, education, work, security of energy supply, food availability, health, human rights, race, land ownership, and poverty could lead to gender vulnerabilities were included. Hypothetical studies, including simulations and modelling studies, are excluded from the review.

Details of the extracted data are coded into calculation spreadsheets designed to document the characteristic details of the studies, including the location of the case study, types of vulnerability, reasons to include or exclude the article and energy resources.

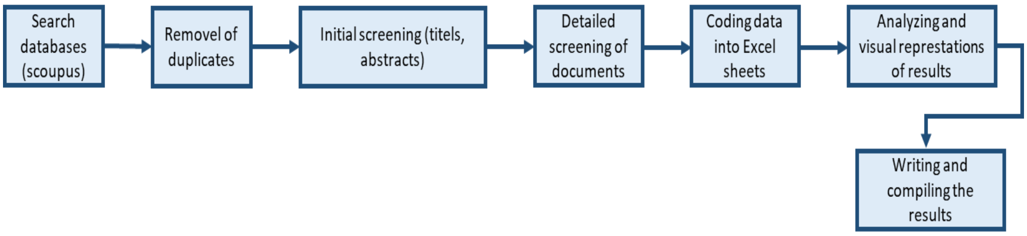

Figure 3.6: Flow chart of the research methodology in **Publication IV**.

4 Results

This section summarises the main objectives of the publications included in this dissertation.

4.1 Publication I: Energy Transition Roadmap towards 100% Renewable Energy and Role of Storage Technologies for Pakistan by 2050

Aim

The main goal of **Publication I** was to simulate and analyse the 100% RE-based power sector, water desalination, and industrial gas for Pakistan by the year 2050 on an hourly resolved basis utilising solar PV, wind, hydro, geothermal, and biomass resources. Pakistan's power generation currently depends on traditional sources of energy. The RE sector is relatively underdeveloped. However, recently, there has been some interest in exploring renewables to accommodate the energy shortage severely affecting the country's economic growth. Rapid urbanisation, industrialisation and rural electrification are increasing the electricity demand, that is resulting in more dependence on depleting conventional energy sources. Traditional energy sources are responsible for greenhouse gas and heavy metal emissions with related severe health issues in the decades to come without a change in the generation mix. There has been no research done till now on a 100% RE system that integrates power, water desalination, and industrial gas demand sectors or incorporates a spatial (0.45ºx0.45º) and temporal resolution of energy supply and demand on an hourly basis for a whole year.

Methodology

The LUT-ESTM was applied to carry out a techno-economic analysis of the transition. Therefore, the simulation was accomplished in 5-year periods from 2015 to 2050 in hourly resolution. Hourly resolution is most important for ensuring a secure energy system for the future since the energy system is based on variable solar PV and wind energy**.**

Two scenarios were modelled to analyse the power system of Pakistan:

- Power scenario: The electricity demand is satisfied. Power may be exchanged between the two regions due to the connection between their energy networks.

- Integrated scenario: simulated a power scenario that included desalination by SWRO and industrial gas use for non-energy purposes. In this case, PtG technology is also used to cover the non-energetic industrial gas demand..

Several reports (Altaf et al., 2009; ANI, 2023; Ministry of Water Resources, 2018) reveal that Pakistan is on the brink of a huge water calamity and is quickly becoming a country with a water deficit. The only desalination plants currently in operation are SWRO plants, which are more effective, based on renewable energy and economical than other desalination technologies (Ajwah, 2021; Pakistan Today, 2022).

Results

The two main features of the modelled scenarios were: 1) the dominance of solar PV technology in the installed technologies providing 92.7% and 96.6% in power and integrated scenarios, respectively. 2) In the integrated scenario, the seawater desalination sector emerges as the biggest sector, where clean water demand is estimated to be 2.8 10^{11} m^3/a by 2050. 3) The levelised cost of electricity drops from 106.6 €/MWh in 2015 to 46.2 €/MWh for power and 46.8 €/MWh for integrated scenario (Figure 4.1). 4) During 2040–2050, gas storage (e-methane produced via the PtG process) will have the highest overall capacity, while battery storage will have the highest storage output.

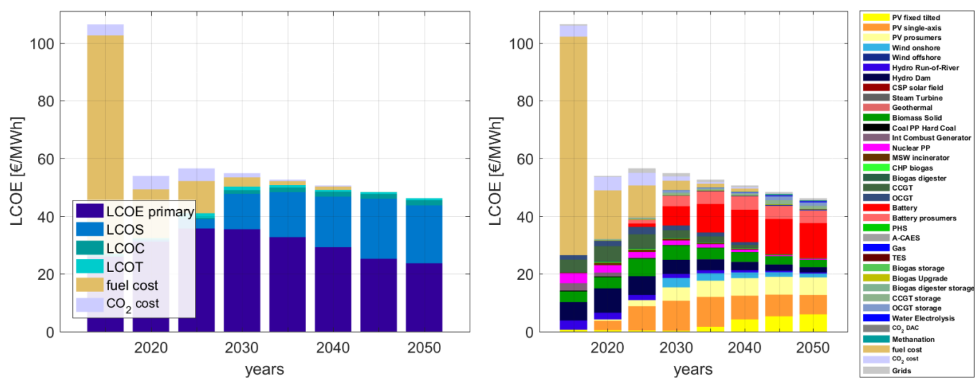

Figure 4.1: Contribution of levelised cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), levelised cost of transmission (LCOT), fuel cost and carbon emission cost to total LCOE (left) and contribution of all technologies to LCOE (right) from 2015 to 2050 for the power scenario.

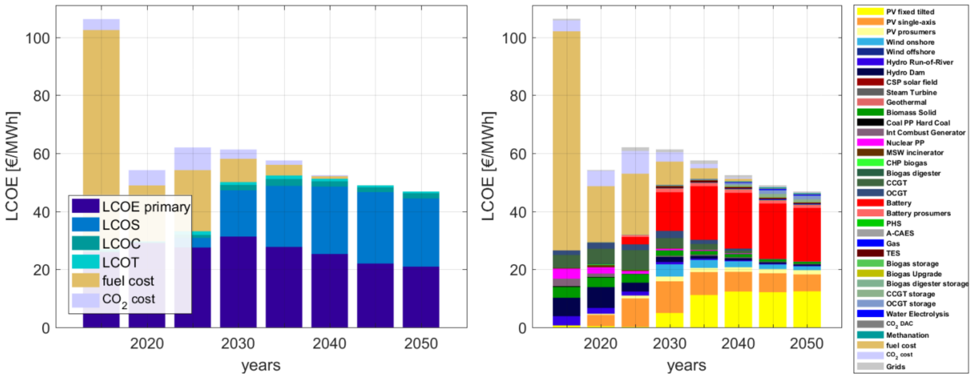

Figure 4.2: Contribution of levelised cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), levelized cost of transmission (LCOT), fuel cost and carbon emission cost to total LCOE (left) and contribution of all technologies to LCOE (right) from 2015 to 2050 for the integrated scenario.

Summary

In **Publication I**, two 100% RE scenarios were modelled using LUT-ESTM for Pakistan. The Power scenario covers the electricity demand, while the Integrated scenario also covers the desalination sector and industrial gas demand. Solar PV in the generation technologies are providing 85.3% and 93.1% in power and integrated scenarios, respectively.

4.2 Publication II: Renewables-Based Energy System across the Power, Heat, Transport, and Desalination Sectors

Aim

Pakistan's energy system transition from one that depends on fossil fuels in 2015 to one that only uses renewable energy in 2050 is modelled. The simulation uses solar PV, wind power, hydropower, geothermal, and biomass resources across the power, heat, transportation, and desalination sectors. **Publication II** answers important questions regarding the country's major technological transition, how the available renewable resources could meet the demand, and how this energy transition could be made a reality. **Publication II** demonstrates that not only can available renewable resources meet the energy demand, but it is also the least-cost option for Pakistan.

This is the maiden research on a 100% RE system, which integrates power, heat, water desalination, transport sectors, and temporal resolution of energy supply and demand hourly for a year. **Publication III** addresses the desalination sector as it is one of the most important aspects of the energy transition for Pakistan. Pakistan has been ranked third among countries facing acute water shortages. The results show that a fully RE-based system for the country is economically viable and provides security and sustainability to the energy system. **Publication II** outlines a plan for Pakistan to shift towards a completely renewable energy system, serving as a roadmap for the transition. It aims to tackle the challenges of energy sustainability and potential water scarcity in the country.

Methodology

The LUT Energy System Transition Model (Bogdanov, Farfan, et al., 2019; Bogdanov, Ram, et al., 2021; Bogdanov, Toktarova, et al., 2019) was used to investigate Pakistan's energy system's transition. Under the imposed limitations, the model optimises the energy system in 5-year increments between 2015 and 2050. The model optimises and applies a cost-optimal solution in full hourly resolution over the year for each 5-year phase. The model was utilised to optimise all key features of an energy system across the power, heat, transport, and desalination sectors to simulate a least-cost energy system under the given assumptions for this dissertation. To establish a sustainable energy system by 2050, the primary goal of this research is to present the optimum policy scenario for utilising local and indigenous RE resources. The following important constraints were considered during modelling:

- Power and heat sector: For every 5-year step, the model defines a cost-optimal energy system structure and operation mode for the constraints. The goal of optimisation is to reduce system costs. The total annualised capital and operational expenses, ramping costs, and GHG emissions costs for all technologies are added to determine the system costs.

- Transport sector: Massive electrification occurs across the transportation modes in the transportation industry as anticipated in energy scenarios. However, synthetic fuels based on RE satisfy the demand for various forms of transportation that cannot be directly electrified. Demand information for fuel and transportation is provided (Khalili *et al.*, 2019).

- Desalination sector: Desalination is considered a separate sector in Pakistan's energy system modelling due to its significant energy demand, comparable to other major energy industries in the country. This highlights the importance of considering desalination as a distinct sector when analysing Pakistan's energy transition and its impact on the overall energy demand. Since agriculture uses more than 70% of the country's water, the agricultural sector is primarily responsible for the demand for desalination. As a result, other sectors are often divided from the agriculture sector.

Results

In Pakistan's energy system scenario modelling, solar PV plays a crucial role and is expected to contribute around 92% of the total primary energy demand in all sectors by 2050. The estimated levelised cost of energy for a 100% renewable energy system is projected to be 56.1 €/MWh in 2050 (Table 1). A significant factor that will drive the demand for energy across all sectors in Pakistan is the increase in demand for desalinated water, which is expected to account for more than 19% of the total energy demand. The energy demand of sustainable transport in 2050 will be covered by direct electricity (40%), synthetic liquid hydrocarbon fuels (34%) and hydrogen (26%). Road transportation will experience a transition to a combination dominated by battery-electric vehicles complemented by plug-in hybrids and fuel cell electric vehicles. Marine and aviation demand will be mainly covered by synthetic fuels and hydrogen from low-cost electricity.

Table 1: Cost of the different components of the renewable energy-based system for Pakistan from 2015 to 2050.

	LCOE primary [€/MW]	**LCOC [€/MW]**	**LCOS [€/MW]**	**LCOT [€/MWh]**	**LCOE system [€/MWh]**	**LCOH [€/MWh]**	**LCOW [€/m³]**	**Levelised cost of energy [€/MWh]**	**Total annualised cost [b€]**	**Total Capex [b€]**
2015	113.5	1.5	0.0	2.8	117.8	67.6	2.7	70.1	52.8	238.4
2020	72.0	0.0	0.5	1.5	74.0	69.8	1.1	64.4	57.9	204.6
2025	70.8	0.2	1.1	2.2	74.9	67.3	0.1	68.0	65.8	171.4
2030	58.5	0.8	6.7	2.4	69.6	67.8	1.0	68.3	76.3	215.9
2035	47.0	1.0	6.2	1.3	56.6	66.2	0.8	64.6	91.1	224.7
2040	42.5	1.1	8.0	0.9	53.2	60.9	0.8	59.3	118.8	266.1
2045	32.9	1.3	15.6	0.8	50.5	59.9	0.8	56.7	140.1	320.8
2050	22.0	1.2	28.6	0.7	50.8	64.2	0.7	56.1	161.6	4230

Summary

Publication II covers the energy system, including power, heat, transport, desalination sectors in the analysis. It presents the techno-economic analysis of 100% RE scenario. Solar PV plays an important role in the modelled scenario by contributing 92% of total primary energy.

4.3 Publication III: Irrigation Efficiency and Sustainable Water Supply for Pakistan's Water Management Strategy

Aim

Pakistan is one of the nations with the most water shortages globally. The country's water demand is expected to exceed the locally available water resources by 2047. **Publication III** aims to analyse the potential of agricultural efficiency improvements and SWRO desalination to solve the looming water issues in the country.

Methodology

Three different scenarios with varying levels of irrigation efficiency are used to study the effects on Pakistan's water consumption up to 2050 using LUT-ESTM. The subsequent water stress and demand from 2020 to 2050 are estimated and then used to calculate the necessary desalination capacity (Caldera, 2020; Caldera et al., 2016). To meet the desalination demand, MED stand-alone, MSF (multi-stage flash), and SWRO plants are used by LUT-ESTM. MED and SWRO offer lower thermal and electricity demand than MSF. MED stand-alone plants are installed based on excess heat during the transition. Excess heat may be generated from gas turbines and PtG units. Based on the availability of heat in the system and the cost of required heat generation, the model optimises the clean water supply from MED stand-alone plants. MSF stand-alone plants are not installed after 2015. This is due to the higher thermal energy consumption compared to MED stand-alone plants. The MSF and MED cogeneration plants are phased out based on the lifetime of the plants. The ultimate goal of this dissertation is to propose a pathway for Pakistan's energy transition towards powering desalination plants with 100% renewable energy by 2050. The study divided the country into 12 sub-regions (Figure 4.3) and modelled three different scenarios - Base, Irrigation Efficiency Push (IEP), and Highest Possible Irrigation Efficiency (HPIE) - to assess the impact of agricultural efficiency on water and desalination demand from 2020 to 2050.

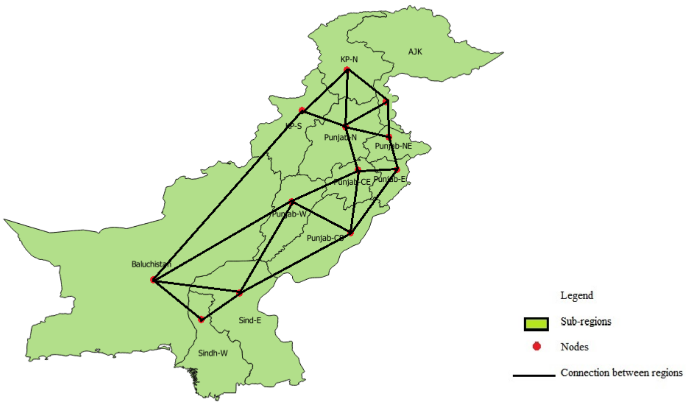

Figure 4.3: Map showing Pakistan's 12 sub-regions designed for **Publication III**.

Results

Figure 4.4 shows how irrigation efficiency affects the demand for desalination in each of the three scenarios. The desalination and overall water demand for Pakistan in 2030, 2040, and 2050 are compared. The Basic, IEP, and HPIE scenarios require desalination facilities to supply 55%, 45%, and 21% of the nation's total water consumption by 2050, respectively. According to the findings, Pakistan's total water demand can be decreased by 54% and 21%, respectively, compared to the total water demand in the Base scenario, under the most optimistic HPIE and IEP scenarios (each of which assumes an annual efficiency gain of 1%). One of the suggestions is to use sprinkle and drip technologies that can reduce the irrigation demand by 40-60% (Jo-Ellen, 2016). Table 2 displays the total CAPEX as well as the annualised cost. Pakistan’s GDP in 2022 was 376 b€ (Billion Euros) and is projected to be approximately 407 b€ in 2025. The annualised cost in Base, IEP and HPIE scenarios are 5, 4 and 2.5 b€ in 2030, respectively. To lower the overall cost, Pakistan needs to invest in efficient water irrigation technologies (Bakhsh et al., 2020).

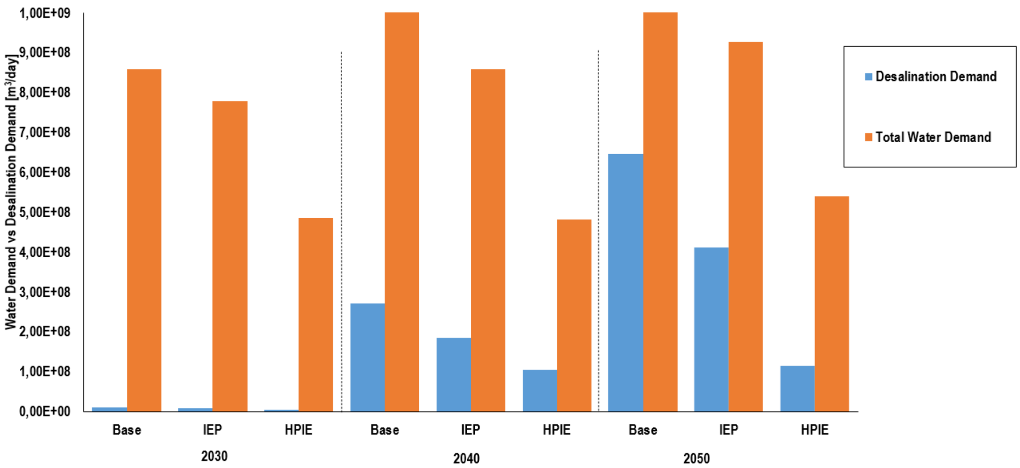

Figure 4.4: Scenario comparison of desalination and total water demand for Pakistan in 2030, 2040 and 2050.

Table 2: Comparison of the total capex (energy system and desalination) and annualised costs for the Base, IEP and HPIE scenarios.

	2030	2050
Total CapEx	b€	b€
Base	28	1557
IEP	23	988

HPIE	14	286
Annualised Costs		
Base	5	190
IEP	4	119
HPIE	2.5	36

Summary

In this research, the water savings potential of upgrading the current irrigation infrastructure to sprinkler or drip irrigation systems across three scenarios was analysed. It was observed that increasing the country's overall irrigation efficiency to 90% by 2050, results in a 54% and 80% reduction in total water and desalination demand, respective to a business as usual scenario. However, in a more moderate scenario, where the maximum increase in irrigation efficiency is 1% per year, the 2050 total water and desalination demand are reduced by 21% and 40%, respectively. The final 2050 LCOE for Pakistan, in all three scenarios, was about 40 €/MWh. The corresponding 2050 LCOW was 0.6 €/m^3 and includes the cost of water transportation.

4.4 Publication IV: Gender Vulnerabilities in Low-Carbon Energy Transitions: a Conceptual Review

Aim

Publication IV aims to map the gender vulnerabilities related to low-carbon energy transitions in the existing body of literature. The conceptual literature review methodology examined how gender has been discussed in academic literature to illuminate the pathways for future directions.

Methodology

An initial search found 8115 articles; after eliminating non-peer-reviewed articles and initial examination of titles and abstracts, 147 articles were initially short-listed for the complete text evaluation. The article search was not solely focused on studies related to Pakistan but on the overall literature. The large number of articles selected for text analysis were case studies, but few of them were related to the analysis of data. Table 3 shows the search terms used to identify the articles. After a full-text review, 65 relevant articles were included in **Publication IV** for the review. Methodologically, reviewed literature varies with the question posed in the search. For **Publication IV**, the following guiding questions are framed to understand the gendered vulnerability framework in literature. Table 3: Search strings used to search research articles.

Database	Date	Search string
Scopus (title, keywords, abstract)	July, October 2021	((("sustainable energy" OR "low carbon" OR renewable*)) AND ((development OR energy OR power OR electricity OR generation OR industry)) OR ((solar* AND (power OR photovoltaics OR pv OR concentrated OR "home system*" OR industry))) OR ((wind* AND (power OR electricity OR turbine* OR industry))) OR ((geothermal AND (power OR electricity OR industry))) OR (hydropower*) OR ((biomass AND energy) OR bioenergy OR biofuel* OR agrofuel* OR "mini grid*") OR ((geothermal AND (power OR electricity OR industry)))) AND((transit* OR transform* OR change* OR shift* OR pathway* OR polic* OR strateg*)) AND (("social impact*" OR "social outcome*" OR "socioeconomic* OR vulnerability")) AND ((gender* OR women* OR men OR girl* OR boy*))

1. What gendered vulnerabilities have been discussed in literature based on case studies or data/evidence?

2. What parameters and drivers have been mentioned that could lead to gendered vulnerabilities?
3. What are the future implications and directions that could emerge from these vulnerabilities?

Results

Based on the reviewed literature, Figure 4.5 was constructed, which shows the relationship between different enablers and vulnerabilities that emerged from the reviewed literature in the context of low-carbon energy transitions. To categorise the different vulnerabilities, they were merged into four main themes: *land use change*, *gender-neutral energy policies*, *access to resources*, and *green practices as gendered*. One important conclusion is that these vulnerabilities and enabling mechanisms cannot be considered in isolation but in relationships with others. For example, pre-existing gender social discriminations marginalise women’s access to land and resources. According to studies, this limited access to land is the leading cause of gender discrimination. This social discrimination and power dynamics between genders manifest in other vulnerabilities, such as exclusion from decision-making processes. This absence of carbon market policies and decision-making practices limits women’s capacity to gain from carbon projects.

It is essential to examine the direct connection between vulnerabilities and various enabling mechanisms, as well as their intricate interrelationships. The main themes identified in the literature can be grouped into four categories: changes in land loss, policy exclusion, access to resources, and the gendered nature of green practices.

Summary

Academic literature was studied to understand gender vulnerabilities in low-carbon transitions and what sociocultural and socioeconomic factors could contribute to these gendered vulnerabilities. Four major themes from this literature review emerged as a result of the analysis: land use change, gender-neutral energy policy, resource access, and green practices, gender, and culture. These four themes show that social and structural disparities give rise to a number of enabling mechanisms, indicating that vulnerabilities should not be thought of in isolation but rather in connection to others. Four dimensions of vulnerability were analysed, including exposure, sensitivity, and adaptability.

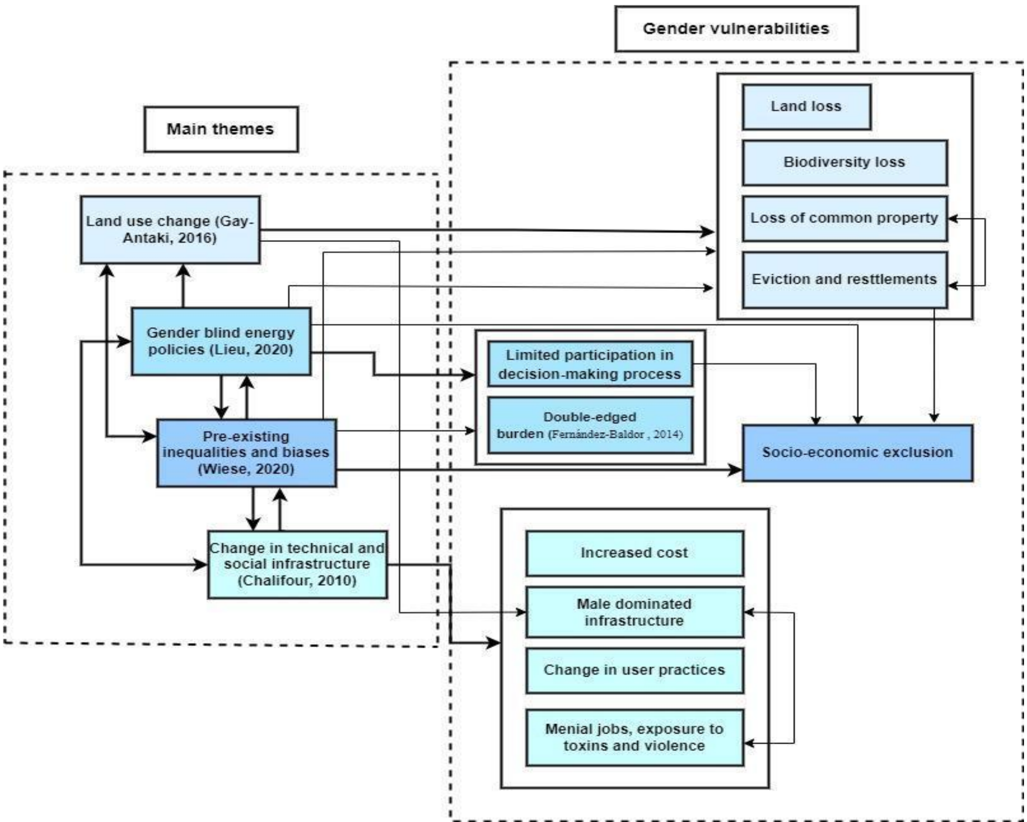

Figure 4.5: Diagrammatic representation of mechanisms and relationships within and between different enablers and vulnerabilities emerged from the literature.

5 Discussion

5.1 General Discussion of the Presented Results

The key objective of this dissertation is to show the technical and financial viability of a sustainable and cost-effective energy system in Pakistan. Furthermore, the gender vulnerabilities of low-carbon transitions are analysed to understand and address the challenges. To find the solutions to the research questions posed (see section 1.3), energy system modelling scenarios were developed using LUT-ESTM. The results of this dissertation show that a fully sustainable energy system for Pakistan is not only technically achievable but also economically viable. However, shifting from expensive and polluting fossil fuels requires political will and implementing policies to integrate higher shares of RE technologies.

1. **Energy mix and cost:** According to **Publication I-III**, Pakistan's electricity mix can change from fossil fuel-based to completely renewable-based. By 2050, all generated electricity can be based on sustainable energy resources, where solar PV emerges as a pivotal technology to cover the electricity demand. The projected declining cost of solar PV and resource abundance in the region are the primary reasons for the increasing share of solar PV in electricity generation in the modelled scenarios. In areas with good wind resources, wind power complements solar PV. The findings in **Publications I–III** reflect that the growing proportion of renewable-based electricity will replace the current reliance on electricity derived from fossil fuels. According to **Publication I**, solar PV outperforms all other deployed technologies, contributing 92.7% and 96.6% in power and integrated scenarios, respectively. In numerous parts of the globe, utility-scale solar PV generation has already reached or beyond grid parity (Breyer and Gerlach, 2013), undermining the currently practiced and least expensive fossil fuel-based power generation (IRENA, 2021a). A similar pattern has been examined in South Asian countries, which depend heavily on fossil fuels (Gulagi et al., 2017, 2020, 2021). Wind energy, however, has a limited impact on installed capacity. In Pakistan, wind resources are primarily concentrated away from the major electricity demand centers. Compared to solar energy, a high-quality resource accessible nationwide, wind energy is less competitive due to the distance between inhabited areas and good wind resource sites. However, some recent studies have assessed the technical potential for wind and solar energy and proposed that wind power could have a promising contribution to Pakistan's future energy mix (Khatri et al., 2022a, 2022b). Seawater desalination plants could provide the possibility for wind power utilisation if established close to high wind potential areas.

   The findings of **Publications I–III** demonstrate that the energy transition will necessitate a substantial increase in investments in RE technology as opposed to fossil fuels. The routes outlined in this dissertation predict the investments required in each technology throughout 5-year intervals, based on the projected capex and opex for each technology. Moreover, annual investments, particularly for providing a kWh or

MWh of electricity or energy, do not give a complete picture of expenses and investment. As a result, the levelised cost of electricity (LCOE) became one of the indications for normalising costs and making them comparable across technologies, contexts, and the transition (Ram et al., 2018). Despite numerous sceptics, LCOE as a tool for cost comparisons is still reliable (Kuckshinrichs, 2021) and is widely employed (Loewen, 2020). Bazilian and Shah (2020) claim that the LCOE would oversimplify some elements of the costs of capital and might lead to difficulties in accurately representing distributed building systems.

Additionally, further investment is required to phase out fossil fuel power generation. Using LUT-ESTM, **Publication II** simulated an energy transition for Pakistan comprising all sectors, including the demand for desalination, and demonstrated a similar trend toward declining costs by 2050. A 100% RE-based energy system's overall levelised cost of energy in 2050 is 56.1 €/MWh, down from 70 €/MWh in 2015, demonstrating renewable energy's cost-competitiveness during the transition.

Pakistan is reported to be one of the world's top ten most water-stressed countries. **Publication III** assesses the potential for using enhanced irrigation systems and seawater desalination based on RE to alleviate Pakistan's water shortage. Suppose the nation's overall irrigation efficiency increases to 90% by 2050. In that case, it can result in a significant decrease of 54% and 84% in demand for water and desalination compared to a business-as-usual scenario. In a more realistic scenario where irrigation efficiency improves by a maximum of 1% each year, there could still be a substantial reduction in demand for water and desalination in 2050. This would translate to a 21% and 40% decrease in total water and desalination demand, respectively. By 2050, renewable energy sources may fully support the expected expansion in desalination demand for each of the three scenarios at an average water production cost of 0.6 €/m^3. The reported cost for water transportation in Pakistan is attractive to farmers and is included in the analysis. The low-cost electricity production in Pakistan, powered by solar PV and battery storage, drives the overall cost efficiency. These findings highlight the potential for Pakistan to enhance its irrigation efficiency systems and achieve water security by leveraging low-cost renewable electricity.

Given Pakistan's plans to invest extensively in coal and hydropower, any adverse social and environmental effects of such a vast hydropower deployment should be considered. More significantly, hydropower plants in Pakistan are vulnerable due to the drastic change in rainfall patterns caused by climate change (Bashir & Road, 2018; Falchetta et al., 2019). Hydropower stations may become stuck due to unpredictable rains and severe water shortages (Falchetta et al., 2019).

According to the analysis presented above, solar electricity generation is less susceptible to the hazards associated with climate change compared to hydropower (Emodi et al., 2019), which is crucial information for decision-makers and energy planners. Solar PV is also more climate change-resistant compared to other RE options. Therefore, it is projected that solar PV will be essential for reducing GHG emissions and altering the energy system to be compatible with changing climatic circumstances (Emodi et al., 2019). The results of this dissertation demonstrate the significance of PV technologies as essential for the transition to RE in Pakistan because capex is predicted to fall. Moreover, cost overruns are least likely to occur with solar PV systems (Nugent & Sovacool, 2014). Systems like solar PV and wind that are decentralised, modular, and scalable experience fewer cost overruns and a decreased risk of technical system failure (Nugent & Sovacool, 2014; Oyewo et al., 2021). Agile energy solutions that can be built over short time frames should be prioritised by developing economies (Ansar et al., 2014). Over time, this will boost energy security and resilience (Azzuni et al., 2020).

2. **Desalination:** Pakistan is suffering from acute water shortage, drinking water pollution, and contamination. The government of Pakistan (GOP) is trying to improve the quantity of drinking water adequately while struggling to provide it at an affordable cost and in an equitable, efficient, and sustainable manner to the entire population (Ministry of Water Resources, 2009, 2018). Based on **Publication III** questions and motivation, renewable-based SWRO desalination and irrigation efficiency was evaluated to overcome the water stress in the country (**Publication III**). Improved irrigation systems can increase water production; the effects on water stress, overall water use, and desalination demand are also evaluated. Without considering irrigation efficiency, the predicted total water and desalination demands by 2050 are 11,600 million m^3/day and 6460 million m^3/day, respectively. By 2050, the total desalination demand in the HPIE and IEP scenarios had fallen by 36% and 82% compared to the Base scenario, respectively. The findings of Publication III demonstrate that RE-based seawater desalination can safeguard Pakistan's water resources regardless of the water demand management strategy. Yet, water demand management systems in Pakistan's irrigation sector can ensure a more reliable and affordable water supply. Pakistan can address its growing water crisis by improving irrigation infrastructure and utilising Pakistan's substantial low-cost solar PV electricity generation potential. SWRO desalination facilities can be run to ensure that potable water is delivered to all sectors in Pakistan at reasonable prices, thanks to the continually falling battery storage costs.

3. **Transport and heating:** The studies show that future pathways with higher shares of RE are cost-effective, efficient, and cleaner than conventional energy-based systems, although the literature analysing the incorporation of greater shares of RE technologies and the transport system in Pakistan is limited (Perwez et al., 2015; Raza et al., 2022). The findings of the analysis of Pakistan's transportation system (**Publication II**) show that the integration of electricity, hydrogen, methane, and liquid RE fuels is the foundation for the country's transportation in the future. Roads are the most significant component of Pakistan's transportation infrastructure, accounting for 92% of passenger and 96% of inland freight transit (Karandaaz Pakistan, 2018). The transportation industry in Pakistan is one of the major sources of greenhouse gas emissions and is highly reliant on imported fuels. To achieve its climate goals and to reduce dangerously high GHG emissions in major cities, the

government announced its first electric vehicle (EV) policy in 2019 (MoCC, 2019). The cheapest option is to electrify road transportation directly. However, this depends on the reliability of the electrical supply, the availability of effective infrastructure for vehicle charging, and consumer acceptability. Since present battery technologies cannot satisfy long-distance transportation needs, direct electrification is impractical for the whole transportation sector. The shift to renewable energy in Pakistan's transportation sector primarily comprises hydrogen and liquid fuels based on RE.

Pakistan’s residential heating sector relies overwhelmingly on raw biomass and natural gas for cooking and heating. According to statistics by IEA (2016), roughly 58% of the population, particularly in rural areas, depends on raw biomass for heating due to insufficient access to alternative heating resources. The modelling scenarios (**Publication II**) indicate an increase in the direct usage of electricity and heat pumps to meet the demand for heating in homes and businesses. In these scenarios, in 2050, the primary source of electricity will be solar PV (99%), and the primary source of heat will be heat pumps (47.1%), with the remaining fossil fuels being replaced by direct electric IH (19.5%), biomass-based generation (5.4%), solar thermal (6.5%), and a small amount of synthetic natural gas.

4. **Storage technologies:** In an energy system, storage technologies are a crucial component of the energy transition because they offer alternatives for both short- and long-term flexibility, which is necessary to integrate the significant share of RE technologies. Batteries are becoming more affordable, and their daily charge and discharge profiles allow them to dominate the storage output. However, during the changeover, gas storage (e-methane produced via the PtG process) might make it possible to balance out seasonal variances. Grid interconnections can also offer flexibility by balancing supply and demand and enabling the most effective use of RE. Dispatchable REs like hydropower reservoirs and bioenergy are essential when balancing daily and seasonal needs. Flexible gas turbines are a useful balancing technology because they can run at low output levels and ramp up and down their power production as needed. The modelling strategy used in this research offers insightful information on various adaptable choices for policy discussion and system development in Pakistan.

   Pakistan’s renewables-based power system is dominated by solar PV installations (92%-96%) in the scenarios presented in this dissertation. Therefore, storage technologies are essential for flexibility and keeping supply and demand in balance. Although PtG is used as seasonal storage in the later stages of the energy transition (after 2040), when the installed renewable capacity exceeds 80%, gas storage plays a crucial role by providing 26 TWh (**Publication II**). Battery storage accounts for the most significant portion of the total storage output, ranging from 69% to 88% (depending on the case). Nonetheless, the findings indicate that batteries will become relevant after 2030. The country's power system depends on installing PV, which makes battery storage necessary to address the fluctuation of the energy source and provide crucial system flexibility. By 2050, utility-scale and prosumer batteries will meet 99% of Pakistan's electricity storage needs (**Publication II**). Since the PV-battery combination emerges as the least cost alternative to distribute electricity through 2050, the growing percentage of solar PV translates into a growing share of battery output.

Addressing the intermittency of variable renewable resources can bring potential challenges for future renewable-based energy systems. Different materials are necessary for manufacturing the required equipment for the future energy transition. Lithium is essential for the manufacturing of rechargeable batteries, but it is also considered a critical material (Breyer et al., 2022; Greim et al., 2020). Lithium mining is also associated with negative environmental and social impacts (Gaines & Dunn, 2014). There is considerable and growing concern by both private industry and government entities over the environmental impact of lithium-ion battery production and especially the mining, particularly by countries rich with lithium deposits that are being heavily mined. Lithium mining could lead to the contamination of local ecosystems and water basins, which makes water consumption for people and animals in those localities harmful. Lithium mining requires a considerable amount of fresh water. The mining process is done by pumping water into the reserves in a manner similar to fracking used in oil drilling. It leaves behind a toxic stew of waste that takes centuries for nature to clear up. Lithium batteries also have materials within them, such as manganese, cobalt, and nickel, which are harmful to the environment when not properly handled (Boyden et al., 2016). Proper disposal and recycling practices can result in the saving of considerable natural resources and environmental pollution reduction. A well-established recycling system, the achievement of vehicle-to-grid integration, and the realisation of transportation services with lower lithium intensity can ensure the balance of supply and demand for the energy transition. As a result, it is imperative to achieve a concerted global effort to enforce a mix of policy goals (Breyer et al., 2022; Gaines & Dunn, 2014).

5. **Understanding social and gendered aspects:** Energy transitions are both techno-economic and deeply gendered and societal phenomena (Lawhon and Murphy, 2011; Johnson, J. Y. C. Han *et al.*, 2020). Despite the established link between gender, society, and energy use, concentrated research and literature on the gendered effects of low-carbon energy transitions are emerging very slowly. Moreover, modelling approaches and studies provide valuable insight into the attributes and nature of low-carbon transitions but also have significant limitations (Geels et al., 2017b; Lieu et al., 2020b; REEEM, 2019). Such studies involve a limited number of actors and stakeholders, while energy transitions involve a more comprehensive range of actors. To better understand the dynamics of gender vulnerabilities, a systematic literature survey was conducted (**Publication IV**). Four main themes emerged from the text analysis of the literature corpse: *land use change, gender-neutral policies, access to resources and green practices are gendered*. The literature review reveals different kinds of gender vulnerabilities and their technological and social relevance (**Publication IV**). These four themes indicate several enabling mechanisms/drivers of vulnerabilities arising from existing social and structural inequalities. The analysis

also shows the overlapping nature of vulnerabilities and emphasis that vulnerabilities should not be considered in isolation but in relationship with others (**Publication IV**: Figure 12). For example, pre-existing gender inequalities and power structures may marginalise women's access to resources when new energy projects are implemented (Tsagkari, 2022; Gay-Antaki, 2016). Lack of resource access can further exclude women from decision-making spaces. This limited participation in carbon market policies and decision-making practices limits women's capacity to gain financial benefits from low-carbon energy projects (Gay-Antaki 2016).

Publication IV also identified the gaps that could open new avenues for future research on energy transitions and gender. These future paths were grouped into *vulnerability and intersectionality and gender-inclusive policies and practices*. One main understanding from mapping gender vulnerabilities was that the resilience mechanisms (government assistance and community strength) are often missing within the literature. Therefore, future research ought to consider how low-carbon energy transitions are adapted in communities through a gendered dimension.

5.2 Policy Implication

Publications I-III illustrate that a transition towards a sustainable energy system is technically and economically viable. However, political will at the state and local levels and detailed policy frameworks are required to steer this transition. Pakistan's RE policy is ambitious, but some experts think that current actions are insufficient to address climate change (Mittha, 2021). **Publications I-III** provide energy scenarios and guidance for planning the RE system.

1. **Timely actions:** Linking with climate change, Pakistan is facing the most devastating and widespread floods, where water has reached one-third of the country with further devastation of the country's economy and critical food shortage (Clarke et al., 2022). The country faced the same level of destruction by floods in 2010. According to Global Climate Risk Index (Eckstein et al., 2021), Pakistan is the eighth most vulnerable country to climate change but responsible for less than 1% of global GHG emissions. The timing of the energy transition is crucial because the destruction is already becoming a reality. The window of opportunity to counteract climate change is increasingly decreasing; urgent steps are needed to keep the temperature rise at 1.5°C, or even below 2°C (IRENA, 2019a).

2. **Techno-economic understanding: Publications I-III** present the technical and cost implications of Pakistan's 100% RE scenarios. This work provides policymakers a good insight into techno-economic dynamics to guide future investment decisions on technological build-up. The optimal pathway is the least-cost option; therefore, no new fossil fuel utility and nuclear power capacity build-up are considered in scenarios. Recent technology advancements, market dispersion, and increased economies of scale have dramatically lowered the cost of wind and solar energy (IRENA, 2021a;

Kavlak et al., 2018). It is also noteworthy that the price of solar PV and wind power has decreased sharply and will strongly influence future decision-making on technologies, energy markets, planning and operation. These technologies will shape the landscape of the energy system, particularly for countries like Pakistan, which have abundant solar resources.

3. **Water desalination:** Pakistan faces an acute water shortage, with annual water availability falling below 1000 m^3 per person (Liu, 2022). Furthermore, water availability is unevenly distributed throughout the country. Pakistan's water irrigation system is highly inefficient and responsible for 90% of the water withdrawal (Ministry of Water Resources, 2018). Many researchers have suggested shifting from inefficient irrigation systems to better irrigation technologies, such as drip and sprinkle irrigation systems. According to **Publication III**, bringing the nation's overall irrigation efficiency up to 90% by 2050 will result in a 54% and 80% decrease in the total demand for water and desalination, respectively. **Publication III** demonstrates how improving irrigation systems and utilising abundant solar PV and affordable electricity generation potential can help Pakistan address its growing water crisis. SWRO desalination plants can be run to ensure that potable water is delivered to all sectors in Pakistan at reasonable prices, thanks to the continually declining battery storage costs. Batteries are used to enable the desalination operation in maximum capacity during the day and night.

4. **Just energy transition:** Decarbonisation can bring potential benefits and enhance possible vulnerabilities (Sovacool et al., 2021). The political and economic responses to mitigate global warming can come with differential access to employment and resources, externalities, displacements, and societal impacts. The challenge for policymakers is to connect complex climate change mitigation strategies with efforts to address vulnerabilities or equitable distribution of benefits by energy transition (Geels et al., 2017a; Sovacool & Dworkin, 2014). We must recognise the full continuum of winners and losers across geographical scales, gender, economics, and ethnicity. **Publication IV** addresses the disengagement between the techno-economic attributes of low-carbon transitions prioritised in energy and environment policy debates and the consequences these energy transitions can have on various groups.

5.3 Limitations of the Current Research and Future Research Prospects

The fundamental limitations and prospects of the research carried out for this dissertation are discussed below:

1. **Sector coupling and rural electrification:** The techno-economic evaluation of Pakistan's energy system has been presented in **Publications I-III**. The sectors discussed are power, heat, transport, desalination and industrial gas demand. Further research on Pakistan's energy system and more detailed industrial sector

analysis is needed. Another limitation is the geographical restructuring of the country. However, the country was divided into 12 regions only for **Publication III,** and **Publications I and II** considered the country into two regions. Energy demand and heterogeneity of RE sources could be more precisely considered while decreasing the requirement for transmission lines. Sector coupling has been applied in a limited way because the desalination and transportation sectors are considered independently while the power and heat sectors are being integrated. Future studies could address the limitation by carrying out more detailed sector coupling options and dividing the country into more geographical regions.

2. Furthermore, Investigation of PtX technologies, such as power-to-heat and power-to-hydrogen, is also required to defossilise the entire energy system. These analyses will identify the most economically attractive synthetic fuel sites in Pakistan. Further studies on Pakistan's energy transition are required, and models that can incorporate off-grid electrification in evaluations of energy systems must be developed.

3. **Cost assumptions:** The results of this dissertation, as presented in **Publications I–III**, highlight the significance of PV technologies and batteries in Pakistan during the transition period. Yet, given the correlation between cost and pace of capacity installation, it must be noted that modifying cost parameters would impact a technological roll-out. Additionally, a combination of market development and research can identify the future's most cost-effective energy systems. Cost estimates, though, could eventually be overly pessimistic or optimistic. For instance, the insight by Vartiainen et al. (2020) demonstrates that studies frequently assume conservative capex for PV and batteries.

4. **Integration of techno-economic and social perspective:** Decision-makers can use energy transition scenarios to evaluate the scope of the necessary transformation. However, caution should be exercised when determining the precise technology mix, price, and cost projections (IRENA, 2022; Paltsev, 2017). Effective climate change mitigation requires massive changes in power, industry, transport, heating, agriculture, and other sectors. Energy studies and modelling approaches give valuable insight into the attributes and nature of low-carbon energy transitions but have numerous crucial limitations. These studies involve a limited number of actors, such as firms, consumers, and policymakers.

5. In contrast, a wider range of actors, including civil society organisations, media, ministries, communities, local governments, politicians, and advisory bodies, are involved in energy transitions (Geels et al., 2017b). Social behaviour is governed by various factors, including beliefs, unequal assets, competing values, complex public relations, and cost-benefit analysis. Energy transitions involve more than just new technology market diffusion; they also include shifting social norms, cultural debates, and broader political conflicts. Transitions are disruptive, contested, and non-linear processes (Anderson & Peters, 2016; Farla et al., 2012).

Integrating distributional social impacts into modelling is under-researched, but the subject is gaining attention in academic research (Fodstad et al., 2022). A study by REEEM (2019) proposed the approach to better consider the vulnerabilities in modelling approaches to enrich the scenario analyses by providing additional information to enable a discussion of distributional impacts.

6 Conclusions

The primary purpose of this dissertation is threefold: first, to evaluate the techno-economic viability of a 100% renewable energy system (power, heat, transport and desalination) in Pakistan. Second, to investigate and assess the options to resolve the issue of water scarcity; and third, to identify the gender vulnerabilities of the low-carbon energy transitions in literature for a fair and just energy transition aligned with the Paris Agreement and Sustainable Development Goals.

The findings of this dissertation demonstrate that a cost-effective transition to 100% renewable energy is feasible by integrating large shares of solar photovoltaics, complemented by wind power and other storage and flexibility alternatives. Pakistan has abundant, inexpensive renewable resources, especially solar energy, but energy policies must take advantage of this potential. To meet Pakistan's energy needs, this dissertation presents scenarios with least cost options to utilising this potential. By gradually replacing costly and inefficient fossil fuels, this transformation not only lowers the cost of producing power but also permits a rapid reduction in CO_2 emissions, better energy security, and reduced water stress.

Large-scale renewable energy system integration demands the development of novel least-cost flexibility and storage solutions. Power-to-gas, transmission grids, lithium-ion batteries, and resource complementarity offer the necessary flexibility for an energy system dependent on renewable resources. Storage technologies, particularly Lithium-ion batteries, play a crucial role in giving power systems flexibility as the percentage of renewable energy sources rises, as highlighted in **Publications I and II**. In Pakistan's energy system, Lithium-ion batteries and transmission grids play a very important role by providing flexibility during the transition without raising the overall cost of the system. Since Lithium-ion battery prices continue to drop, a rapid transformation in the power industry is now a distinct prospect. Sector coupling may also provide additional advantages, such as decreased curtailment while offering an entirely sustainable energy system. Furthermore, utilising the abundant solar photovoltaic potential could pave the way for new industrial avenues such as green e-hydrogen, e-fuels and fertilisers production.

Pakistan is one of the most water-stressed nations, with escalating water scarcity problems. **Publications I, II, and III** show that seawater reverse osmosis desalination and can overcome water shortage. Furthermore, **Publication III** discusses the potential of improved agriculture efficiency with renewables-based seawater reverses osmosis desalination. In addition to addressing the problems of water scarcity and reducing harmful air pollution, low-cost renewable energy sources will also lower the rising import costs for fossil fuels. Such a switch also reduces the significant losses connected with producing power from fossil fuels. A completely renewable energy system will be very effective as a result.

Low-carbon energy transitions are of paramount importance in achieving climate goals. These transitions are technical, economical, and deep societal and gendered. **Publication**

IV mapped the gender vulnerabilities and enabling mechanisms arising from social and structural inequalities. Renewable energy initiatives alone, however, are unable to accomplish gender and social equity since they do not automatically address the structural dynamics that are ingrained in sociocultural and socio-economic environments. For instance, existing power disparities in access and resource distribution are not addressed early. The new energy regimes would recreate the same structural inequalities and differences.

Publication I and II provide answers to the research questions posed in section 1.3 of this dissertation. These publications discuss the feasibility, cost, and flexibility of Pakistan's energy system to ensure the security of supply by modelling scenarios. **Publication III** reflects on these questions by providing a discussion on future desalination demand, renewable energy-based desalination and the need for improved irrigation systems. **Publication IV** explores the gender vulnerability dimension in low-carbon energy transitions in the existing literature. In a nutshell, a transition towards a sustainable, technically viable and cost-competitive future for Pakistan also presents a pathway to address issues such as global warming, energy shortage, greenhouse gas emissions, fossil fuel dependency, and growing energy demand. A real policy option requires a well-planned energy transition that integrates techno-economic and social perspectives.

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Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050

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Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050

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ABSTRACT

The main aim of this study is to present an energy transition roadmap for Pakistan in which the total energy demand by 2050 is met by electricity generated via renewable sources, in particular, solar photovoltaic. Efforts have been made to assess the energy and cost required for the transition towards a sustainable energy supply covering the demand for power, desalination and industrial gas sectors. Hourly resolved model was used and optimization was carried out for each time period (transition is modeled in 5-year steps) on the basis of assumed costs and technological status till 2050 for all energy technologies involved. Solar PV dominates the installed technologies and contributes 92.7% and 96.6% in power and integrated scenarios. Seawater desalination sector dominates the integrated scenario and clean water demand is found to be $2.8 \cdot 10^{11}$ m^3 by 2050. The levelised cost of electricity declines from 106.6 €/MWh in 2015 to 46.2 €/MWh in 2050 in power scenario. In country-wide scenario, gas storage rules from 2040 to 2050 in terms of total storage capacities while battery storage is prominent in terms of storage output. The results indicates that, 100% renewable system is cost competitive and least cost option for Pakistan's future energy transition.

1. Introduction

Industrialization, intensive use of fossil fuels and nitrogenous fertilizers has pumped more greenhouse gas (GHG) into atmosphere than any natural processes could possibly have done. It is urgently crucial to reduce the carbon dioxide emissions by a significant amount [1]. The level has been estimated at 450 ppm, which would mean a global increase of 2° Celsius in mean ground temperature [2].

Pakistan with more than 188 million inhabitants stands as the sixth most populous country in the world (2013). Traditionally, Pakistan was an agrarian economy, but over the time, industry and services sector have become main contributors to the GDP [3]. Presently energy production and consumption in Pakistan basically depend on conventional fuels. Pakistan's total installed capacity breakdown for the year 2014 has been shown in Fig. 1. Oil and gas contribute 63% (gas 33.0% and oil 30.0%) to the total energy supplies [3,4]. However, the increased dependence on natural gas cannot continue owing to the rapid depletion of country's gas reserves. It has been assessed that only 25–30% of the total assets will be left by the year 2027–28 [5]. The commercial sector is the biggest consumer of energy by consuming 37.6% of total energy, while the transport, residential and commercial sectors consumed 31.4%, 23.4% and 4.0% respectively in 2013 [6,7]. Pakistan's electricity consumption has grown at a compound annual growth rate (CAGR) of 4.6% from 2000 to 2015 [8]. The growth in electricity consumption has been mainly attributed to the increase in population, economic growth, increase in income per capita and urbanisation [9,10]. Additionally, increase in rural electrification has contributed to the rise in electricity consumption [11]. However, in the future the same factors would contribute to the growth in electricity consumption as Pakistan would aim to transit itself in the league of developed countries [12]. Efforts have been made to explore and exploit the indigenous energy resources. Despite the struggles, the imports of energy are about 30% of the total consumption [13]. In the imports, the major part (i.e., ~88%) is of oil (i.e., crude oil and petroleum products), in which, a major share is used for power generation [14]. Any oil price change in the global market extremely influences Pakistan's energy generation rendering existing circular debt issue even more seriously [15].

Pakistan's current installed electricity capacity is 25,000 MW and it is not sufficient to meet the existing electricity demand

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Nomenclature

A-CAES	Adiabatic compressed air energy storage
Capex	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CSP	Concentrating solar thermal power
FLH	Full load hours
GHG	Greenhouse gases
HVDC	High-voltage direct current
IEA	International Energy Agency
LCOC	Levelized cost of curtailment
LCOE	Levelized cost of electricity
LCOG	Levelized cost of gas
LCOS	Levelized cost of storage
LCOT	Levelized cost of transmission
OCGT	Open cycle gas turbine
Opex	Operational expenditure
PHS	Pumped hydro storage
PtG	Power-to-gas
RE	Renewable energy
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
WACC	Weighted average cost of capital

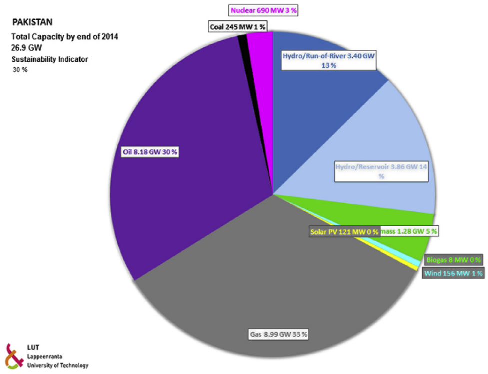


Fig. 1. Pakistan's total installed capacity breakdown till 2014 [4].

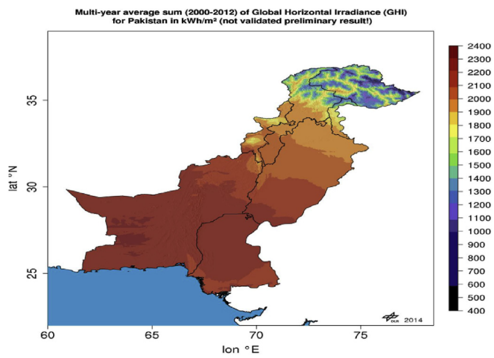


Fig. 2. Pakistan's annual global horizontal irradiation map [28].

resulting into extended load-shedding to the extent of virtual suspension of the social life. The estimated difference in supply-demand is about 5000 MW and projected to be 13,000 MW by 2020 [14]. According to assessments, the energy crisis cost the country 6 bUSD in 2008 [16] while causing losses upwards of 2% of GDP in 2009–2010 [11,17] and resulting into loss of 40,000 jobs annually. The recent findings of a World Bank survey reveal the effects of the electricity shortage on society and the economy in Pakistan and it was found that 66% of business activities are affected by load shedding meaning it has a more significant effect than terrorism [18,19]. Due to dearth in fossil fuel reserves, Pakistan is highly dependent on imports, which severely questions the energy security of the country. Additionally climate change is severely affecting the agricultural sector due to change in the monsoon cycle. Also, investing in fossil fuel power plants would lead to stranded assets [4,20] and high cost of electricity [21]. Investing in renewables could be the answer to the list of problems mentioned as Pakistan does not have to depend on its neighbours for fossil fuels and the cost of power produced from renewables is declining at a rapid pace all over the world.

Apparently, a large potential of power generation from renewable sources such as wind, solar, biomass, geothermal, and tidal is available in the country. Pakistan's solar resources are extremely good and have relatively low seasonal variation. An annual global horizontal irradiance map has been shown in Fig. 2. The economic constraints, poor energy planning, governance issues, underdeveloped technological sector and the capacity building have been recognized as major constraints in harnessing the renewable energy sources [18]. There are some ongoing projects like one of the solar project added a 100 MW of energy in the national grid in 2015 and is being upgraded to add 900 MW [19]. According to the Alternative Energy Development Board, 3 bUSD have been invested in renewable sources in the year 2016 which indicates the investment potential [22]. Numerous studies have demonstrated that Pakistan possesses a huge overall renewable energy potential [23–25]. The wind potential is mainly concentrated in the coastal areas of Sindh and Baluchistan with 2000–3000 full load hours (FLH) and 1000–1500 FLH, respectively. The total potential for wind energy in these areas is around 123 GW [23]. Pakistan is located in the Sun Belt region and therefore has 1500–3000 sun shine hours across the country [24]. The average yearly global horizontal insolation in the province of Baluchistan is 1930–2030 kWh/(m^2·a) [25] which can be observed from Fig. 2. Studies also reveal that growth rates of markets for wind and PV power are 4.7% higher in late adopters than the early adopters of the technologies due to global knowledge build-up [26].

With all the abundant potential available, it is the right policies and commitment of the government towards the renewables that would enable faster uptake of these technologies. There have been some policies of the Pakistani government for the faster uptake of renewables. The 2006 policy for renewable energy had main features of feed-in tariffs, reduced transmission and distribution costs, net metering and carbon credit transactions [27]. In addition competitive bidding for the renewable energy projects which is the normal all around the world has helped to reduce the price of the projects and create competition among the developers. Also, the State Bank of Pakistan offers loans to RE project developers [27]. A clear strategy and commitment from the government is needed to achieve a high share of renewables in the future.

Due to the novelty of the topic in Pakistan, there are no comprehensive studies among the technical literature which integrate all the aspects of a 100% RE system for Pakistan. The majority of the technical writings on the renewable energy sources mostly deal with the technological aspect of the subject.

Several reports [29–31] indicate that Pakistan is on the verge of disastrous water shortage and turning into a water scarce country. Pakistan's water demand is projected to reach $3.4 \cdot 10^{11}$ m^3 by 2025, while the supply expected to remain stagnate at $2.4 \cdot 10^{11}$ m^3 resulting in a demand supply gap of $1.0 \cdot 10^{11}$ m^3 [31]. According to WWF-Pakistan [32], with per capita water availability reducing down to 1090 m^3, Pakistan is approaching towards threshold level of water scarcity (1000 m^3). Low irrigation efficiency, low water use efficiency, population growth and inadequate water allocation are the key factors in present water scarce condition. The decline in the river inflows, increased variability and location changes of monsoon and shift in the temporal patterns of glacial melt is in line with the data on climate change, resulting in increased vulnerability of the agriculture sector [33,34]. Given this water crisis, policies that would improve irrigation, water use, allocation and distributive efficiencies need to be undertaken.

There have been some energy transition studies with high renewable energy shares (Table 1) for Pakistan. The brief analysis of the results is presented in Table 1.

Table 1
Future energy transition scenarios for Pakistan.

Study	Key findings
Jamal N. [14]	A model for hourly demand-supply balance of Pakistan's power system was developed. The electricity demand was projected 430.1 and 566 TWh in two different scenarios till 2050. Different supply cases were discussed varying the capacities of wind and PV. PV contributes 97–386 TWh, wind 116–132 TWh and biomass 39–111 TWh in different supply system scenarios. Contribution from hydro remains constant at 213 TWh in total electricity supply by 2050. The role of hydro as seasonal storage was also discussed. The discounted system cost was calculated using MESSAGE framework. In all supply cases, system discounted cost was in the range of 170–240 bUSD by 2012.
Jamal N. [35]	In the study, it was found that Pakistan's total electricity demand (587 TWh) is achievable by renewables by 2050. Wind, hydro, solar and biomass will contribute 107.9 TWh, 33.7 TWh, 47.3 TWh and 21.0 TWh respectively.
Perwez U. [36]	"The Long Range Energy Alternative Planning" (LEAP) software is employed to assess different scenarios in the study over the period of 20 years (2011–2030). Increasing the coal composition to 14.1% and that of renewable energy sources to nearly 46% was suggested by 2030. Remaining demand will be fulfilled by conventional energy sources.
Valasai D. G. [37]	Three different electricity generating scenarios were developed using TIMES modelling framework for the period 2013–2033 following BASE, REN50 and REN60 scenarios. Renewable energy share was increased to 50% in REN50 and 60% in REN60 scenarios. The study suggests REN50 and REN60 as more feasible and sustainable scenarios.

This study presents the Pakistan's transition towards a 100% renewable based energy system. Hourly resolved model was used to simulate 100% RE scenario in Pakistan from 2015 to 2050, covering demands of the power, desalination and non-energy industrial gas sectors. The optimization is done on the basis of assumed costs and technological status for every 5-years from 2015 to 2050 for all energy technologies involved.

2. Methodology

The LUT Energy System Transition model was used for the transition research of the Pakistan power system from 2015 to 2050 in 5-year time steps. This model optimizes linearly the energy system parameters under previously defined constraints and the assumption for future RE power generation and demand in the particular region. Bogdanov and Breyer [38] define the model in detail, explaining equations and constraints used in the modelling. The most important parameter, which differentiates the LUT model, is its hourly resolution for an entire year. An hourly resolution for an entire year guarantees an energy system which is much closer to reality and enables a more accurate description which includes the synergy between the different system components utilised. The hourly resolution is similar to EnergyPlan [39], however the LUT Energy System Transition model has an added advantage of modelling a transition pathway of an electricity system using an optimal dispatch of generation and storage technologies and transmission between the two regions of Pakistan. Also utilization of different types of storage technologies, which are often lacking in many of the transition models provides an edge over other modelling tools. The multi-node approach which is utilised in the model, enables a country or a region to be divided into different sub-regions and each sub-region can act as different node and the nodes can be interconnected to form a transmission network. The model is mainly compiled using Matlab. The optimisation is currently carried out in a third party solver, MOSEK ver. 8, however other solvers (Gurobi, CPLEX, etc.) can be used. The post processing of the simulation results is carried out using Matlab.

Fig. 3 gives the main input and output parameters of the model. To achieve a least cost energy system is the main target of system optimization. The cost related to the system are calculated as sum of the annual cost of all power generation capacities, energy generation and generation ramping of the different technologies.

Additionally, included in the energy system are the PV prosumers for residential, commercial and industrial sectors. The term prosumer is used to refer to energy consumers, producing their own power from solar PV systems. Minimizing cost of consumed electricity is the target function for prosumers. The cost related to self-consumed electricity is calculated as a sum of generation, annual cost and cost of electricity consumed from the grid. The prosumers can benefit from the excess electricity generated by feeding into the national grid at an assumed price of 0.02 €/kWh, however prosumers have to fulfil their own demand before selling.

The main constraint of the system optimization is given as Eq. (1).

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

It is defined for every hour of a year in a particular region, electricity generation from all the technologies ($E_{gen,t}$), imported

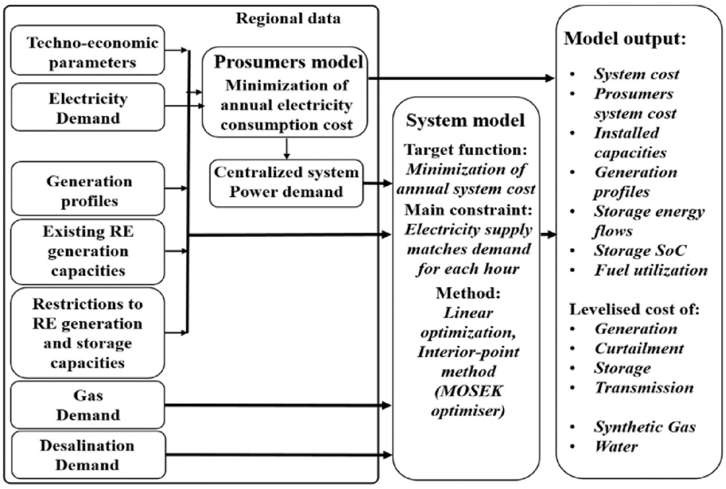


Fig. 3. The LUT Energy System Transition model from inputs to outputs [40].

electricity from the regions ($E_{imp,r}$) and electricity from storage discharge ($E_{stor,disch}$) should be equal to the total demand for an hour (E_{demand}), electricity exported to other regions ($E_{exp,r}$), electricity for charging storage technologies ($E_{stor,ch}$) and curtailed electricity (E_{curt}). The other abbreviations used in this equation are: hours (h), technology (t), all technologies used in modelling ($tech$), sub-region (r) and all sub-regions (reg).

The target function for the optimization is given in Eq. (2).

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

The abbreviations used here are: ($CAPEX_t$) - capital cost of each technology, (crf_t) – capital recovery factor for each technology, ($OPEXfix_t$) – fixed operational cost for each technology, ($OPEXvar_t$) - variable operational cost each technology, installed capacity in a region ($instCap_{t,r}$), electricity generation by each technology ($E_{gen,t,r}$), ramping cost of each technology ($rampCost_t$) and annual total power ramping values for each technology ($totRamp_{t,r}$). The target function was applied in time steps of 5-year from 2015 to 2050.

The other important constraints applied were:

- No more than 20% growth in RE installed capacities share compared to total power generation capacities could be achieved for each 5-year time step so as to avoid disruption to the power system.
- No new nuclear or fossil-based power plants could be installed after 2015. However, installation of gas turbines were allowed as they are a highly efficient technology that can accommodate RE-based synthetic natural gas or bio-methane into system [41].

The energy model with all the technologies utilized is provided in Fig. 4.

2.1. Technologies utilized in the transition

Different technologies are utilised for the energy system transition of Pakistan and are divided into four main categories:

- Technologies for electricity generation
- Technologies for electricity storage to provide flexibility to the system
- Transmission technologies for the generated electricity
- Bridging technologies such as Power-to-Gas (PtG) process and Seawater Reverse Osmosis (SWRO) desalination

3. Assumptions for the energy system analysis of Pakistan

3.1. Subdivision and grid structure for Pakistan

The subdivision of Pakistan into two regions was based on population distribution, consumption of electricity and the grid structure. Fig. 5 shows the two sub-regions of Pakistan and interconnection between these regions.

3.2. Scenarios

Two scenarios were studied for the energy system analysis of Pakistan:

- Power scenario, only electricity demand is covered and the energy systems of the regions are interconnected, so trading of electricity between the two regions is possible.
- Integrated scenario, power scenario with SWRO desalination and non-energetic industrial gas demand, where PtG technology is also used to cover the non-energetic industrial gas demand in addition to the storage option

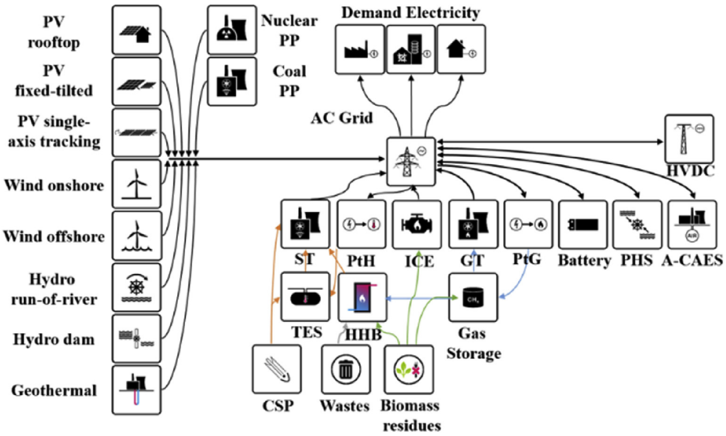


Fig. 4. The LUT Energy System Transition model [21], made up of major renewable energy sources (PV rooftop for prosumers, PV fixed-tilted, PV single-axis tracking, wind onshore and offshore, hydro, geothermal, biomass and waste-to-energy), various storage technologies (batteries, PHS, A-CAES, TES), transmission options (HVDC lines) and different demand sectors (electricity, desalination, non-energetic industrial gas).

Fig. 5. The two sub-regions in Pakistan and the grid connection.

3.3. Financial and technical assumptions

The economic and technical assumptions for the technologies utilised for the transition of Pakistan from 2015 to 2050 are tabulated in Table A.1. In Table A.1, individual references are given for each of the technologies utilised in the transition. The decrease in Capex and Opex from 2015 to 2050 are based on the current trends and international literature. For example: The PV rooftop (residential, commercial and industrial) assumptions are based on the data given in Ref. [42] for every 5-year interval. The rationale behind the financial assumptions of the important renewable technologies has been the steady cost decline around the world and the costs assumptions which are expected to fall further in the future. This is based on the number of established studies and international literature [43,44]. For example the cost of power produced from solar PV has gone down to 14.9 €/MWh [45], with many such low cost all around the world. It is assumed that, with the ongoing improvements in technology and production processes the cost of materials and installations will fall considerably from their current values till 2050. Also, in addition cost of batteries have decreased by 77% in the last 7 years [46,47]. The conditions for solar in Pakistan are one of the best in the world and with a surge in investor interest in the solar sector the cost of producing electricity from solar will go down [48].

The cost of onshore and offshore wind power plants, particularly the offshore wind plants are expected to decline sharply in the future [49]. The sharp decline in cost is possible due to the expected learning curves and technological advancements in construction and wind power systems will play a vital role [50].

The weighted average cost of capital (WACC) is set to 7% (in real terms) for all investments, except residential PV prosumers, for which a real WACC of 4% is applied, due to lower financial return requirements. The assumed WACC maybe be lower and do not reflect the financing situation however an increase in WACC does not alter the cost of energy system considerably [51]. The authors assume that a 7% real WACC is possible by the year 2050 in Pakistan. The electricity prices for 2015 for the three prosumer categories are assumed from Gerlach et al. [52] and future prices till 2050 were calculated according to the methodology described in Breyer and Gerlach [53]. The electricity prices for Pakistan are provided in the Supplementary Material (Table 1).

3.4. Potential for renewable technologies

The potential for biomass and waste for the two regions in Pakistan are taken from Ref. [54] and divided into: solid wastes, solid residues and biogas. The associated cost calculations for all the biomass categories described above were done according to data from International Energy Agency [55] and Intergovernmental Panel on Climate Change [56]. For solid fuels a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for waste incineration plants and this is reflected in the negative cost for solid waste.

The geothermal energy potential is calculated for the two regions according to the method described in Gulagi et al. [57].

The current installed capacities for solar PV, wind, hydro power and PHS are taken from Farfan and Breyer [4]. The upper limit of these renewable technologies is based on land use limitations and density of capacity [38]. The lower and upper limits of renewables and fossil fuels are given in the Supplementary Material (Tables 4 and 5, respectively).

3.5. Input profiles for solar and wind

The generation profiles for single-axis tracking and optimally tilted PV, solar CSP and wind energy were calculated according to Bogdanov and Breyer [38]. For hydro power, feed-in profiles for the two regions were calculated using the daily resolved water flow data for the year 2005 [58] as a normalized sum of precipitation in the regions.

3.6. Demand

The hourly load profile for electricity for each region is calculated as a fraction of the total demand in Pakistan based on synthetic load data weighted by the region's population. The electricity demand is taken from the National Transmission and Despatch Company Pakistan [8] and extrapolated till 2040 by a policy research working paper from World Bank [59] and till 2050 by South Asian Regional Initiative for Energy Integration [60]. The calculations related to seawater desalination demand and technical and financial assumptions for seawater reverse osmosis (SWRO) are given in Caldera et al. [61]. The electricity demand till 2050 is given in the Supplementary Material (Table 1). The data for non-energetic industrial gas demand is taken from IEA [62] and extrapolated till the year 2050 from the IEA assumptions of non-energetic industrial gas demand growth rate for India [63].

4. Results

4.1. Cost structure of an energy system from 2015 to 2050

The results related to the cost structure of an optimized energy system are presented in Tables 2 and 3 for the power and integrated scenario respectively. The results of these scenarios were evaluated with a set of parameters and formula described in Bogdanov and Breyer [38].

The levelized cost of electricity for both of the scenarios (Tables 2 and 3) is highest for the current setup of power generation technologies which is primarily composed of fossil fuels. The high fuel cost of the fossil fuels and the associated cost of emissions contribute to the increase in LCOE. The fuel costs for all the fossil fuel technologies and the emission cost assumed are shown in the Supplementary Material (Fig. 5 and Table 7 respectively).

The reduction of LCOE from 2015 which is a fossil fuel based system to 2050 which is a fully renewable system is 56–57% depending on the scenario. The cost of power produced will depend on solar PV and batteries as these two technologies contribute majorly to the LCOE.

At first a slight increase in LCOE is observed in both of the scenarios for the year 2025 and then it starts decreasing again from the year 2030 onwards. The current energy system is mainly based on fossil fuels contributing to high total primary LCOE due to high fuel costs and a smaller share of GHG emission costs (Figs. 6 and 7). In 2020, total primary LCOE decreases considerably in the scenario due to decrease in expensive fossil share in the electricity generation which is being replaced by renewables particularly solar PV. The slight increase observed for the year 2025 for both of the scenarios is due to new investments in the renewables sector and need to install storage capacities due to the intermittency created by the renewables. However, fossil gas is still utilized to overcome intermittency as it is a cheaper source for power generation. This creates an additional fuel cost and associated GHG emission costs as observed from Figs. 6 and 7. After 2025, a constant trend of decrease

Table 2
Financial results from 2015 to 2050 — power scenario for Pakistan.

	LCOE total [€/MWh]	LCOE primary [€/MWh]	LCOC [€/MWh]	LCOS [€/MWh]	LCOT [€/MWh]	Total annualized cost [b€]	Total capex [b€]	Capex needed in 5-years period [b€]
2015	106.6	105.5	0.5	0.0	0.5	12.0	25.9	–
2020	54.1	52.9	0.3	0.6	0.3	8.0	40.3	14.4
2025	56.6	51.3	0.5	3.3	1.5	10.9	69.3	29.0
2030	55.0	40.2	1.3	12.3	1.2	13.7	113.1	43.8
2035	52.7	34.6	1.6	15.6	0.9	17.3	150.3	37.2
2040	50.7	30.8	1.7	17.5	0.7	21.9	191.9	41.6
2045	48.4	25.2	1.6	20.8	0.7	25.0	225.0	33.2
2050	46.2	23.7	1.8	20.1	0.6	28.8	259.1	34.1

Table 3
Financial results from 2015 to 2050 — integrated scenario for Pakistan.

	LCOE [€/MWh]	LCOE primary [€/MWh]	LCOC [€/MWh]	LCOS [€/MWh]	LCOT [€/MWh]	Total annualized cost [b€]	Total capex [b€]	Capex needed in 5-years periods [b€]
2015	106.3	105.2	0.5	0.0	0.5	12.94	25.9	–
2020	54.2	53.6	0.3	0.0	0.3	10.76	53.4	27.5
2025	62.0	56.4	1.0	3.3	1.3	27.35	197.6	144.2
2030	61.3	42.5	1.9	15.9	1.0	46.28	475.8	278.2
2035	57.5	32.9	2.4	21.1	1.2	76.42	881.5	405.7
2040	52.5	26.5	1.8	23.2	0.9	90.27	1113.8	232.3
2045	49.0	22.0	1.7	24.6	0.7	109.04	1376.7	262.9
2050	46.8	20.9	1.8	23.5	0.6	122.20	1534.5	157.8

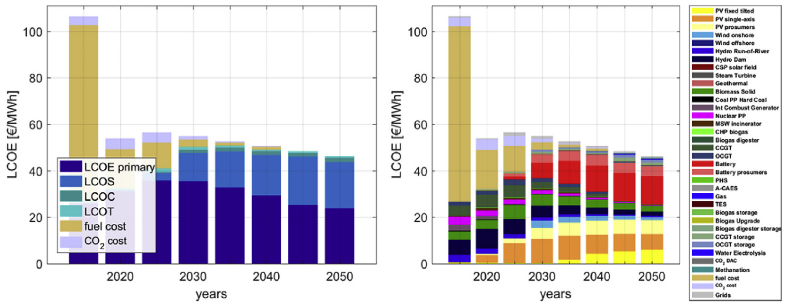


Fig. 6. Contribution of levelized cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost and carbon emission cost to total LCOE (left) and contribution of all technologies to LCOE (right) from 2015 to 2050 for the power scenario.

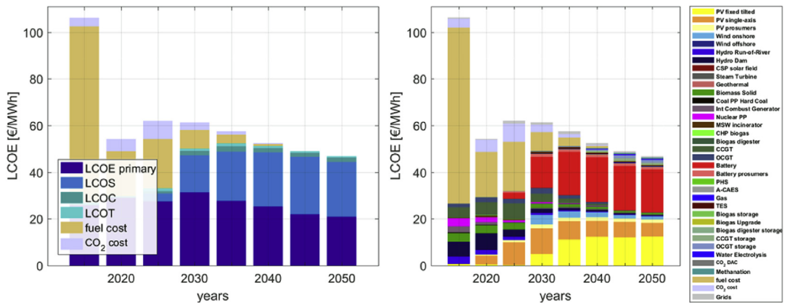


Fig. 7. Contribution of levelized cost of primary generation (LCOE primary), storage (LCOS), curtailment (LCOC), fuel cost and carbon emission cost to total LCOE (left) and contribution of all technologies to LCOE (right) from 2015 to 2050 for the integrated scenario.

in LCOE is observed till 2050, due to decrease in the share of fossil fuels, and also associated costs of GHG emissions and fuel costs.

Sector integration of desalination and non-energetic industrial gas demand does not provide the expected benefit in terms of reduction of LCOE in comparison to the power scenario. This is due to the huge demand created by the desalination sector. However, even a huge electricity demand for desalination does not increase the price of electricity considerably in comparison to the country-wide scenario for the year 2050.

4.2. Installed capacities of generation technologies in the energy transition

The installed capacities for a fully renewable energy system in 2050 are dominated by solar PV and batteries (Table 4) due to its low cost and the excellent solar resource conditions. The gradual increase in installed capacities for the energy transition period is shown in Fig. 8 and absolute numbers can be found in the Supplementary Material (Table 2). The total power plant capacity is dominated by fossil gas and oil for the year 2015. However, after 2015, renewables, particularly solar PV, start to dominate the installed capacities to overcome the current and future supply deficit created by phasing out of the fossil fuel power plants. The electricity generation is mainly based on PV technologies, complimented by wind, hydro and biomass in periods of low solar

Table 4
Key power plant capacities required to achieve a fully renewable energy system for Pakistan in 2050 for the two scenarios.

		Power	Integrated
PV prosumers	[GW]	87	87
PV single-axis tracking	[GW]	102	382
PV optimally tilted	[GW]	133	1047
Wind energy	[GW]	8	34
Geothermal power	[GW]	0	0
CSP	[GW]	0	0
Hydropower	[GW]	10	11
Biomass PP	[GW]	6	6
Biogas Digester	[GW]	1	1
Biogas Upgrade	[GW]	0	0
Battery self-consumption	[GW]	207	207
Battery system	[GW]	567	3430
Gas storage	[GW]	15051	87549
PHS	[GW]	0	0
TES storage	[GW]	9	346
PtG electrolyser input	[GW_{el}]	8	112
A-CAES storage	[GW]	0	0
CCGT PP	[GW]	7	27
OCGT PP	[GW]	15	59
Oil PP	[GW]	0	0
Nuclear PP	[GW]	0	0
Coal PP	[GW]	0	0

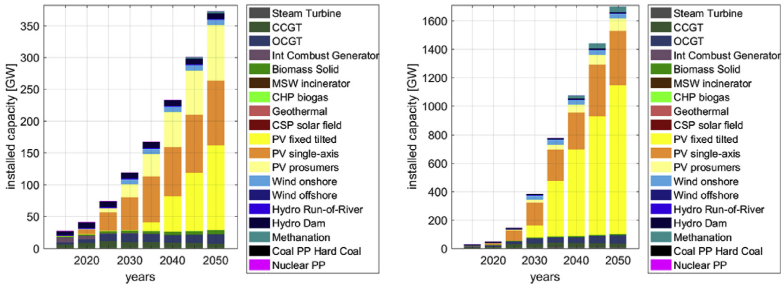


Fig. 8. Cumulative installed capacity for all generation technologies from 2015 to 2050 for the power (left) and integrated (right) scenarios.

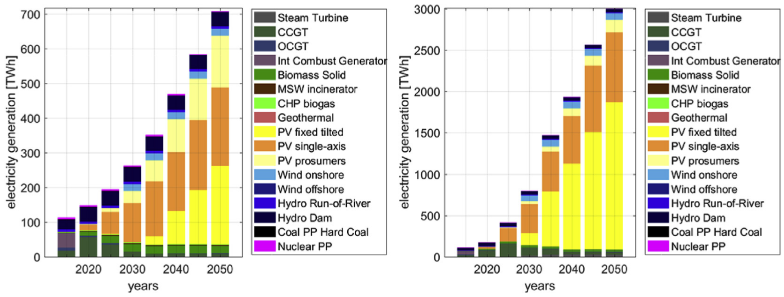


Fig. 9. Total annual electricity generation from all technologies from 2015 to 2050 for the power (left) and integrated (right) scenarios.

irradiation for both of the scenarios which can be seen from Fig. 9. Due to a low availability of wind in the areas of high population density, wind does not play a vital role as the cost of transmission is higher for importing wind from western Baluchistan to Karachi. In comparison, solar PV which is available all over the country and it can provide in combination with low cost batteries a least cost solution to satisfy the increasing electricity demand.

The higher installed capacities for the integrated scenario is due to additional demand created by non-energetic industrial gas and seawater desalination. The additional demand is satisfied mainly by installation of additional PV power plants. For the year 2050, 371% more solar PV and 370% of additional battery capacities are installed in the integrated scenario in comparison to power scenario. Solar PV plants develop quickly after 2020 and wind power develops after 2025 and remains almost constant till 2050. The renewables especially solar PV grow at a constant rate for all the years.

For the year 2050, PV optimally tilted contributes 63% and PV single-axis contributes 23% to the total RE generation capacity in the integrated scenario. In 2050, PV optimally tilted contributes to 227 TWh and 1785 TWh of electricity and PV single-axis contribute to 226 TWh and 845 TWh to the total electricity generation in the power and integrated scenarios, respectively. The PtG technology creates an additional demand of 15 TWh_{el} for the power and 194 TWh_{el} for the integrated scenario in the year 2050, which is observed in increased generation capacity. The full load hours for all the technologies in the power scenario can be found in the Supplementary Material (Table 3). As the share of renewables increases, curtailment increases due to the intermittency of the renewables (Supplementary Material Fig. 6). However, the curtailment remains less than 8% of the total electricity generated.

4.3. Desalination sector

Fig. 10 explains the growth of Pakistan's seawater reverse osmosis (SWRO) desalination sector from 2015 to 2050 and the red

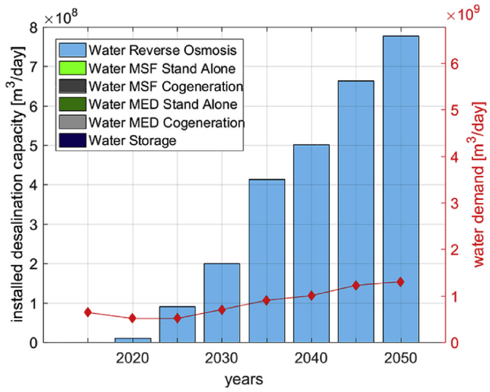


Fig. 10. Water desalination installed capacities to meet Pakistan's total water demand.

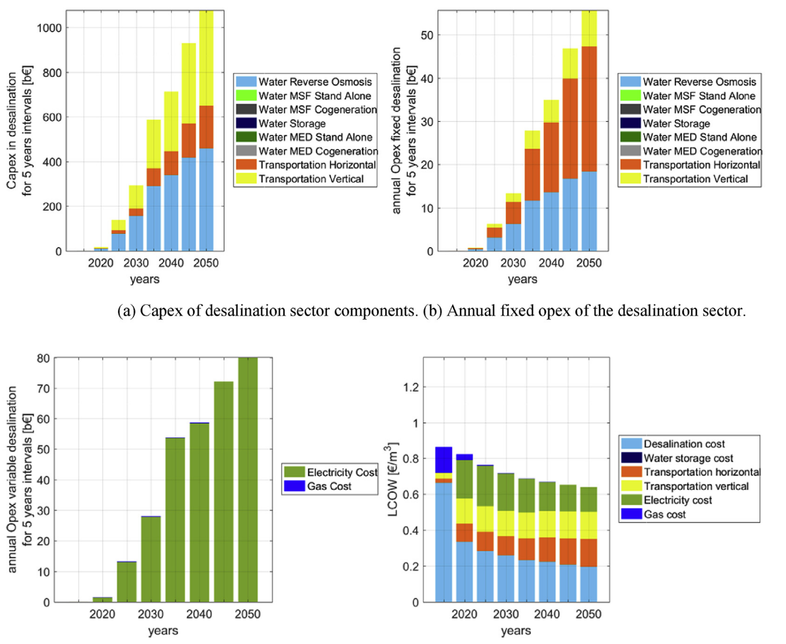
line shows water demand in m^3/day. The installed desalination capacity in 2050 is $7.8 \cdot 10^8$ m^3/day while the water requirement is $1.3 \cdot 10^9$ m^3/day. The difference between the total water demand and installed desalination capacity is met by the renewable water sources and non-renewable groundwater sources. Installed water desalination capacity is becoming noticeable after 2025. The statistics also indicate the existing desalination water demand [m^3/day] for Pakistan is extremely high [31,34].

Fig. 11(a) shows the capital expenditure of different components of the desalination sector in 5-year intervals. The share of water transportation (vertical and horizontal) is gradually increasing and is the biggest expenditure in 2050. The fixed operating cost increases as the installed desalination capacities increases in 2050 dominated by the expense on water transportation. The share of the transportation factor is going to increase to 67% in 2050 from 5% in 2020 in total annual operational expenditures. The annual variable operating cost explains the cost of gas and electricity consumption of the desalination plants. The increase in consumption of electricity is due to the installation of more desalination plants over the years to meet the country's increasing water demand. In Fig. 11(c) LCOW is decreasing continuously for the desalination from 2015 to 2050 especially in the initial years when the system will gradually get accustomed with new technology. The gradual decrease in desalination cost is attributed to the expected increase in the efficiency of desalination plants in the coming years.

4.4. The role of storage technologies in the energy transition

Comparing Figs. 8, 9, 12 and 13, it is observed that the role of storage technologies increase with the rising share of renewable energy in the system. As, there is no PHS storage available in Pakistan, batteries provide electricity on daily basis and gas storage is used as an option for long-term storage. By 2025, prosumer and system batteries come into effect due to the increasing influence of solar PV on the system. The batteries provide the system with the required flexibility and they emerge as a more cost effective option than utilising the fossil fuel power plants for electricity generation. The batteries provide 39% and 47% of electricity of the total electricity demand in the year 2050 for the power and integrated scenario, respectively. The increasing share of solar PV (Figs. 8 and 9) corresponds to the increasing share of batteries output (Figs. 12 and 13), as hybrid solar PV-battery systems evolve as the least cost combination to provide electricity till 2050. Batteries help electricity generated by solar PV to be used in the evening and night time.

The gas storage is utilised from the year 2030 when the share of renewables crosses 80%, however huge installed capacities of gas storage are observed in the year 2045 and 2050. The storage output of gas storage is very low in comparison to batteries as seen from Figs. 12 and 13. The gas storage provides around 3% of electricity of the total electricity demand in the year 2050 for the power and integrated scenario. Gas storage is required as a seasonal storage



(a) Capex of desalination sector components. (b) Annual fixed opex of the desalination sector.

(c) Annual variable opex of desalination sector components. (d) LCOW of all components of the desalination sector.

Fig. 11. (a) Capex of desalination sector components. (b) Annual fixed opex of the desalination sector. (c) Annual variable opex of desalination sector components. (d) LCOW of all components of the desalination sector.

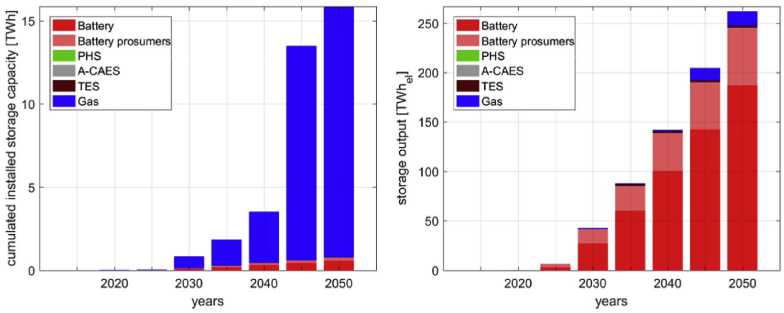


Fig. 12. Cumulative installed capacities of storage technologies (left) and storage output (right) required from 2015 to 2050 for the power scenario.

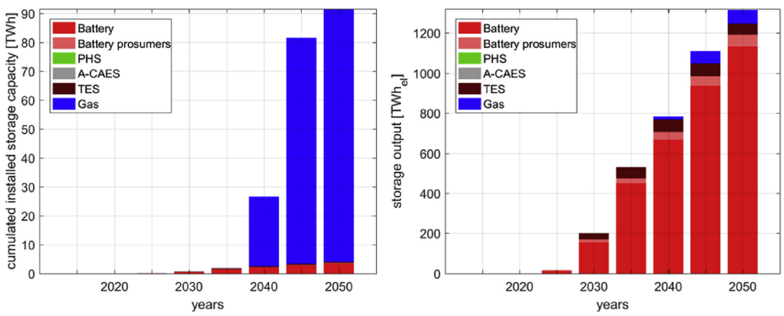


Fig. 13. Cumulative installed capacities of storage technologies (left) and storage output (right) required from 2015 to 2050 for the integrated scenario.

from 2040 and the reason for the huge installed capacities in 2045 and 2050.

4.5. Sub-regional analysis of an optimized fully renewable energy system

The installed capacities for a fully renewable energy system in 2050 for the two sub-regions: Pakistan North and South for the two scenarios is shown in Fig. 14. The installed solar PV capacities exceed 70% of the total RE installed capacities in each of the regions, despite FLH of wind exceeding full load of solar PV. It is observed that for the year 2050, solar PV is the cheapest option to power the electricity demand. However, in Pakistan South the available wind resources are utilized due to good wind conditions on the Southern coast which helps balancing the system in periods of low solar radiation. The diagram for electricity generation from the installed

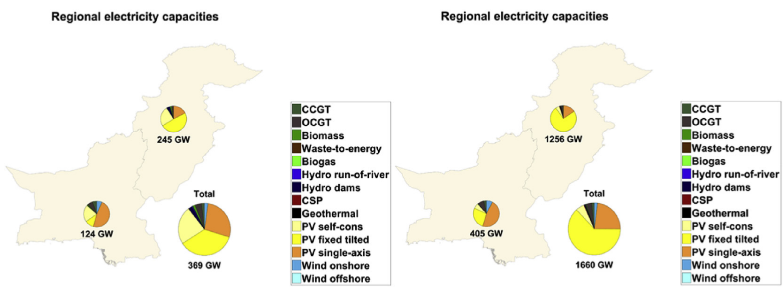


Fig. 14. Installed RE capacities for power (left) and integrated (right) scenarios for the two sub-regions of Pakistan for 2050.

renewable sources can be found in the Supplementary Material (Figs. 17 and 18).

The sub-region of Pakistan North is a region with high demand and a region with best RE resources which helps to balance out the sub-region of Pakistan South where the availability of RE resources is limited. From Fig. 15 it can be observed the demand (solid circle) and generation (line circle) with Pakistan North as a net exporter of electricity. The import and export of electricity and loss due to storage creates a difference observed between the demand and generation.

4.6. Annual CO_2 emissions in the transition period

Annual net zero CO_2 emissions are achieved for the year 2050 which is illustrated in Fig. 9 for the power and integrated scenario. In the integrated scenario, an increase in annual GHG emissions is observed for the year 2030 due to a high electricity demand by the additional desalination and gas sectors and solar PV and other renewables are not yet cost competitive. The additional demand is satisfied by increased electricity generation from gas power plants. However, the ratio of GHG emitted per MWh of electricity produced decreases in the transition period to ultimately zero in the year 2050 as observed from Fig. 16. As the renewables become cost competitive and its share increases in the energy system there is a substantial decrease in the GHG emissions. The power system of Pakistan is completely decarbonized by 2050.

5. Discussion

The main aim of this study was to show a least cost electricity transition pathway for Pakistan, which is compatible to the Paris Agreement [64]. This can be realised with the abundant renewable energy potential available in the country and with some political will and change in policies regarding renewables. This study describes a pathway, which avoids the risk of climate change, in addition to stranded assets caused by investing in fossil fuel technologies and the high cost of electricity generation from nuclear.

A 100% renewable based electricity system for Pakistan by 2050 is found to be least cost and most efficient electricity option. This study incorporates all aspects of a fully sustainable energy system including RE technologies and energy storage solutions. The LCOE are 46.2 €/MWh and 46.8 €/MWh for the year 2050 for the power and integrated scenario respectively. There is a considerable decrease in LCOE from 2015 to 2050 because of the transition from the fossil fuel to a RE-based electricity system.

By the year 2050, PV single-axis tracking and PV optimally tilted power generation dominates the energy transition towards a sustainable energy system by contributing 453 TWh and 2630 TWh in total electricity supply in the power scenario and integrated scenario respectively. In another study [35] contribution is 160 TWh only one-fourth of the energy supply and wind contribute an even higher proportion to total supply mix. The solar resource available in the country are excellent with a very low seasonal variation in most parts of the country except in Northern areas. The main load

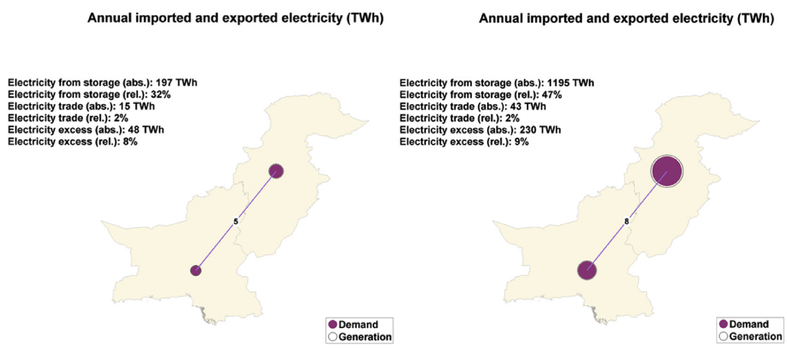


Fig. 15. The annual import and export of electricity between the two sub-regions for power (left) and integrated scenario (right) scenarios for year 2050.

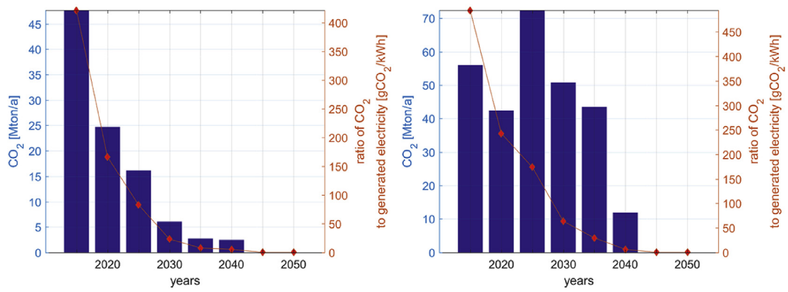


Fig. 16. Total annual GHG emissions and ratio of GHG emissions to electricity generation during the transition period for the power (left) and integrated (right) scenario.

centers of the country are located in very high solar insolation areas. Therefore, a photovoltaic based power generation system is ideal for this demand-supply scenario. Another study [14] proposed the hydro power share of 213 TWh and a maximum PV share of 386 TWh in the total energy supply mix. The hydro power would increase the vulnerability of the water sector in the country which is already in stress and facing problems like mismanagement and shortage. Solar PV and wind energy can also be used to reduce the risk in the hydropower system [65]. The discounted cost of the system is estimated to be 162 to 240 bUSD in two different supply cases by 2012. Perwez and Sohail [36] and Valasai et al. [37] report that an optimal mix of solar and wind energy will increase the energy sustainability in the country. These studies report a higher share of wind than PV in the total energy mix. But according to Muneer and Asif [66] wind energy is a less economical option as compared to solar energy. The average wind speed does not cross the economical threshold in most parts of the year except the four monsoon months. It was also found [35] that integration of wind resources also poses serious challenges to system stability. However, wind energy can be utilized by the energy system in periods of low solar irradiation as observed from this study. Of the total available wind energy potential of 123 GW [23], 6–28% is developed in the year 2050 depending on the scenarios. All the installed capacities of wind are situated in the Pakistan-South region which has the best wind sites. The contribution of PV prosumers to the total electricity generated is low due to the low cost of electricity from the grid. The PV prosumers contribute about 5% to the total electricity generation in 2050. Wind power generation starts after 2025 and remains constant throughout the period contributing about 8 GW. Storage technologies play a vital role in the 100% renewables based sustainable electric system providing flexibility and maintaining a balance between demand and supply. By 2050, gas storage dominates the total installed capacities of storage technologies as PtG is used as seasonal storage after 2040 when the installed renewable capacity exceeds 80%. But the results show that batteries come into effect after 2030. In terms of storage output, battery storage represents the largest share of 69% and 88% of the total storage output in power and integrated scenarios respectively. The installation of PV results into the system reliance on battery storage especially to use the power in evening and night generated in daytime. The role of the batteries in the PV based power system intensifies due to the favorable economics of system batteries. As fossil-based electricity generation is replaced by RE generation, the relevance of storage increases significantly from 2030, particularly, due to the dominance of solar PV in the energy system.

The results obtained are comparable to Gulagi et al. [57] for the SAARC region, which apply an overnight approach for the year 2030 with slightly different cost assumptions for some of the technologies. However, the LCOE obtained for both the studies is lower than the cost of the current system. The energy system of Pakistan will be powered by solar PV and supported by batteries according to both the study results. However in this research we do not consider HVDC connections with neighbouring countries, i.e India and Afghanistan which would further impact on the cost of electricity by reducing the need to store electricity and reducing the curtailment. According to Gulagi et al. [57], HVDC grid connection between neighbouring countries has a positive impact on reducing cost of electricity, which is attributed to less installed capacities of generation technologies.

The integrated scenario is dominated by an extremely high desalination water demand. Water desalination can make a real difference solving the looming water crises in the country. By 2050, seawater desalination demand is expected to rise to $2.8 \cdot 10^{11}$ m^3/a which is in line with other studies [29,30]. The only installed desalination plants are seawater reverse osmosis (SWRO) plants because they are more efficient and cost competitive as compared to other desalination technologies and would be powered by RE energy [67]. SWRO plants and renewables could be combined to solve water and power problems [68]. The estimated installed desalination capacity to meet the demand in 2050 is $7.8 \cdot 10^8$ m^3 and energy required for the SWRO plants is 1721 TWh. The levelized cost of water (LCOW), which includes water production, electricity, water transportation and water storage costs is found to be 0.84 €/m^3 and 0.62 €/m^3 in 2015 and 2050 respectively. The capex to meet Pakistan's water demand by 2050 is estimated to 1100 b€. The total annual opex fixed and variable are found in study to be 60 b€ and 80 b€ by 2050. Thus, our work presents that the water crisis in Pakistan could be averted in a productive and sustainable manner. Water desalination is a new technology to the country but recently some SWRO plants had started working [69] in Gwadar City, which is on the southwestern coast of Pakistan.

Despite being a low emitter of GHG emissions (0.8% of the total global GHG emission), Pakistan is highly vulnerable to climate change owing to its geographic location, elevation as well as demographics. Moreover, the electricity sector in Pakistan is currently facing formidable challenges of an insufficient installed capacity, a suboptimal infrastructure, circular debt and revenue shortage. The government's plan to depend on imports of fossil fuels and invest in fossil fuels would backfire in terms of highly unstable fossil fuel prices in the global market, energy security, huge part of GDP going to the imports, climate change and electricity shortages. On the other hand, renewables can reduce the reliance on depleting natural gas resources and substantial oil imports and would result into an independent and secure energy supply. In order to continue the pace of economic growth, electrification of villages and to cope with the rising gap between energy supply and demand, renewable energy is the optimal option for Pakistan [70].

The renewable energy sector in Pakistan is in its nascent stage. However, successful installation of 400 MW of solar PV and 256 MW of wind power plants has encouraged further investment in this sector [71]. There are 35 projects with 1.1 GW capacity, which are under development within the framework of the policies of Alternative Energy Development Board (AEDB) [48]. The government expects to add 1556 MW of solar PV to the national grid in 2018 [72]. The formation of AEDB has given a boost to the renewable energy sector with increased investments in recent years with AEDB issuing letters of intent (LOI) to 24 projects with a combined capacity of 556.8 MW [72]. With a clear government strategy, support, commitment towards renewable, stability and long-term targets will attract huge investments. There has been a good beginning, however Pakistan has a long way to go.

Huge potential for solar PV and wind is available in the country to materialise the required solar and wind capacity by 2050. However, some barriers do exits for the renewable energy sector like the policy barriers, institutional barriers, financial barriers and information and social barriers [73]. With the formation of AEDB, some of the policy and regulatory barriers have been addressed in the last years. It can be seen from the installation of renewables and number of projects in the pipeline. However, some of the other barriers need to be addressed to fully realise the renewable energy potential of the country and join the league of countries leading in renewable energy.

The cost of electricity obtained from this study can be compared with the LCOE of the alternative technologies of ‘clean’ energy which has been a discussion in Pakistan and around the world such as a new nuclear power plant (assumed for 2023 in the UK and Czech Republic) and gas CCS (assumed for 2019 in the UK) with LCOE of 112 €/MWh, and 126 €/MWh for coal CCS (assumed for 2019 in the UK) [74]. According to a report [75], CCS technology will not be available until 2030, and lot of questions are being asked whether it will be profitable at all [76]. The results obtained for a 100% RE-based system would help achieve the goal of net zero GHG emissions set at COP 21 [77].

6. Conclusion

Pakistan needs to concentrate on renewables for achieving a secure, cost effective and reliable electricity supply system. A 100% RE based power system is possible for Pakistan by 2050. Exploitation of indigenous energy resources should be the real policy option to enhance energy security of the country through lessening reliance on energy imports. RE technologies can produce enough electricity to cover the total demand by 2050 on significantly lower cost compared to the current non-renewable based electricity system. The LCOE obtained for a fully sustainable energy system for Pakistan by 2050 is 46.2 €/MWh for the power and 46.8 €/MWh for integrated scenario, while covering the huge water desalination demand of country. Solar PV and batteries dominate the installed RE technologies due to their low cost and excellent solar resource conditions in Pakistan. Solar PV provides almost 86% of the total electricity demand and is complimented by wind and biogas in low solar irradiation areas. The huge share of solar PV in electricity generation corresponds to the huge share of batteries as storage technology as the least cost and sustainable option. The gas storage becomes prominent in 2030 when the RE share crosses 80%, however the storage output of gas storage is very low in comparison to batteries. Water desalination demands appear as the dominating factor in the integrated scenario and this problem needs to be solved on urgent basis. This study shows that RE can not only solve the energy but also the looming water crises in the country. However, there exits several barriers for renewable energy development in the country which needs to be addressed. Adequate planning among the stakeholders and implementation by the government is needed to harness the available renewable resources to overcome the present energy crisis. Examples of innovative financing programs can be taken from elsewhere in the world and adopted to local conditions. Local manufacturing of renewable energy systems could reduce investment costs and create employment for the local people. The key to renewable energy future is the political will.

In the present research, the methodology is focusing on two regions of Pakistan and demand sectors of power, desalination and non-industrial gas demand. Future research will be based on higher spatial resolution which will better describe the regional variation and in detail analysis of the transmission lines plus addition of all energy sectors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2018.01.027.

Appendix A

Table A.1
Technical and financial assumptions of all energy system components used in the energy transition from 2015 to 2050 for Pakistan. Assumptions are taken from Pleβmann et al. [78] and European Commission [79] and further references are individually mentioned.

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
PV rooftop - residential	Capex	€/kWp	1360	1169	966	826	725	650	589	537	[42]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kWp	1360	907	737	623	542	484	437	397	[42]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kWp	1360	682	548	459	397	353	318	289	[42]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally fixed-tilted	Capex	€/kWp	1000	580	466	390	337	300	270	246	[42]
	Opex fix	€/(kWp a)	15	13,2	11,8	10,6	9,6	8,8	8,0	7,4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kWp	1150	638	513	429	371	330	297	271	[42] [80]
	Opex fix	€/(kWp a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW	1250	1150	1060	1000	965	940	915	900	[81]
	Opex fix	€/(kW a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/m^2	270	240	220	200	180	170	150	140	[82] [83]
	Opex fix	%	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	
	Opex var	–	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal power	Capex	€/kW	5250	4970	4720	4470	4245	4020	3815	3610	[79] [84]
	Opex fix	€/(kW a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	

Table A.1 (*continued*)

Name of component			2015	2020	2025	2030	2035	2040	2045	2050	Reference
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW	800	685	500	380	340	310	280	260	[85] [86]
	Opex fix	€/(kW a)	32	27	20	15	14	12	11	10	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW	492	421	310	234	208	190	172	160	[85] [86]
	Opex fix	€/(kW a)	10	8	6	5	4	4	3	3	
	Opex var	€/(kWh)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	
CO_2 direct air capture	Capex	€/kW	749	641	470	356	314	286	258	240	
	Opex fix	€/(kW a)	29.9	25.6	18.8	14.2	12.6	11.4	10.3	9.6	
	Opex var	€/(kWh)	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
	Lifetime	years	30	30	30	30	30	30	30	30	
CCGT	Capex	€/(kW_{el})	775	775	775	775	775	775	775	775	[87]
	Opex fix	€/(kW_{el} a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	58	58	58	58	59	60	60	60	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT	Capex	€/(kW_{el})	475	475	475	475	475	475	475	475	[87]
	Opex fix	€/(kW_{el} a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	43	43	43	43	43	43	43	43	
	Lifetime	years	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	Capex	€/(kW_{el})	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW_{el} a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	42	42	42	43	44	44	45	45	
	Lifetime	years	25	25	25	25	30	30	30	30	
Steam turbine (coal-fired PP)	Capex	€/(kW_{el})	1500	1500	1500	1500	1500	1500	1500	1500	[87] [88]
	Opex fix	€/(kW_{el} a)	20	20	20	20	20	20	20	20	
	Opex var		0	0	0	0	0	0	0	0	
	Efficiency	%	45	45	45	45	46	46	47	47	
	Lifetime	years	40	40	40	40	40	40	40	40	
Biomass CHP	Capex	€/kW	3400	2900	2700	2500	2300	2200	2100	2000	
	Opex fix	€/(kW a)	238	203	189	175	161	154	147	140	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	36	37	40	43	45	47	47.5	48	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas CHP	Capex	€/kW	503	429	400	370	340	326	311	296	
	Opex fix	€/(kW a)	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	35	36	39	42	44	46	46	47	
	Lifetime	years	30	30	30	30	30	30	30	30	
Waste incinerator	Capex	€/kW	5940	5630	5440	5240	5030	4870	4690	4540	
	Opex fix	€/(kW a)	267.3	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
	Opex var	€/(kWh)	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Efficiency	%	27	31	32.5	34	35.5	37	29.5	42	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW	771	731	706	680	653	632	609	589	
	Opex fix	€/(kW a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW	340	290	270	250	230	220	210	200	[89]
	Opex fix	€/(kW a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	98	98	98	98	98	98	98	98	
	Lifetime	years	20	20	20	20	25	25	25	25	
Battery, Li-ion	Capex	€/(kWh_{el})	600	300	200	150	120	100	85	75	[90]
	Opex fix	€/(kWh_{el} a)	24	12	8	6	4.8	4	3.4	3	
	Opex var	€/($kWh_{throughput}$)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
Adiabatic compressed air energy storage (A-CAES)	Capex	€/kWh	35.0	35.0	33.0	31.1	30.4	29.8	28.0	26.3	
	Opex fix	€/(kWh a)	0.46	0.46	0.43	0.40	0.40	0.39	0.36	0.34	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh_{th}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Table A.2
Energy to power ratio and self-discharge rates of the storage technologies

Technology	Energy/Power Ratio (hrs)	Self-Discharge	References
Battery	6	0	[78]
PHS	8	0	[78] [79]
A-CAES	100	0.001	[79]
TES	8	0.002	[78]
Gas storage	80*24	0	[78]

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Publication II

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Renewable energy in Pakistan: Paving the way towards a fully renewables-based energy system across the power, heat, transport and desalination sectors by 2050

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ORIGINAL RESEARCH PAPER

Renewable energy in Pakistan: Paving the way towards a fully renewables-based energy system across the power, heat, transport and desalination sectors by 2050

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Abstract

Pakistan is currently undertaking a substantial expansion of electricity generation capacity to provide electricity for all its end-users and to satisfy a fast-growing economy. Adoption of low-cost, abundant and clean renewable energy will not only fulfil its growing electricity, heat, transportation and desalinated water demand but also help achieve the goals set under the Paris Agreement. A technology-rich energy system model applied in hourly resolution has been used for investigating the transition in 5-year periods until 2050. This study demonstrates that a 100% renewable energy system across the power, heat, transport and desalination sectors is not only technically feasible but also economically viable. Solar photovoltaics emerges as a key technology to generate electricity and contribute a share of 92% to the total primary energy demand across all sectors by 2050. The levelised cost of energy for a 100% renewable energy system is calculated as 56.1 €/MWh in 2050, lower than 70 €/MWh for the current fossil fuel-based system. A key feature of Pakistan's future energy system is the huge increase in demand across all energy sectors, particularly for desalinated water, which is almost 19% of the final energy demand. This share of energy for desalination is among the highest in the world. Direct and indirect electrification across all demand sectors increases the efficiency of the future energy system. Moreover, GHG emissions from all the sectors will drop to zero by 2050 in a fully sustainable energy scenario.

KEYWORDS
energy storage technology, renewable energy policy, renewable energy sources, solar power, wastewater treatment

1 | INTRODUCTION

The Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC) [1] declared that warming in the South Asian region is expected to be higher than the global average. Demographic trends, socioeconomic factors, dependence on agriculture and slow adaptation of measures make this region more vulnerable to the detrimental effects of the climate change. Moreover, climate change is likely to impact the rate of glacier melt and change in weather patterns, in particular, the strength and timing of the monsoon, with consequences also for the energy systems [2].

The energy sector is the largest producer of GHG emissions in Pakistan [3]. In recent years, power generation capacity has been increased significantly, from all energy sources, as Pakistan tries to meet its growing electricity demand. Nevertheless, high dependence on imported fossil fuels, construction of controversial hydropower projects and increased dependence on outdated coal technology is not only reducing energy security [4], but also creating a significant headwind to economic growth.

1.1 | Overview of Pakistan's power generation mix

Figure 1 shows the current power generation mix of Pakistan for the year 2018. According to the National Electric Power

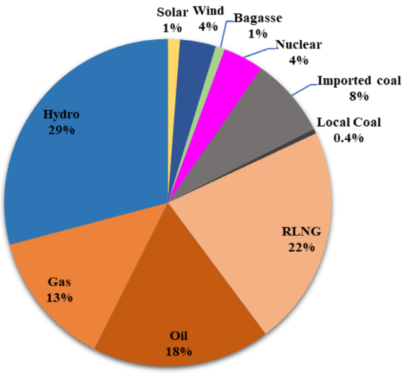

FIGURE 1 Power generation technologies mix in Pakistan in 2018 [6]
Abbreviations: RLNG – Re-gasified liquified natural gas.

Regulatory Authority (NEPRA) of Pakistan [5], reduction in imports of fossil fuels, increase in renewable energy-based power generation, diversification of fuel sources, and improvements in fuel supply are the principal objectives of Pakistan's future power generation policy. In Pakistan, renewable electricity generation, especially from wind turbines and solar photovoltaics (PV), is cheaper than thermal and hydropower plants and the costs are expected to reduce significantly in future [6]. An increased emphasis on renewable electricity would thus reduce the cost of electricity generation, reduce GHG emissions, and can address the cost-tariff deficit, without the need for a tariff increase that would impact end-users and businesses. The average levelised cost of electricity (LCOE) from solar PV is around 70 USD/MWh (59.43 €/MWh)[1], according to an announcement made by NEPRA in January 2019. For projects with a generation capacity of 50–100 MW, the tariff falls to around 50 USD/MWh (42.45 €/MWh) [7].

Pakistan has a huge potential for the generation of electricity from renewable sources, especially, solar PV. Decreasing global cost trends and advantageous solar insolation conditions, due to its location in the Sun Belt region, provide the right motivation for exploring the potential role of solar resources in the future energy supply of Pakistan [8, 9]. Several studies have estimated the potential of different renewable resources like solar, wind, hydropower and bioenergy [10–13]. In this study, the aggregated renewable energy potential of the country is examined to ascertain to what extent renewable energy may be able to satisfy energy demand from the power, transport, heat and desalination sectors during the transition period from 2015 to 2050.

1.2 | Overview of the power sector

Over the last few decades, Pakistan's energy sector is trapped into a series of crises. To overcome its energy deficiencies, Pakistan has implemented numerous energy projects adding a cumulative power generation capacity of 12.2 GW during last few years. Although the increased capacity has helped to ease immediate shortfalls, an inefficient transmission and distribution system has hindered delivery of energy services to end-users. In 2018–2019, total installed capacity reached 34.2 GW, a year-on-year growth of 2.5%, while electricity generation increased from 82 to 84.7 TWh during the same period. Gas accounts for 13% share of the total power generation, approximately 14.3 TWh. Pakistan's depleting domestic gas resources can increase dependence on imported liquefied natural gas (LNG) and coal. Currently, the residential sector represents the biggest demand segment with a 48% share, followed by industrial demand with a 25% share in 2018 [14]. According to the Asian Development Bank, energy consumption grew at an annual rate of 7.7% from 2013 to 2018 and is expected to increase at a compound annual growth rate (CAGR) of 5.8% by 2030 [3].

As a key part of the power sector, planning for renewable energy (RE) systems should integrate different planning approaches, technologies and strategies to accommodate highest possible shares of variable renewables, in particular solar PV and wind [15–17]. Additionally, as the current power grid is underdeveloped, for example, over half of Pakistan's rural population lack access to electricity [18], decentralised renewable energy (DRE) can offer a cost-efficient option for electrification of rural areas and can help achieve universal access to electricity by 2030. Greater local energy autonomy [19] with more local grid-based solutions [20] or household solutions [21] can thus translate into positive environmental and societal benefits in terms of shrinking GHG emissions, improved efficiency and greater financial opportunities [22]. Indeed, decentralised options such as small grids [21] and stand-alone solar systems [20] for distant households are becoming increasingly common and these options are often more affordable and can play an important role in adoption of RE technologies.

As generating investment in RE is a challenge in struggling economies, Pakistan needs to advance the role of domestic PV prosumers [23] as the active participation of residents and a push at the basic level can assist de-fossilisation of the economy. Unfortunately, the current power system structure in Pakistan is unlikely to attract PV prosumers on a significant scale, and a fundamental challenge is development of a regulatory framework that actively supports the move towards a desirable energy system [24]. The current share of renewable energy sources in the country's energy system stands at a meagre 4% [6].

1.3 | CPEC implication and integration of renewable technologies

Pakistan is increasing its electricity generation capacity by developing coal power plants as a part of the CPEC (China–Pakistan Economic corridor). These CPEC projects will add considerably to Pakistan's debt burden and pose further threat to an already deteriorating environment [24]. Moreover, mining and burning of coal for power production is water-intensive and the coal power plants, which have a technical lifetime of about 40 years [25], could aggravate Pakistan's existing water scarcity [26, 27]. It should be noted, that these coal power plants will be located near densely populated areas such as Karachi to provide electricity for residential, commercial and industrial purposes, coinciding with regions which are already under water stress. When CPEC power plants were planned in 2015, cost of solar PV and wind generated electricity was higher than that of electricity from coal-fired power plants in Pakistan. In the meantime, however, renewable based electricity generation costs, especially for solar PV, have fallen and RE is now cheaper than other electricity generation options in Pakistan [5]. As a signatory of the Paris Agreement [28], Pakistan is also committed to increase the share of electricity generation from renewables. According to the RE policy released in 2019 [29], Pakistan is planning to increase the share of new RE technologies to 25% and 30% by 2025 and 2030, respectively. Moreover, a target has been set to increase the share of hydropower to 30% during the same period, which would increase the overall share of renewable electricity to 60% of the total electricity mix. Pakistan is also facilitating the production of solar PV panels and wind turbines by removing taxes to support the manufacturing of RE technologies [30]. The new Alternative and Renewable Energy (ARE) policy introduced in 2019 [29] includes projects in both the public and private sectors and public-private collaboration for electricity generation. The technologies covered under this policy are solar, wind, geothermal, biomass, as well as other supportive technologies like biogas, syngas, waste-to-energy, energy storage systems, ocean energy, and various hybrid RE approaches.

1.4 | Domestic and industrial heating sector

Literature and data availability on the heating sector, is very limited. The main energy source to fulfil the heating demand in rural and low-income households is firewood, supplemented by crop residues and animal dung [31]. Estimates show that biomass provided 27% of the total energy supply in 2015 and the biomass used was predominantly firewood (50%) and crop residues (34%) [31]. Pakistan's per capita fuelwood consumption was 0.205 m^3 in 2015 [32]. As used in Pakistan, combustion of raw wood is an inefficient, harmful and unhealthy source of energy, affecting particularly the health of women and children [33]. Pollutants and gases released by indoor biomass combustion have been linked to various diseases like chronic respiratory disorders and lung cancer [33].The industrial sector in Pakistan accounts for 20% of the total GDP [34] and it is the second largest energy consuming sector, utilising 38% of total energy consumed. Industrial sector energy demand is expected to continue growing in the future [34]. Currently, natural gas is the main source of energy used in industrial heating processes. Historically, coal demand was limited to cement and brick industries, although use of coal for power generation has been gradually increasing in recent years [35] and imports have increased substantially due to the commissioning of new coal-based power plants at Sahiwal and Port Qasim [36]. Other significant users of coal are the cement industry and the brick kiln industry. The cement industry is of considerable economic importance since cement is the tenth most exported item. In 2012, about 58% of total coal was consumed by the cement industry, while 41% was utilised in the brick kiln industry.

1.5 | Transport sector and current policies

The transport sector contributed almost 13% to the national GDP in 2016–2017, more than 62% of which was contributed by road transportation alone [37]. Historically, road transportation has been accorded particular significance with the government investing substantial resources in building roads, motorways and highways. As a result, the road network grew by 6.2% annually from 1991 to 2016 [37]. Road freight is the predominant mode, accounting for over 90% of the total tonne kilometers (t-km) transported [37]. Pakistan's railways used to be the leading transport mode with 73% of freight share in the 1970s but rail use has declined sharply and stood at only 4% in 2011 [38]. During the last decade, road passenger transportation increased at a rate of 3.4% annually, while the increase in rail passenger transportation was around 1% annually [37]. According to the CAA (Civil Aviation Authority), the number of domestic and international air travellers grew by 3% to 17.9 million in 2017–18 compared to the previous year. The International Transport Association (IATA) has predicted that Pakistan's domestic air travel will grow at a rate of 9.5% annually, two times faster than the world's average over the next two decades [39]. Pakistan approved an ambitious National Electric Vehicles Policy (NEVP) in 2019 [40], which aims to achieve an electric vehicles (EV) share of 30% of all passenger vehicles and heavy-duty truck sales by 2030, and 90% by 2040. Additionally, the government will lower the unit rate of electricity for charging station operators to encourage private investment in charging infrastructure. The government will also install at least one DC fast-charging station every 10 km^2 in all major cities and every 15–30 km on all motorways.

1.6 | Water situation and water policies

Higher temperatures and extreme, unpredictable, weather conditions because of climate change are projected to affect availability and distribution of river flows and groundwater. Small changes in weather conditions could significantly impact Pakistan's water resources due to semi-arid conditions [41]. Pakistan's annual per capita water availability of 1017 m^3 is close to the scarcity threshold of 1000 m^3 [42]. Various techniques including preservation, desalination, recycling, and management could be implemented to address water scarcity. Over 91% of total fresh water is consumed for irrigation but agricultural production per hectare is lower than of neighbouring countries. Therefore, innovative commercial solutions will not only improve cultivation but can also lower water consumption [43]. A 100% renewable energy system can reduce water consumption by 95% by eliminating water intensive conventional energy generation technologies [26]. Renewable energy based seawater reverse osmosis technology could be potentially cost effective option to supply water for the irrigation sector in Pakistan [43].

Pakistan's new water policy addresses the looming water shortage, which is posing a significant threat to water and food security [44]. Water policy aims at building large dams to increase water storage capacity and to raise electricity production from hydropower to 30% of the total electricity generation by 2030. Building large controversial dams can burden depleting water resources and the economy, especially in developing countries. Globally, eight out of ten large dams suffer from schedule and budget overruns [45]. The single largest factor contributing to cost overruns is the time needed for construction [46, 47]. The Neelum–Jehlum hydropower project in Pakistan is suffering from cost overruns and is the most expensive hydropower plant project in history of the country [48].

1.7 | Literature review

The research field of 100% renewable energy modelling is gaining attention from researchers and policy makers. In recent years, literature on energy modelling has provided valuable insights into different aspects of the future energy transition which is reflected by the fact that a growing number of regions, states and countries are pledging to add higher shares of renewable energy. A large number of studies argue that 100% renewable energy systems are technically feasible [49, 50], but few studies disagree [51, 52]. A growing number of energy modelling studies are performing hourly modelling while integrating the renewable energy technologies. Brown et al. [49] have developed and discussed criteria to address the feasibility of 100% renewable energy systems. Although several studies [6, 9, 53–55] considering high shares of RE in Pakistan's energy system show renewables-based energy systems to be the most cost effective and optimal solution, studies on 100% renewable energy scenarios are still scarce [9, 55, 56]. Table 1 provides an overview of the studies with high or 100% share of renewable energy technologies in Pakistan. To the authors' knowledge, this work is the first of its kind to extensively model the transition of the power, heat, transport and desalination sectors towards a 100% RE-based system.

Two recent international agreements have accelerated the transition to low carbon energy systems. A total of 189 countries have adopted the Paris Agreement, which aims to substantially decrease greenhouse gas emissions [28]. Additionally, UN (United Nations) General Assembly adopted Sustainable Development Goals (SDGs) in 2015 to lay out a plan for eliminating poverty, establishing equity, peace, and protecting the environment. Accelerated deployment of renewable energy technologies on a large scale can help bring affordable, sustainable and modern clean energy to 1.1 billion people who lack access to electricity and realising sustainable development goals (SDGs), which aims for a better and sustainable future for all. Renewable energy deployment is at the core of implementation of SDG 7 and SDG 13 which focuses on affordable and clean energy for all and climate action, respectively. This research also addresses the water crisis, which can help in achieving access to clean water and sanitation (SDG 6). Increasing the access to clean energy and water are most important for increasing productivity and sustainable economic growth, thus contributing in alleviation of poverty and reducing inequalities (SDG 1, SDG 10) [59].

1.8 | Scope, novelty and contribution

The main aim of this study is to model the transition of the Pakistan's energy system towards a fully sustainable, self-sufficient, cost-efficient and zero GHG emission energy system, thus achieving the target of the Paris Agreement and SDGs. This research contributes to the discussion on the feasibility of 100% renewable energy systems and provides a detailed pathway for the energy system transition. Available literature is very limited on South Asia that investigates energy transition pathways towards 100% renewable energy for all energy sectors in an hourly resolution. For Pakistan no such study is available. This analysis covers all sectors (power, heat, transport and desalination) which has not been simulated before in hourly resolution for 100% RE for Pakistan. This study also stresses the importance of seawater desalination and highlights the looming water crisis in Pakistan. The energy demand due to desalination is expected to reach very high levels in the future for Pakistan, which has not yet been considered and studied in energy transition studies. The main outcome is an analysis of the technical feasibility and economic viability of a 100% RE system in Pakistan.

The structure of the paper is as follows: Section 2 introduces the methods and data used in the study. Section 3 presents the main results of the modelling of a fully sustainable energy system for Pakistan. Section 4 discusses the results in depth and limitations and future directions are mentioned in Section 5. The conclusions of the study are drawn in Section 6.

2 | METHODS AND DATA

The LUT Energy System Transition Model [60–62] was applied to examine a transition pathway for the Pakistan's energy system. The model optimises the energy system within the applied constraints in a 5-year time steps between 2015–2050. For every 5-year step, the model linearly optimises and applies a cost-optimal solution in full hourly resolution over the whole year.

2.1 | Basic operation of the model

For this study, the model was used to optimise all significant aspects of an energy system across the power, heat, transport

TABLE 1 Selected studies on the energy system of Pakistan examining the share of renewable energy

Study	Key findings
Nicolas and Buckley [6]	The IEEFA (Institute for Energy Economics and Financial Analysis) model was used for an electricity generation mix in Pakistan of 30% renewable sources by 2029–30. This study roughly splits the electricity generation mix in ratio 30:30:30:10 between new renewables, hydropower, fossil and nuclear sources respectively, where solar and wind energy contribute 23.6 TWh (10.7%) and 32.7 TWh (14.9%), respectively. Total electricity generation considered in this study is 178 TWh by 2030 with 1% energy efficiency gain per annum.
Sadiqa et al. [9]	A 100% renewable electricity system was developed. An hourly resolved model was used and optimisation was carried out in 5 years steps from 2015 to 2050. PV dominated the installed technologies with more than 90% in the analysed scenarios. The desalination sector emerged as an important sector with clean water demand of $2.8 \cdot 10^{11}$ m^3/a by 2050. The LCOE declines from about 100 €/MWh to about 46 €/MWh during the transition period (2015–2050). Gas storage dominates storage capacities from 2040 to 2050 while battery storage is prominent in terms of storage output.
Jamal [55]	A model for Pakistan's power sector based on 100% RE was developed. Two different scenarios of electricity demand were considered with a demand of 430 and 566 TWh by 2050. Different supply side scenarios were discussed with varying capacities of solar and wind. The contribution of hydropower remained constant throughout the transition period (2012–50). Solar and wind energy contributes 97–386 TWh and 116–132 TWh, respectively. A simulation framework was developed for energy supply balance analysis of the system. The MESSAGE energy model was used to find the optimal economic combination of the renewable resources. In all cases, the system discounted cost was in range of 170 to 240 bUSD.
Mirjat et al. [53]	The Low Emissions Analysis Platform (LEAP) model was used for demand projection and to develop four supply side scenarios with different power technologies. A renewable scenario was also discussed with 50% share of renewable resources mainly, solar but complimented by wind and hydropower. The EEC (Energy Efficiency and Conservation) scenario was estimated with the lowest net present value (NVP) compared to all other scenarios at all discounted rates considered in the study (4%, 6%, 8%, and 10%). Projected electricity demand was about 1700 TWh in 2050 and a compound annual growth rate of 8.35% was considered during the transition period 2015–2050.
Gulagi et al. [56]	The LUT Energy System Model was used to model a 100% RE system for the SAARC (South Asian Association for Regional Corporation) region for four different scenarios. For Pakistan, the installed capacities for RE generation for a region-wide, area-wide and integrated scenario are 147 GW, 58 GW and 229 GW respectively. Installed capacities in the integrated scenario also covers desalination and industrial gas demand, while the storage capacities for the region-wide, area-wide and integrated scenario are 34 GW, 8 GW and 30 GW respectively. Battery storage dominates the storage capacities.
Jacobson et al. [57, 58]	Solutions to global warming, air pollution and energy insecurity are evaluated by modelling a renewable energy based system mainly utilising wind, water and solar (WWS) energy, efficiency and storage. The modelling was done for 24 regions which are used to obtain insights for 143 countries and Pakistan is grouped to Central Asia. Low, mean and high levelised cost are derived for the Central Asian region reaching 6.5, 8.8, and 11.6 USDcents/kWh respectively in 2050. Levelised cost of electricity and ratios of WWS to BAU (Business as usual) scenarios were calculated.

and desalination sectors for a least-cost energy system. The target function of the optimisation is minimisation of the total annualised cost of the system calculated as sum of the annualised capital and operational expenditures, including ramping costs, for all the considered technologies in the modelling as given in Equation (1). The main aim of this study is to show a best policy scenario adopting local and indigenous renewable energy resources to achieve a fully sustainable energy system by 2050. Following important constraints were considered during modelling:

- New fossil-fuel and nuclear power plants were not allowed to be installed in the system after 2015.
- Installation of excessive RE capacities is restricted in the simulated scenario, so that no more than 20% of the total installed capacity share can be changed in any 5-year time step to avoid disruption of the power system.

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

Abbreviations: sub-regions (*r, reg*), generation, storage and transmission technologies (*t, tech*), capital expenditures for technology t ($CAPEX_t$), capital recovery factor for technology t (crf_t), fixed operational expenditures for technology t ($OPEXfix_t$), variable operational expenditures technology t ($OPEXvar_t$), installed capacity in the region r of technology t ($instCap_{t,r}$), annual generation by technology t in region r ($E_{gen,t,r}$), cost of ramping of technology t ($rampCost_t$) and sum of power ramping values during the year for the technology t in the region r ($totRamp_{t,r}$).

The prosumers of the power and heat system are realised in an independent sub-model with a slightly different target function. The target function for the prosumers is given in Equation (2). The prosumer system is optimised for each of the sub-regions independently, even if these sub-regions are interconnected. The target function includes annual costs of the prosumer power generation and storage, individual heating equipment, the cost of electricity required from the distribution grid and the cost of fuels required for boilers. Income of electricity feed-in to the distribution grid is deducted from the total annual cost.

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

Abbreviations: generations and storage technologies *(t, tech)*, capital expenditures for technology t ($CAPEX_t$), capital recovery factor for technology t (crf_t), fixed operational expenditures for technology t ($OPEXfix_t$), variable operational expenditures for technology t ($OPEXvar_t$), installed capacity of technology t ($instCap_t$), annual generation of technology t ($E_{gen,t}$), retail price of electricity *(elCost)*, feed-in price of electricity *(elFeedin)*, annual amount of electricity required from the grid (E_{grid}), annual amount of electricity fed-in to the grid (E_{curt}).

The main energy balance constraint for the power sector is matching of the power generation and demand for every hour of the applied year as shown in Equation (3). For every hour of the year the total generation within a sub-region and electricity import must cover the local electricity demand.

$$\forall \mathrm{h} \in [1, 8760] \quad \sum_{t}^{tech} E_{gen,t} + \sum_{r}^{reg} E_{imp,r} + \sum_{t}^{stor} E_{stor,disch} = E_{demand} + \sum_{r}^{reg} E_{exp,r} + \sum_{t}^{stor} E_{stor,ch} + E_{curt} + E_{other} \quad (3)$$

Abbreviations: hours (*h*), technology (*t*), all modelled power generation technologies (*tech*), sub-region (*r*), all sub-regions (*reg*), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies (*stor*), electricity from discharging storage ($E_{stor,disch}$), electricity demand (E_{demand}), electricity exported (E_{exp}), electricity for charging storage ($E_{stor,ch}$), electricity consumed by other sectors (heat, transport, industry) (E_{other}), curtailed excess energy (E_{curt}).

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

$$\forall \mathrm{h} \in [1, 8760] \quad \sum_{t}^{techHH} E_{gen,t} \geq E_{demandHH} \quad (4)$$

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

For other sectors except the power sector a general energy balance constraint is given in Equation (6)

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

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

A description of the model can be found in Bogdanov et al. [60] and Ram et al. [63] for the power sector only and for the power, heat, transportation and desalination sectors in Bogdanov et al. [62]. The specific sector coupling of integrated power and heat sectors is described in detail in Bogdanov et al. [61]. The LUT Energy System Transition model has been rated highest among investigated long-term energy system transition models by Prina et al. [64].

The general flow diagram of the LUT Energy System Transition Model is shown in Figure 2. A principle sectoral overview on the energy system presenting the relevant technologies is provided in Figure 3. The various electricity generation technologies examined are given on the left of Figure 3 from renewables such as rooftop PV [23], optimally fixed tilted PV, single-axis tracking PV [65], onshore wind, hydropower, geothermal, biomass, waste-to-energy to fossil fuels including combined

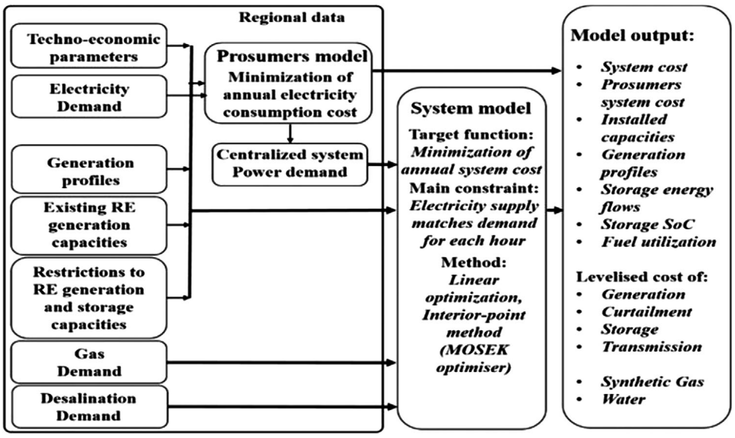

FIGURE 2 Diagram of the LUT Energy System Transition model's diagram showing inputs and outputs [60]

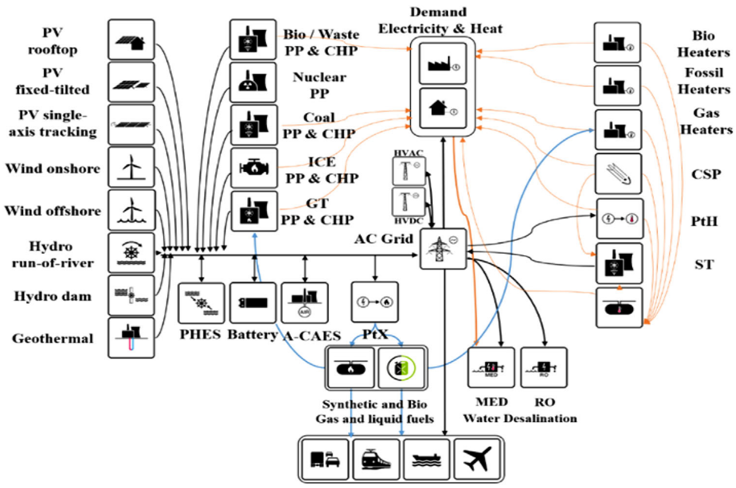

FIGURE 3 The LUT Energy System Transition model for the coupled sectors power and heat [60], transport [63], and desalination [48]. The diagram is based on [62]

heat and power (CHP) plants. The heat generation technologies are given on the right of Figure 3, while the heat and electricity storage technologies such as batteries, pumped hydro energy storage, adiabatic compressed air energy storage (A-CAES) [66], gas storage and thermal energy storage (TES) enable constant supply of heat and electricity. In the modelling, long-distance marine and aviation transportation are powered by synthetic fuels produced via Power-to-X processes.

The desalination technologies of Reverse Osmosis (RO) and Multiple Effect Distillation (MED) help provide clean water during the transition. The supply of generated electricity within each of the regions was assumed by the existing Alternating Current (AC) power lines. A step-by-step approach and various components of the modelling are described below:

2.2 | Data collection

As a first step, the subdivision of Pakistan as shown in Figure 4, was based on population, electricity consumption and grid structure. The hourly load profile of electricity for the two regions of Pakistan was generated from synthetic load data

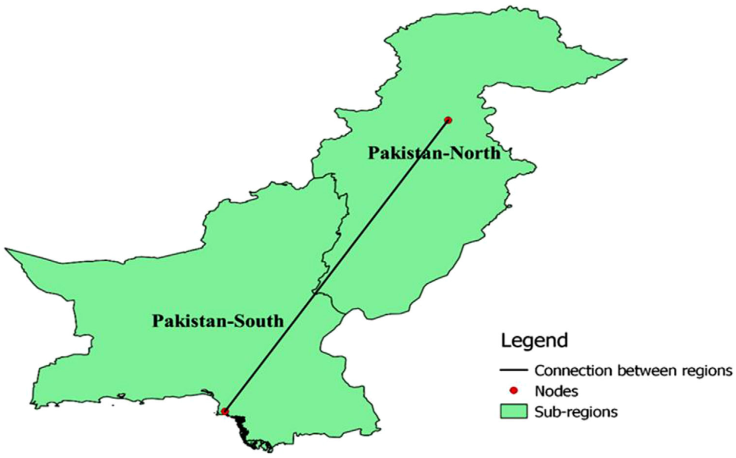

FIGURE 4 Division of Pakistan into sub-regions and connections between the regions [9]

subjected to the area's population according to Toktarova et al. [67]. The electricity demand for 2015 was obtained from the National Transmission and Despatch Company (NTDC) of Pakistan [68] and extrapolated till 2040 using growth rate of 6.1% from World Bank [69] and South Asian Regional Initiative for Energy Integration projections until 2050 using growth rate of 4% [70]. The power demand was categorised into residential, commercial and industrial sectors while the heat demand was divided into space heating, residential hot water heating, biomass for cooking and industrial process heat. The heat can be produced with technologies such as combined heat and power (CHP) plants, solar collectors, electrical heaters, and heat pumps and direct use of fuels in industrial furnaces. The heat levels are assumed within the temperature ranges: up to 100 °C (low temperature), 100–1000 °C (medium temperature) and above 1000 °C (high temperatures). Heat at a higher temperature level can also be used unidirectionally at a lower level. The CHP, heat plants and heat pumps are only allowed on the low temperature level, and fuels have to be used for higher temperatures. The demand, methods and techno-economic assumptions for seawater reverse osmosis (SWRO) are given in Caldera and Breyer [48]. The data for solar irradiation and wind speed are obtained from NASA databases and reprocessed by the German Aerospace Centre. The temporal resolution of solar irradiation and wind speed is hourly and the spatial resolution of the data is $0.45^0 \times 0.45^0$. Resource datasets used are for the year 2005. Further details on data collection and potential of renewable resources in general can be found in [71], and the input profiles for wind and solar can be found in [9]. For the transport sector, demand was obtained according to the method described in [72] for the road, rail, marine, and aviation transport modes. Each mode of transportation was further categorised into passenger and freight transport. The road mode was segmented into passenger light-duty vehicles (LDV), 2-wheelers/3-wheelers, bus, and freight medium-duty vehicles (MDV) and heavy-duty vehicles (HDV). The demand was projected in passenger-kilometres (p-km) for passenger transportation and in tonne-kilometres (t-km) for freight transportation. The calculated demand was then converted into final transport energy demand based on mode and type of vehicle technology [72]. Flexibility offered by Vehicle-to-grid and smart charging is not within the scope of this study, but its possible impact on the energy system is discussed by Child et al. [73].

2.3 | Financial and technical assumption

Details of financial and technical assumptions are given in Table S8, Supporting Information for the transition period 2015–2050. Important renewable energy technologies experienced cost reductions and further cost decrease is projected due to scaling and learning effects. The cost of the energy system was calculated as a total of the annualised capital expenditures applied over the lifetimes of the technologies and weighted average cost of capital (WACC), operational expenditures, including ramping costs, fuel expenses and the cost of GHG emissions for all technologies. The WACC was assumed to be 7% real and uniform across the two regions of Pakistan and through the transition years. For coal power generation higher WACC of 10% was assumed, to represent the higher risk of stranded investments. For the residential prosumers and individual heating, the WACC was set to 4%. Electricity prices for three different prosumer categories were calculated from [74] for 2015 and cost development until 2050 was projected according to the methods described in [75]. Costs for power, heat, transport and desalination are provided in Tables S25–S28, Supporting Information and Figures S28–S38, Supporting Information).

2.4 | Model setup and simulation

To prepare the data for modelling, the potentials of different available RE resources across the country were calculated. Real weather data was used for the assessment of the energy potential, and solar PV, wind energy and hydropower potentials were derived based on [65, 71, 76]. Pakistan's wind and solar resource maps are provided in the Figures S39 and S40, Supporting Information. Biomass and waste resources were categorised into solid residues and solid wastes. The potential estimation was based on Bunzel et al. [77]. The geothermal energy potential was calculated by Gulagi et al. [56] based on methods described in [78]. The different technologies integrated into the model can be categorised as:

- Power generation technologies: renewable (RE), fossil and nuclear energy technologies;
- Heat generation technologies: Renewable and fossil technologies;
- Energy storage technologies: electricity and heat storage technologies;
- Transport technologies;
- Fuel conversion technologies;
- Fuel storage technologies;
- Desalination and water storage;
- Power transmission technologies.

In the initial stage, a cost-effective share of PV prosumers is determined, then the subsequent entire energy system modelling is carried out. PV prosumers comprise of self-generation and consumption of residential, commercial and industrial end-users. PV prosumers can install their own rooftop PV systems with or without Li-ion batteries. PV prosumers are allowed to withdraw electricity from the grid to fulfil the demand and can feed in electricity to the grid in hours of surplus [23]. In the second step, energy system optimisation is carried out in 5-year steps for the period 2015–2050.

- Power and heat sector: For every 5-year step, a cost optimal energy system structure and operation mode is defined by the model for the given set of constraints. The optimisation target is to minimise the total system cost. The system costs are calculated as the sum of annualised capital and operational expenditures including ramping and GHG emissions cost for all technologies.
- Transport sector: Different modes in the transport sector undergo a massive electrification. Renewable energy based synthetic fuels meet the demand for different transport modes that cannot be directly electrified. Demand data for transportation and fuel shares are specified in [72].
- Desalination sector: Desalination has been treated as a separate sector because for the case of Pakistan the energy demand for desalination is comparable to other major energy sectors. Desalination demand in Pakistan is mainly driven by the agricultural sector, as more than 70% of the water is used in this sector. The agriculture sector is typically separated from other sectors, therefore, we separated it to trace the specifics of desalination demand more clearly. The LUT model identifies the lowest cost configuration for a 100% renewable energy based hybrid power plants and optimises for the lowest desalinated water production cost. More details on methods, assumptions and data can be found in Caldera et al. [43].

3 | RESULTS

The following section of the paper presents how a fully renewable energy system for Pakistan could look like by 2050 and how to transition to this status for an assumed Best Policy Scenario. The study covers the techno-economic details of the country's power, heat, transport and desalination sectors. Reduction in GHG emissions across all the sectors is discussed.

3.1 | Primary energy demand trends in the energy system

Figure 5a shows the total primary energy demand from 2015 to 2050 for the main primary energy sources. From the figure, it can be seen clearly that electricity plays an important part in the transition. Direct and indirect electrification of the sectors is observed towards 2050. Electricity can be obtained directly from renewable technologies so that electrifying the system could make it more efficient and cost effective. Currently, Pakistan's energy system depends primarily on fossil fuels and unsustainable forms of biomass. Figure 5a shows the transition of the fossil fuel-based energy system towards a completely sustainable energy system. Based on this scenario, electricity will fulfil almost 98% of the overall primary energy demand of Pakistan in all its sectors by 2050. Fossil fuels will be eliminated from the energy mix while, sustainable bioenergy has a minor role in the entire energy system. Figure 5b presents primary energy demand by sector during the transition period. The heat sector dominates current energy demand owing to inefficient raw biomass consumption. The heat sector demand will remain almost the same with a slight variation throughout the transition period.

Although the population is growing by about 1.1% annually till 2050, shifting to more efficient technologies like heat pumps and direct electrification of the heating system will translate into less increase in the total energy demand. Even though the transport sector has the biggest share of energy demand in 2050, the desalination sector is also important. Pakistan is extremely water stressed, thus it is ranked the third most water stressed country in the world, and it is still an agricultural economy with very high dependence on water resources [79]. The desalination sector will play an important role in the total energy demand in 2050. As the population increases and standards of living rise, the transport sector will expand and will have the largest share in the country's energy system by 2050. Pakistan will be one of the most populous countries in the world with a projected

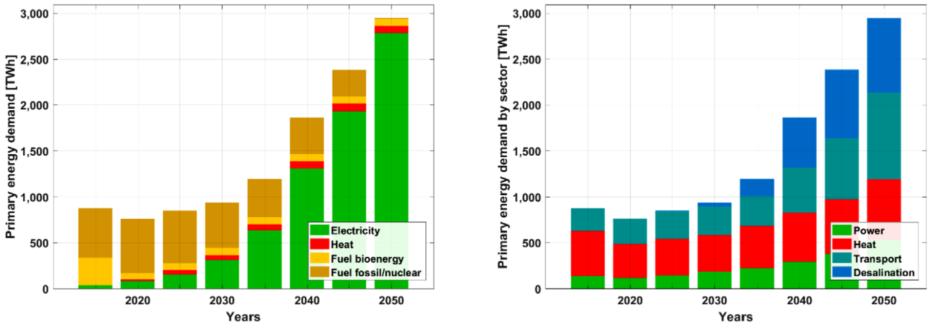

FIGURE 5 Primary energy demand by (a) main energy types and by (b) different sectors

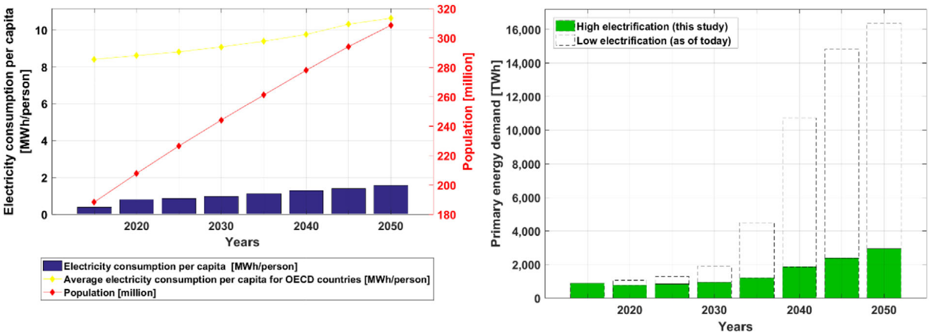

FIGURE 6 (a) Electricity consumption per capita and population across the transition period 2015–2050, and (b) primary energy demand with high electrification and low electrification energy systems

population of 308 million by 2050 (Figure 6a) [80], leading to an increase in energy demand, driven by population growth

Figure 6a shows per capita energy consumption, population and average electricity consumption in the power sector from 2015 to 2050. With projected economic development and population growth, per capita energy consumption increases over the transition period to around 1.8 MWh/person in 2050. Increased efficiency of the renewable energy system can lead to a considerable change in primary energy consumption. This phenomenon is illustrated more clearly in Figure 6b, which shows the difference in primary energy demand for massive electrification using a renewable energy-based system and low electrification as assumed in the applied Best Policy Scenario versus present efficiency and technology standards. Energy demand in a fully renewable energy-based system is considerably lower at about 3000 TWh. With current fossil fuel based technologies and energy system structure, to satisfy the final energy demand from all the sectors in 2050, the TPED would need to reach unrealistic level of 16 PWh, which is strongly driven by low-efficiency desalination, but also low-efficient combustion in vehicles, for heating and thermal power plants.

3.2 | Energy generation and storage capacities for the entire energy system

Figure 7a shows the installed capacities of all power generation technologies across the transition period from 2015–2050 and Figure 7b shows electricity production during the same period. Solar PV demonstrates high installed capacity due to its decreasing costs and the excellent solar irradiation in most parts of the country. The gradual increase in installations of renewable energy technologies can be seen in Figure 7 and more comprehensive numbers are given in Tables S11–S13, Supporting Information and Figures S26 and S27, Supporting Information. In 2015, fossil fuel technologies dominate the installed power plant capacity. From 2020 onwards, renewables, especially solar PV, are installed to overcome the demand-supply gap and to compensate for the phasing out of fossil fuel technologies. Solar PV completely dominates the installed capacity in 2050. Electricity generation follows the same pattern and is built primarily on solar PV, while wind energy, hydropower and bioenergy complement in smaller quantities. The limited availability of good wind resources and being located far from populated areas

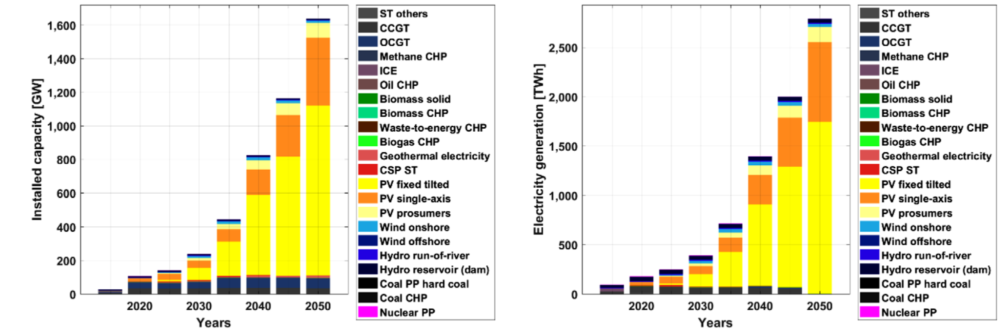

FIGURE 7 Pakistan's (a) installed capacity and (b) electricity generation in the transition period 2015–2050

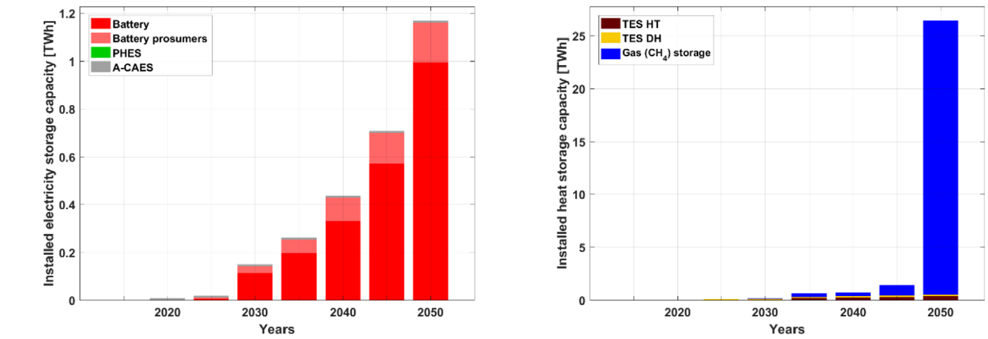

FIGURE 8 Installed storage capacity for (a) electricity and (b) heat and gas for the transition period until 2050

result in a limited contribution of wind for electricity generation. Abundant availability of solar PV across the country, the cost efficiency of solar PV and the availability of low-cost batteries bring these technologies into a prime position to meet increasing future energy demand. By 2050, the contribution of utility-scale PV is about 66% and 12% for optimally fixed tilted and single-axis tracking systems, while PV prosumers contribute about 15% to the total electricity generation. The increase in renewable generation triggers also curtailment as a consequence of the variable nature of solar, but also wind and partly hydro, resources, as shown in Figures S16–S18, Supporting Information.

As the share of RE technologies increases during the transition period, the role of storage technologies also increases to overcome mismatch between the variable supply and mainly inelastic demand. Prosumer and utility-scale batteries are installed in the system by 2025 due to the growing share of solar PV. The storage solution with batteries is more cost effective than utilising imported fossil fuels and provides essential system flexibility. Batteries of prosumers and utility-scale systems provide 99% of total electricity storage demand by 2050. The growing share of solar PV (Figure 7) translates into a rising share of output from batteries (Figure 8), since the PV-battery combination emerges as the least cost option to deliver electricity till 2050. Batteries facilitate the use of daytime generated solar PV electricity during the evening and night-time. Gas storage emerges as a part of overall system by 2030, when the electricity generation share of renewables crosses 80%. However very large gas storage capacities of about 26 TWh to balance seasonal effects can be observed first in 2050 (Figure 8b). The output from the gas storage is significantly lower in comparison to that of the batteries as shown in Figure 9. Both, high temperature (HT) and district heating (DH) thermal energy storage (TES) have a significant share in heat storage output by 2050, reaching a total of 121.3 TWh_{th} while gas storage requires the largest capacity in the system with 155.6 TWh_{th}.

3.3 | Cost of the future energy system

The levelised cost of electricity (LCOE) as shown in Tables S25–S28, Supporting Information is maximum for the current energy generation setup consisting primarily of fossil fuels

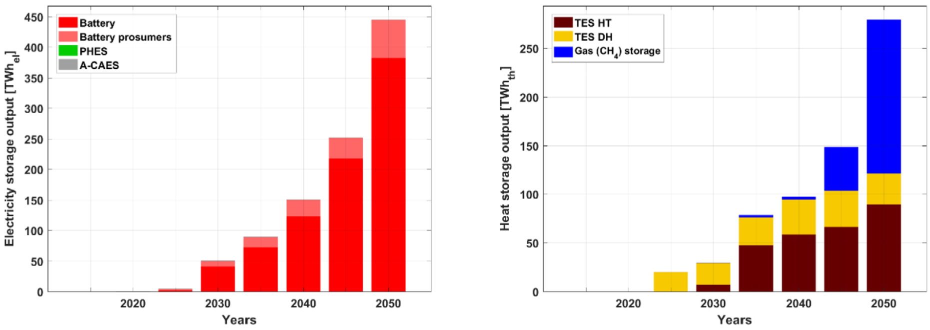

FIGURE 9 Storage output of (a) electricity and (b) heat and gas for the transition period until 2050

TABLE 2 Cost of the different components of the renewable energy-based system for Pakistan from 2015 to 2050. Abbreviations: LCOE - Levelised cost of electricity, LCOC - Levelised cost of curtailment, LCOS - Levelised cost of storage, LCOT - Levelised cost of transmission, LCOH - Levelised cost of heat, LCOW - Levelised cost of water

	LCOE primary [€/MWh]	LCOC [€/MWh]	LCOS [€/MWh]	LCOT [€/MWh]	LCOEsystem [€/MWh]	LCOH [€/MWh]	LCOW [€/m^3]	Levelised cost of energy [€/MWh]	Total annualised cost [b€]	Total capex [b€]
2015	113.5	1.5	0.0	2.8	117.8	67.6	2.7	70.1	52.8	238.4
2020	72.0	0.0	0.5	1.5	74.0	69.8	1.1	64.4	57.9	204.6
2025	70.8	0.2	1.1	2.2	74.9	67.3	0.1	68.0	65.8	171.4
2030	58.5	0.8	6.7	2.4	69.6	67.8	1.0	68.3	76.3	215.9
2035	47.0	1.0	6.2	1.3	56.6	66.2	0.8	64.6	91.1	224.7
2040	42.5	1.1	8.0	0.9	53.2	60.9	0.8	59.3	118.8	266.1
2045	32.9	1.3	15.6	0.8	50.5	59.9	0.8	56.7	140.1	320.8
2050	22.0	1.2	28.6	0.7	50.8	64.2	0.7	56.1	161.6	4230

and is on a fully loaded cost basis greater than 100 €/MWh. The high fuel cost of imported fossil fuels is responsible for the high LCOE. Fuel and GHG emission costs are shown in Table S10, Supporting Information. The results related to the cost structure of an optimised energy system are presented in Table 2. The LCOE reduction from a fossil fuel-based energy system in 2015 to a fully renewable based-energy system in 2050 is 57%. The power generation costs are mainly dependent on costs related to PV and battery systems, since the fully renewable energy system in Pakistan depends primarily on these two technologies. A similar trend can be observed for the levelised cost of energy, as shown in Figure 10. After a decrease in 2020, the levelised cost of energy increases slightly over the next decade until 2030, whereupon it continues a decrease until 2050. The current energy system of Pakistan depends mainly on fossil fuels, which are responsible for the high cost. Imported and domestic fossil fuel costs and GHG emission costs make the current energy system expensive and unsustainable. The decrease in the levelised cost of energy in the 2020s is due to the replacement of expensive fossil fuels by renewables-based electricity generation options. The cost stability observed after the early 2020s is caused by continued investments in renewables and respective storage capacities to balance the variable nature of renewables, in particular solar energy. Fossil gas is still utilised to balance supply and demand for power and heat. After 2035, constant decrease in the levelised cost of energy is observed until 2050, due to further decrease in fossil fuels use in the heat and transport sectors in particular. The heat sector is the largest contributor to the total annual system cost, as shown in Figure 10a, while the cost of desalination to address the water supply crises increases through the transition. The levelised cost of water (LCOW), made up of the cost of water production, electricity, water transportation and water storage is found to be 2.74 and 0.73 €/m^3 in 2015 and 2050, respectively. Fast growing electricity demand across all sectors is mainly fulfilled by low-cost solar PV in Pakistan, which further decreases not only the cost of electricity but also the overall cost of energy.

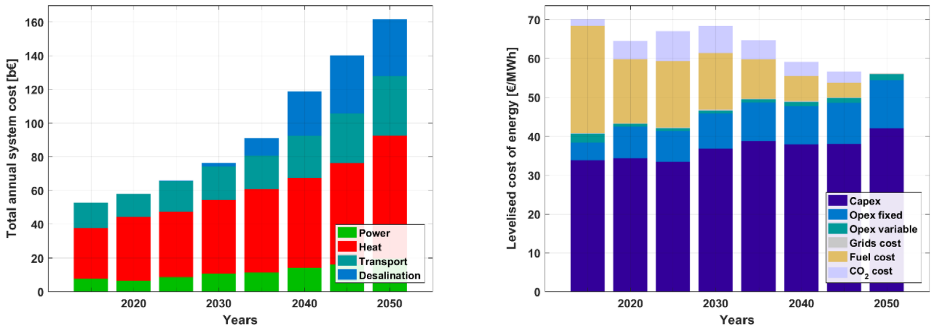

FIGURE 10 Cost of the energy system (a) annualised across different sectors and (b) levelised cost of energy from 2015 to 2050

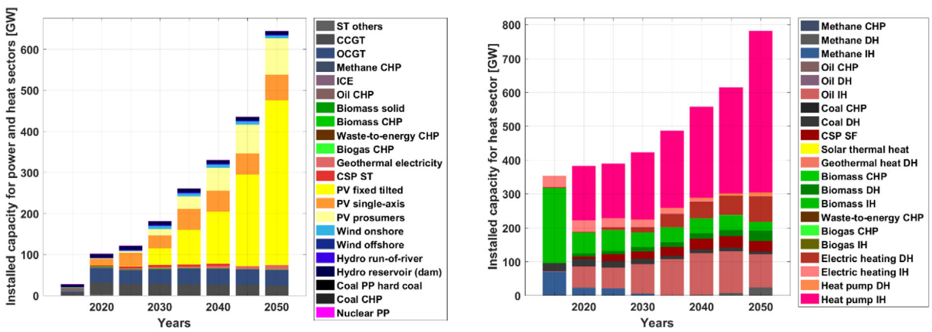

FIGURE 11 (a) Installed capacity of energy technologies for the (a) power and (b) heat sector for the transition period until 2050

3.4 | Power and heat sector

Figure 11 shows the installed capacity of power generation and heat supply technologies required for the power and heat sectors through the transition period. The total installed generation capacity for the power and heat sectors surges to 650 GW by 2050. A major part of the total installed capacity corresponds to solar PV with a share of 88%, while wind energy does not play a significant role in installed capacity. Wind resource availability in Pakistan is mainly concentrated in coastal areas of Sindh and Balochistan, away from the main electricity consumption centres. The distance between populated areas and good wind resource sites lowers the competitiveness of wind energy compared to solar energy which is available across the country as a high-quality resource. The PV prosumers' installed capacity contributes about 100 GW based on cost-attractiveness for the prosumers. The use of solid biomass is noticeable before 2030 and its share remains almost the same during the transition period (Figure 11b). From Figure 11b it is evident that heat pumps for individual heating (IH) will play a significant role throughout the transition period. Heat pumps (IH and DH) contribute around 161 GW in early 2020s for reducing heating cost and continue to increase their share in heating technologies with a capacity of 477.5 GW by 2050. Power and heat generation follow the same trends as installed capacities during the transition period as it is shown in Figure 12. In 2050, electricity generation is primarily dominated by solar PV (99%) and heat generation is largely supplied by heat pumps (47.1%), complemented by direct electric IH (19.5%) and biomass-based generation (5.4%), solar thermal (6.5%), and a small contribution from synthetic natural gas to replace remaining fossil fuel.

3.5 | Transport sector

Figure 13 shows the final energy demand of the transport sector by transport modes and by fuel types for the transition period. As can be seen from Figure 13a, after an initial increase in 2020, final transport energy demand will become stable over the next decade with only slight variation. Although the overall transportation demand increases steadily, the final energy demand does not change significantly until 2040, mainly due to efficiency gains caused by direct electrification of the sector. In the last decade of the transition, increased demand for marine and road

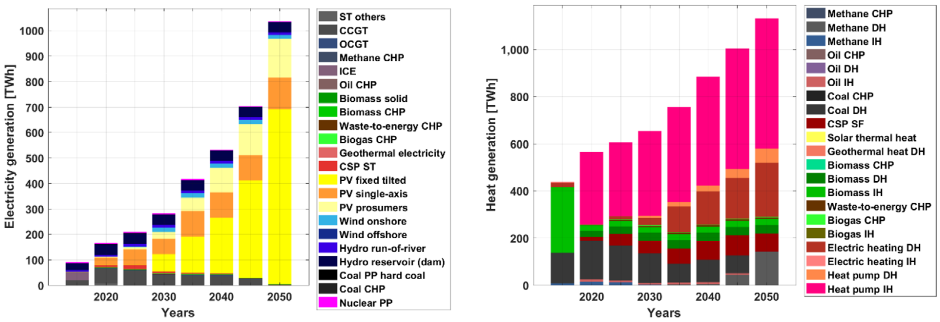

FIGURE 12 (a) Electricity generation by all energy technologies and (b) heat generation by different technologies for the transition period until 2050

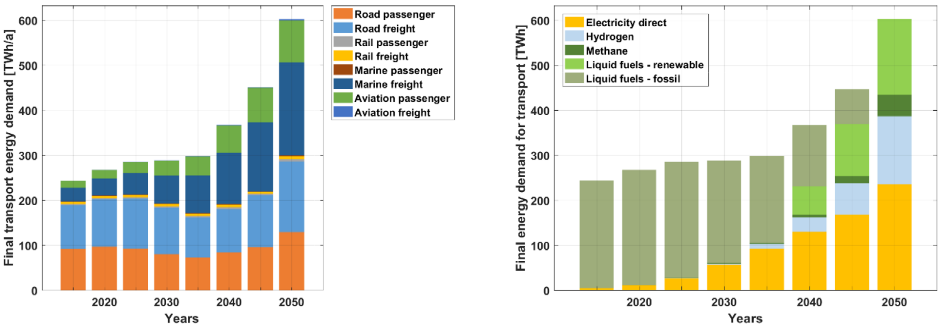

FIGURE 13 Energy demand by (a) all transport modes and by (b) transport sector fuels for the transition period until 2050

freight and passenger aviation contribute to the total increase in energy demand.

The energy demand of sustainable transport in 2050 will be covered by direct electricity (40%), synthetic liquid hydrocarbon fuels (34%) and hydrogen (26%). Road transportation will experience a transition to a combination dominated by battery-electric vehicles complemented by plug-in hybrids and fuel cell electric vehicles. Marine and aviation demand will be mainly covered by synthetic fuels and hydrogen generated from low-cost electricity. The energy demand for the transport sector by mode, vehicle type and fuel supply is shown in Table S3, Supporting Information. Figure 14 reveals that around 500 GW of installed solar PV capacity is necessary to attain a sustainable transport system for Pakistan by 2050 while supplying more than 900 TWh of electricity. Indirect electrification for synthetic fuels production accelerates the PV demand during the last periods of the transition.

The total installed capacity for direct electrification and to produce sustainable fuels (hydrogen, liquid fuels, and synthetic natural gas) in the transport sector will rise at an average annual growth rate of 9.3% (see Figure 14a). This also includes energy needed for CO_2 direct air capture [81], which is used to supply the carbon for producing synthetic hydrocarbon fuels. As indicated in Figure 14b, renewable electricity generation will dominate from 2025 onwards.

3.6 | Desalination sector

Pakistan is facing a serious water crisis [48] with an annual water availability falling below 1,000 m^3 per person [42]. Furthermore, water availability is unevely distributed throughout the country. In urban areas, only 41% of the total population has access to safe drinking water [82]. Water desalination is an important engineering task that coastal regions and cities, such as Karachi, are facing to satisfy the increasing water demand. Figure 15a shows the power generation capacities required to operate desalination plants during the transition period. The installed power generation capacities will be overwhelmingly dominated by solar PV, complemented by a very small amount of wind energy. Renewable energy technologies start appearing in 2025, as is observed from Figure 15 and will reach more than 450 GW in 2050. Figure 15b shows that with the rise in demand for clean water, the desalination capacity also increases

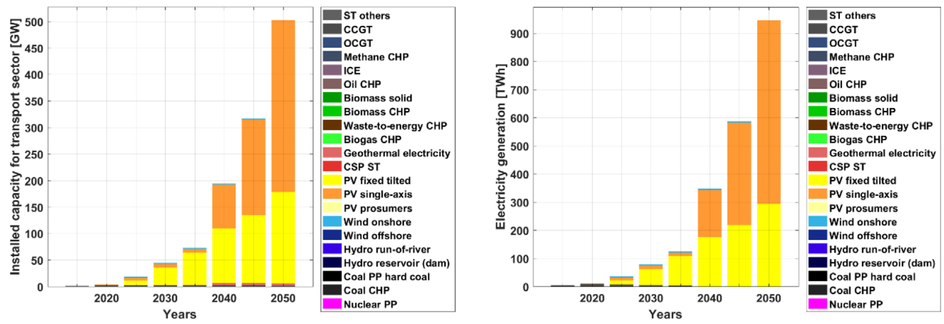

FIGURE 14 (a) Installed capacity of power generation technologies and (b) electricity generation for the transport sector by 2050

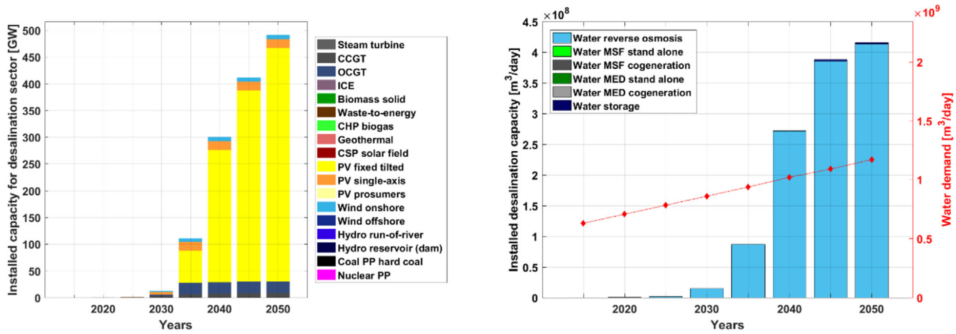

FIGURE 15 (a) Installed power generation capacity for the desalination sector and (b) installed desalination capacity and water demand for the transition period until 2050

considerably to 4.1×10^8 m^3/day providing 1.2×10^9 m^3/day of desalinated water in 2050. Desalination is provided by seawater reverse osmosis (SWRO) plants, which at the end of the studied period are entirely supplied by renewable electricity.

3.7 | GHG emissions

The primary aim of the energy transition is to achieve zero GHG emissions by 2050, which is possible for all the investigated sectors by 2050, as shown in Figure 16a. The slight increase in GHG emissions in the early 2020s due to further increase in energy demand and a slow adoption of renewable energy technologies. From 2025 onwards, GHG emissions start decreasing gradually as installations of renewable technologies increases in all sectors. The heat and transport sectors are the largest emitters followed by the power sector while the desalination sector does not make a contribution in the beginning of the transition and benefits from renewable electricity supply by 2050. The GHG emissions of all sectors are at an annual maximum of about 160 $MtCO_{2eq}$ in 2020 and reach zero in 2050 as shown in Figure 16a. Figure 16b details the GHG emissions for all transport modes. GHG emissions in the transport sector follow a similar pattern as total GHG emissions. The road transport mode contributes most to GHG emissions in the beginning of the transition, while marine freight and aviation passenger are the last segments of the transport sector to reach zero GHG emissions in 2050.

3.8 | Energy flow diagrams

Figure 17 shows the energy flow of Pakistan's energy system with detailed end use sectors in 2015. The primary energy sources of fossil oil, biomass and fossil coal contribute 134.3, 300.2 and 134.3 TWh to the energy system respectively. Renewable energy sources (solar, wind) do not make any significant contribution, while fossil gas (52 TWh), hydropower (35 TWh) and nuclear energy (10.9 TWh) have notable shares in the energy supply. The heat sector (space heating, domestic hot water, biomass for cooking and industrial process heat) is the largest energy consuming sector with 444.2 TWh followed by

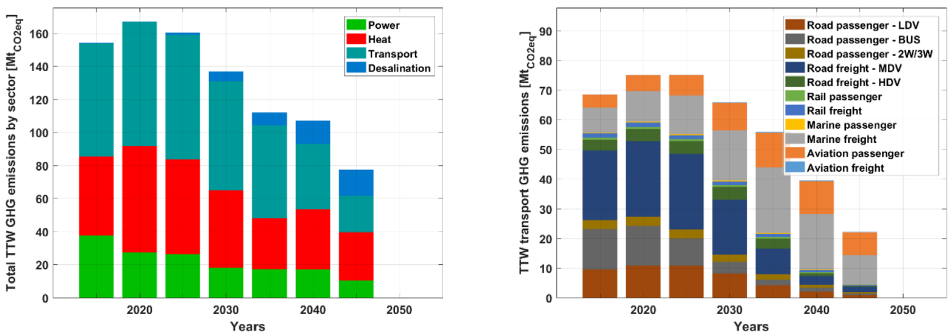

FIGURE 16 GHG emissions by (a) different energy sectors and (b) different transport modes in Pakistan for the transition period until 2050

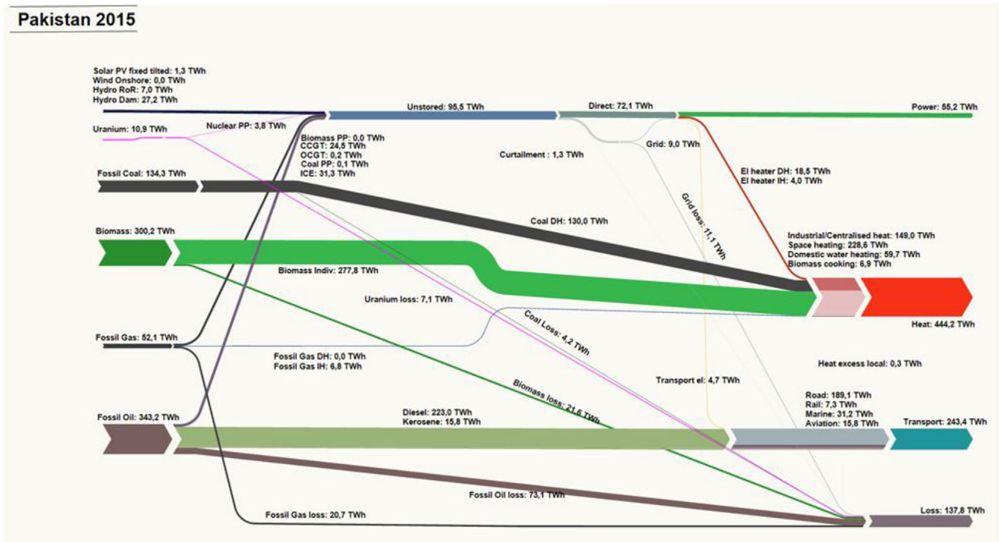

FIGURE 17 Energy flow of the energy system in 2015

the transport (243 TWh) and power (55 TWh) sectors. Figure 17 shows that 15.7% of the total energy input is wasted in the system with 11.1 TWh grid losses of the total losses of 137.8 TWh.

Figure 18 shows the energy flow in 2050 giving detailed uses in different energy sectors. Energy supply has shifted from fossil energy sources to renewable energy sources. Solar PV emerges as the most significant and largest energy supply technology with contribution of 82.2% of total energy. Wind and hydropower supply increase to 31.5 and 91.3 TWh, respectively, while the contribution of bioenergy decreases to 77.5 TWh. The heat sector is the largest energy consumption sector followed by the desalination, transport and power sectors. Grid losses have decreased from 20.1% in 2015 to 7.8% in 2050.

4 | DISCUSSION

The goal of this study is to find a cost-optimised techno-economic pathway for Pakistan towards a 100% renewable energy system by 2050 across the power, heat, transport and desalination sectors. A fully renewables-based energy system is not only possible but also a low-cost option for the country. Massive electrification of the energy system across all sectors (power, heat, transport, industry, desalination) makes the energy system more efficient, flexible and resilient [83]. According to this study, electricity can contribute 98% of the total primary energy demand complimented with very small quantities of bioenergy. Solar PV emerges as the most important

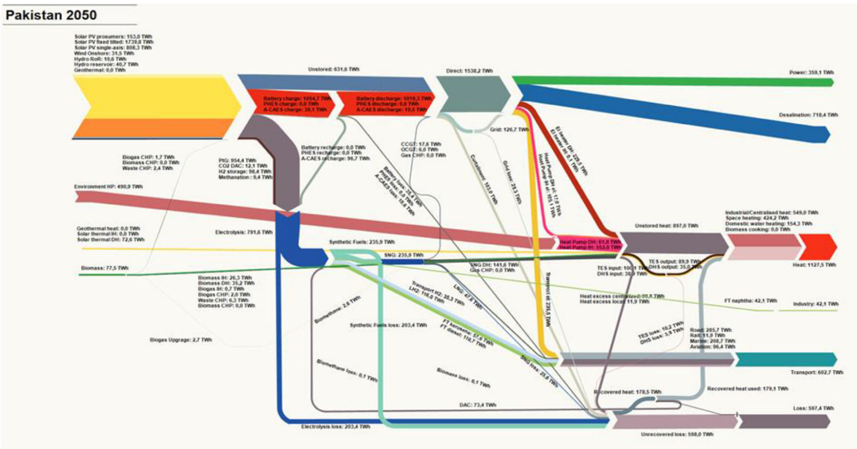

FIGURE 18 Energy flow of the energy system in 2050

energy generation technology with a share of around 86% of total installed capacity by 2050. Pakistan's geographical location, and the declining cost of solar PV and batteries make solar PV an evident choice for the future energy system. Solar PV is accompanied by widespread usage of batteries as a highly effective combination to overcome the day-night cycle. Batteries are an integral part of the energy transition and provide the energy system with the required flexibility to operate effectively day-by-day and over the long term.

The final calculated energy demand for the power, heat and transport sectors implemented in this scenario study is in line with other studies [55, 53]. Pakistan's current power generation policies [29] align with current and projected trends in power generation and aim to increase overall installed capacity while including a massive roll-out of renewable energy technologies, but Pakistan has to allocate substantial resources to cover the soaring desalination water demand in future.

The results for the Pakistan's transport system (Figure 13b) show a transition from fossil fuels to use of direct electricity, hydrogen, methane and RE generated liquid fuels. Roads are the most important segment of the transport infrastructure and account for 92% of passenger and 96% of inland freight transportation [37]. Pakistan's transport sector is heavily dependent on imported fuels and it is one of the largest emitters of GHGs. The government announced its first electric vehicle (EV) policy in 2019 to support its climate goals and to curb dangerously high GHGs emissions in major cities. Direct electrification of road transportation is the cheapest option, but its success depends on reliable access to electricity, development of a vehicle charging infrastructure and consumer acceptance. Direct electrification of the entire transport sector is not possible as current battery technologies cannot meet the requirements of long-distance transportation, which is a particular issue for the aviation and marine transportation. Hydrogen and RE-based liquid fuels form a substantial part of Pakistan's RE transition in the transport sector (Figure 13b). In the scenario calculations, the cost of RE-based liquid fuels becomes comparable to fossil fuels by mid-century. Thus, direct and indirect electrification of the transport sector has potential to breathe new life into Pakistan's economy. The electrification of the transport sector has potential to breathe new life into Pakistan's economy, as also concluded in [40].

Seawater desalination will play a critical role in solving the looming water shortage in the country and Pakistan will have to allocate substantial resources to cover soaring demand for desalinated water. This study projects demand for desalinated seawater as 1.51×10^{11} m^3/a by 2050, which is in line with other studies [84, 85]. The desalination plants identified as the least-cost option are SWRO plants because of their high efficiency and cost competitiveness compared to other desalination technologies. In the conditions found in Pakistan, they can be powered by solar PV [86]. The installed desalination capacity to cover the demand for desalinated water is estimated to be 4.14×10^{8} m^3/day by 2050, which requires a solar PV capacity of about 460 GW with generation of about 810 TWh. Pakistan is a predominantly agrarian economy, and almost 68% of the population is directly or indirectly involved in agriculture and agriculture-related activities. The agricultural sector has the highest water consumption and Pakistan currently has one of the most inefficient irrigation systems in the world [43]. The country's future water demand thus depends on water management and a massive improvement in the efficiency of the irrigation system is required.

Pakistan's current residential heating sector has an overwhelming dependence on raw biomass. According to EIA [87], approximately 58% of the country's population (105 million) use biomass for heating purposes due to inadequate or non-existent access to electricity and natural gas. As a consequence of the lack of a distribution system, particularly in northern areas of Pakistan, the scenario indicates a growth in direct use of electricity and heat pumps to cover residential and industrial heating demand. Heat pumps for residential use (IH) are a substantial part of heat generation technologies by 2050 with a share of about 47% (Figure 11b). Introduction and implementation of RE technologies together with energy conservation and energy efficiency measures are required.

The levelised cost of energy for Pakistan declines over the period studied and reaches 56.1 €/MWh in 2050. This cost reduction is mainly due to the transition from a fossil fuel-based energy system to a RE-based system. In 2015, the RE share of overall energy production was just 4%, which is almost negligible, even though Pakistan possesses an enormous RE potential. Pakistan has announced new policies related to power generation and battery-electric vehicles [40] with the aim of increasing the share of RE and electric vehicles to 30% by 2030.

Although, very limited literature is available examining high shares of RE technologies in Pakistan, the few studies hitherto published nevertheless demonstrate that future pathways with higher shares of RE are cost effective, efficient and cleaner compared to conventional energy based schemes. Most reviewed articles [54, 55, 88] focus on the power sector and ignore other sectors such as heat, transport, desalination and industry. For a sustainable and cleaner future, all sectors need to shift from fossil fuels to renewable energy solutions. Mirjat et al. [53] used the LEAP model to project various supply side scenarios using four different technology mixes for the transition period 2015–2050. The maximum RE share considered was 50%. The scenario with 50% RE was not the least-cost option but the least polluting one and lower in cost than the business-as-usual scenario. The Institute for Energy Economics and Financial Analysis modelled Pakistan's energy system with a 28% RE share by 2030 [6]. Sadiqa et al. [9] showed earlier for a 100% RE power system for Pakistan that this solution is a low-cost policy option with LCOE of 46.8 €/MWh. This current study, which considers the entire energy system in 2050, finds LCOE of 41.0 €/MWh. The further decrease in cost is due to higher shares of low-cost solar PV and batteries in the system because of large electricity demand in the transport sector, in particular in the 2040s. It can be expected that the LCOE will decline further after 2050, since the system structure as of 2050 for the cost assumptions would lead to LCOE of 34.4 €/MWh, that is, a further cost decline of 16%.

The results show that an increase in the RE share not only increase energy security [89], but it is also the most cost-effective option, similar results have also been found for other Sun Belt countries [90–93]. Electrification and sectoral integration also allow the defossilisation of electricity supply system and also lowers the energy and product cost. Studies on the South Asian region [56, 90, 94] show that RE access can solve several issues, such as, lack of access to reliable and sustainable electricity, vulnerability to climate change and looming water scarcity. Favourable for fast RE ramping will be the fact that densely populated urban areas in the region have a high solar irradiation and an energy infrastructure that make them suitable for grid connected solar PV generation [56]. Best policy scenarios in Sun Belt countries demonstrate that an energy system based on low-cost solar technology and storage is the most cost optimal solution [92, 95–97]. South Asia hosts a large population, thereof many live in poverty [56]. Access to sustainable supply of energy and water is highly important given the severe water stress in several parts of the region. Many people do not have access to sustainable electricity and water resources. Other 100% RE system studies also show that it can overcome the problem of rising water demand in water stressed countries without substantially increasing the cost of electricity [93, 98]. The levelised cost of electricity in 2050 in countries with high SWRO desalination water demand is 41 €/MWh in Saudi Arabia [98] and about 41 €/MWh in Iran [93]. The reduction in the LCOE of the system, contributes to the rapid decrease in the LCOW.

This study demonstrates that a fully renewable energy system is not only technically feasible for Pakistan, but it is also economically viable. Despite the remarkable promotion and policies, Pakistan is generating only a fraction of electricity from renewable energy resources particularly from solar and wind. Scaling up renewable energy requires strong political will and a respective regulatory framework. Although, government policies approved priority for renewable energy, obstacles and limitations still exist [99]. Several economic, institutional, regulatory, socio-cultural, and technical barriers slow the penetration of renewable energy technologies into the system. Subsidies to fossil fuels and inadequate financial incentives for renewable energy technologies resulted in a slow adoption of renewable technologies. Limited availability of infrastructure and technologies, lack of research and development and lack of maintenance and operational culture are few challenges among others to address. The transition of the energy system from fossil fuels to renewable energy also requires a skilled labour force [100]. The actual challenge in achieving a renewable energy transition is not a technical or financial one but the required political will to enable the transition. The frequency and intensity of extreme weather events caused by global warming are stark evidence that efforts to reduce GHG emissions need to be accelerated. The results of this study show that the transition towards a 100% renewable energy system will also decrease energy system costs while reducing dependence on imported fossil fuels, which will increase energy security.

5 | LIMITATIONS AND FUTURE DIRECTIONS

One of the limitations of the results in this study is that the country was structured in only two geographic nodes. Heterogeneity in renewable energy resources and final energy demand can be more precisely considered by resolving Pakistan into more regions so that also power lines can be better represented by the model. Future energy transition studies on Pakistan may further subdivide the country into several nodes based on population, energy demand and ability to fulfil these demands while minimising the need for transmission lines. The geographic occurrence of water stress and respective desalination demand can also be better described in a model with more regional differentiation. An additional limitation is that the most recently commissioned power plants may not be considered within the constraints of this study. Sector coupling has been applied to only a limited extent, since only the power and heat sectors are integrated, whereas the transport and desalination sectors are considered separately, so that the highest sector coupling efficiency has not yet been examined. This study presents a Best Policy Scenario which is focused on fast electrification rates, access to clean water and electric vehicles, phasing out of fossil fuels and effective integration of renewable technologies. The limitations could be addressed in future studies by carrying out detailed investigation of different sectors coupling options, and a diversified comparison of a Current Policies Scenario and other scenario variations.

6 | CONCLUSION

Pakistan needs an integrated energy policy and control mechanism to achieve a reliable, secure and cost-effective renewable energy system. The renewable energy market in an emerging market, such as Pakistan, presents unlimited opportunities and numerous challenges. A 100% renewable energy system is technically and economically possible by 2050. Reduced dependence on imported fossil fuels and increased utilisation of indigenous renewable energy resources is the solution for the climate urgency and the expensive fossil fuels based energy system in Pakistan.

According to the modelling results levelised cost of energy will reduce from about 70 €/MWh to about 51 €/MWh in 2050 because of the very low-cost solar PV electricity, low-cost batteries and efficient Power-to-X technologies. The primary LCOE decreases from more than 113.3 €/MWh in 2015 to 21.9 €/MWh in 2050, driven strongly by declining cost of solar PV, batteries and electrolysers. The most important energy technology for Pakistan is solar PV, as the prime and dominating source for the entire energy system, covering 92% of total primary energy demand. Batteries help to overcome the day-night cycle, while efficient Power-to-X solutions enable indirect electrification of synthetic fuels to meet demand in transport sector and high-temperature applications in the industrial sector. Comprehensive electrification of the energy system unlocks an enormous energy efficiency potential, since the primary energy demand based on present technologies would be 450% higher by 2050.

Along with a power shortage, Pakistan is also facing an extreme water shortage. Seawater desalination has been proposed as a solution to address the country´s approaching water crises. However, high electricity cost, energy consumption and greenhouse gas emissions, has hindered the uptake of desalination in the country in the past. This study indicates very high desalinated water demand of $1.5{\cdot}10^{11}$ m^3/a by 2050. Renewable electricity-based SWRO plants can solve the looming water problem, although such a solution requires adequate planning and implementation to overcome the severe challenges faced already in near future. A renewable electricity-based energy system for Pakistan will not only reduce economic pressure by reducing reliance on expensive imported fossil fuels, but also reduce GHG emissions to zero while enabling access to modern energy services for all Pakistanis.

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Publication III

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Irrigation efficiency and renewable energy powered desalination as key components of Pakistan's water management strategy

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Irrigation efficiency and renewable energy powered desalination as key components of Pakistan's water management strategy

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A B S T R A C T

Pakistan is reported to be one of the top ten, most water stressed, countries in the world. In this research, the potential to use renewable energy-based seawater desalination and improved irrigation systems to overcome the water stress in Pakistan is evaluated. It was observed that increasing the country's overall irrigation efficiency to 90% by 2050, results in a 54% and 80% reduction in total water and desalination demand, respective to a business as usual scenario. In a moderate scenario, where the maximum increase in irrigation efficiency is 1% per year, the 2050 total water and desalination demand are reduced by 21% and 40% respectively. The projected desalination demand growth, across the three scenarios, can be powered solely by renewables by 2050, at an average cost of water production of 0.6 €/m^3. This includes the cost of water transportation in Pakistan and is reported to be an attractive water cost for farmers. Solar photovoltaics and battery storage drive the low cost electricity generation production in Pakistan. Thus, the results show how Pakistan can use improved irrigation efficiency systems and the low cost renewable electricity to achieve water security for the country.

1. Introduction

Pakistan is in the throes of an unrelenting water crisis [1,2]. The country's freshwater availability per capita has declined from that of a water abundant country in 1951, with 5000 m^3 per capita, to that of a water stressed country by 2015 with 1100 m^3 per capita [3]. However, according to the World Bank [3], Pakistan has been well endowed with its own water resources – only 16 other countries have more fresh water resources. UNDP Pakistan [2] explains that an increasing population, poor management of existing water resources and climate change are the biggest contributors to Pakistan's growing water scarcity.

The FAO Aquastat Global Water Information System [4] reports that in 2008, 94% of Pakistan's total water withdrawals was for the agricultural sector, 5.3% for municipal and 0.8% for the domestic sector. Pakistan is said to have the fourth highest water use per capita and the world's most water intensive economy with 38 m^3/USD of gross domestic product (GDP) [5,6]. This is due to the pivotal role agriculture plays in the economy [5,6]. The agriculture sector is reported to contribute up to 25% of the country's total GDP and employs 43% of the country's labour force. However, according to a recent report by the World Bank, the contribution towards the agricultural GDP from the more water dependent cropping is declining whilst that of livestock dominates. In fact, the four major crops grown in the country, wheat, rice, sugarcane and cotton, account for up to 80% of the agricultural sector's water consumption, but only 5% of Pakistan's total GDP and is in decline. The report explains that with groundwater resources exploited, arable land almost fully used, fertilizer use already high, there are not many options left for Pakistan to improve economic returns of the irrigation sector. Pakistan needs to improve irrigation water use efficiency markedly and employ better water management if the country wants to revitalize economic growth [3].

While agriculture accounts for the highest share of Pakistan's total water withdrawals, the municipal sector has experienced the largest relative increase in water demand with a 530% increase from 1975 to 2008 [2]. This increase is attributed to the burgeoning population of Pakistan and portends the need to divert water resources from the crucial agricultural sector to other sectors [2,3,7]. The projected increase in water demand, from all sectors, on an already stressed water supply highlights the growing deficit between supply and demand in Pakistan. The World Bank has analysed several water security trajectories and finds that in 2047 the country's total water demand will significantly exceed the water

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supply.

The UNDP report [2] presents steps to improve the efficiency and resilience of Pakistan's agricultural sector against climate change events. One of the suggestions is the adoption of sprinkler and drip irrigation technologies that reduce the irrigation water demand by 40–60% [2]. Even though Pakistan is one of the major breadbaskets of the world, the country has an old and poorly maintained irrigation system [2]. According to the FAO, 100% of the Pakistan's irrigated area is equipped with surface irrigation systems with an average irrigation efficiency of 40% [2–4]. Surface water is conveyed to the field by a large network of canals while groundwater is pumped through tube-wells and wells [7]. The efficiency of surface irrigation systems is relatively low and can lie between 30 and 60%, while that of sprinkler and drip is between 50 – 70% and 70–90% respectively. The global irrigation efficiency is estimated to be 58%. The average share of global irrigated area equipped with surface, sprinkler and drip irrigation systems is found to be 54%, 20% and 8% respectively [8].

Pakistan's major crops for local consumption and export are wheat, rice and maize [9]. Consequently, Pakistan's crop exports in 2010 accounted for 29% of the unsustainable groundwater traded worldwide [10]. With limited arable land for irrigation, reduced water availability and increase in demand for food production, it is vital that Pakistan increases the productivity of the irrigation sector within the constraints of natural resources. Despite the obvious benefits of high efficiency irrigation systems, the acceptance of the technology by farmers has been low. This is attributed to the lack of overall support and training for farmers and the initial high investment costs [3]. Prevalent notion is that drip technologies are suitable for high value cash crops such as fruits and vegetables. However, forms of drip technology are being utilised in many countries for the irrigation of thirsty crops such as rice and wheat [11–13].

Wada et al. [14] discuss a six wedge approach to reducing the global population living in water stressed regions by 2050. Four of the wedges proposed aim to restrict the water demand through measures such as improved irrigation efficiency and agricultural water productivity. The remaining two wedges suggest an increase in water supply by building infrastructure such as desalination plants. Increased investment in desalination infrastructure is also a strategy presented by the World Bank [3]. In 2015, the total desalination capacity online in Pakistan was approximately 188,168 m^3/day [15]. Seawater reverse osmosis (SWRO) accounted for 25% of the online capacity. Almost half of the online capacity are brackish water desalination plants located inland and used for industrial purposes. However globally, seawater desalination accounts for 60% of all installed capacity in 2018, whilst brackish water accounts for only 22% [15]. Brackish desalination is chosen due to the lower investment and energy costs. Ghafoor et al. [16] recently demonstrated the cost benefits of using solar PV to run a brackish RO plant in Faisalabad, Pakistan. However, brackish desalination poses the issues of limited suitable feedwater sources and the locations for disposal of brine discharge [17].

The concerns that hinder the deployment of SWRO desalination plants are often the high energy and capital costs [17,18]. Desalination is the most energy intensive water treatment method and is estimated to account for 0.4% of the world's electricity consumption [19]. [19] further highlight the increasing global demand for desalination, with demand expected to increase by 40% by 2030, relative to the total capacity of 2016. The electricity-based SWRO plants are reported to have a specific energy consumption of 3.5 kWh/m^3, while the thermal driven technologies such as multi-stage flash (MSF) and multiple effect distillation (MED) require both electricity and low grade steam at 60–90 kWh/m^3 [20]. Durrani [21] highlights the plight of existing desalination plants in the Balochistan region of Pakistan which have had shut down due to breakdown in electricity supply or some instances abandoned entirely. Therefore, the author calls for better management of desalination plants in Pakistan and the use of solar and wind to run the plants. Caldera et al. [22]; 2020) demonstrate how the dependency of desalination plants on fossil fuel can be overcome through the use of hybrid renewable energy (RE) power plants. The projected cost of water production of RE powered SWRO plants is found to be competitive with that of fossil powered SWRO plants today. The rapidly dropping costs of solar photovoltaics (PV), wind energy and battery storage, the increasing cost of fossil fuels, as well as the global push to cut down greenhouse gas emissions, drive the desalination sector's uptake of RE power plants [23,24]. Furthermore, the capex of SWRO plants has been decreasing by 15% for every doubling of the global cumulative capacity and will continue to be the dominant global desalination technology [25]. In Caldera and Breyer [26] the role for RE-based seawater desalination in the global water supply portfolio, together with the use of higher irrigation efficiency systems, was analysed. Improved irrigation systems allowed a reduction of up to 25% in the projected global water withdrawals by 2050 and subsequently a reduction in global water stress. It was also estimated that by 2050, in a solely RE-based desalination sector, the average cost of potable water globally, including transportation, would be about 1 €/m^3. The observed trends in the cost of RE power plants and SWRO desalination plants highlights the untapped potential of desalination in the future global water supply mix.

To help secure water supplies in Pakistan, the government has suggested the construction of dams to increase the country's water storage capacity [1,6]. However, this has raised concerns as the construction of dams will reduce the flow of water going to the fragile Indus delta. The purpose of this research is to analyse improved irrigation methods and RE-based desalination as alternative means to overcome Pakistan's water crisis. The research builds on the methods and concepts defined in Caldera and Breyer [26] within a global context and focuses on Pakistan. Thus, this work describes pathways for Pakistan to manage the country's future water demand through improved irrigation efficiency and to augment stressed water supplies with low cost RE powered desalination plants.

2. Pakistan's water policy and plans to manage the country's water stress

After a decade of debating and wrangling, Pakistan approved the country's first national water policy in 2018 [27]. The policy addresses issues regarding management of water resources, effects of climate change, disputes between provinces, and concerns of the stakeholders. It also highlights the threats posed to water, food and energy security in the country and how provincial and federal governments can address the factors responsible for declining water supply and quality.

The policy emphasizes the importance of increasing the country's water storage by rehabilitation of current resources and by building new small and large dams. The construction of mega-projects and rehabilitation of the existing infrastructure has historically shaped the water policy of Pakistan. The Water and Power Development Authority of Pakistan (WAPDA) has decided to implement various multipurpose water and hydropower projects to ensure the water and power security in the country [28]. Advocates of large dams believe in multiple benefits offered by this infrastructure such as: increase in hydropower capacity which can reduce fossil fuel consumption, flood control, irrigation, water supply, increase in storage, inland water transport, and job creation [29]. However, the policy document fails to address the challenges posed by these mammoth structural interventions such as logging, salinity, cost and time overruns [29].

The policy document also notes the development of water management strategies through the idea of 'More Crop per Drop' with technological interventions in the irrigation sector. Different practices at the local, provisional, and national level have been proposed to support the idea. For instance, the gradual banning of flood irrigation across the country and the use of better suited crops [27]. Pakistan's water policy also emphasizes the use of water recycling and desalination to increase water supply.

In this research, the impacts of improved irrigation infrastructure and RE-based seawater desalination, as mentioned in the new National Water Policy document, on Pakistan's water crisis is assessed.

3. Method

The impacts on Pakistan's water demand are studied through three scenarios with different rates of improved irrigation efficiency up to 2050. Based on the subsequent water stress and demand, the required desalination capacity from 2020 to 2050 is established. The final objective is to present an energy transition pathway for Pakistan to power the desalination capacities, such that by 2050 all plants are powered by 100% RE. The overall approach taken in the paper maybe summarized as below:

The following sub-sections describe the scenarios, assumptions and modelling tool used in this study.

3.1. Pakistan sub-regions

Pakistan is divided into 7 main administrative units: Azad Jammu Kashmir, Baluchistan, Gilgit Baltistan, Islamabad Capital Territory (ICT), Khyber Phaktunkhwa, Punjab and Sindh. These administrative units are further divided into several districts [30]. For this research, the districts have been merged into 12 sub-regions as explained in Table 1 and illustrated in Fig. 1. Sub-regions are the combinations of the divisions and districts that provisionally and administratively work together.

3.2. Irrigation efficiency and water stress

The beneficial irrigation efficiency distribution for Pakistan is presented in Fig. 2 (a) and is obtained from Jägermeyr et al. [8]. Beneficial irrigation efficiency accounts for the efficiency of water application in the field and the water conveyance efficiency from the source to the field. Thus, the water that drains to the basins and may be reused are not accounted for [8]. The efficiency values shown in Fig. 2 (a) are the area weighted average values of the irrigation efficiencies for the staple crops rice, wheat and maize.

Fig. 1. Map showing the 12 sub-regions within Pakistan defined for this study.

The area extent of irrigation for different crops and the corresponding beneficial irrigation efficiencies have been provided by Jägermeyr et al. [8] as a global dataset in a gridded scale of $0.5° \times 0.5°$. These data sets are used to extract the beneficial irrigation efficiencies for rice, wheat and maize in Pakistan [31]. The average beneficial irrigation efficiency for Pakistan is estimated to be about 30%, with most of the irrigation systems found in the Sindh and Punjab regions as shown in Fig. 2 (a).

Fig. 2 (b) illustrates the spread of surface irrigation systems in Pakistan. Most of the irrigation systems are found in the Sindh and Punjab regions with some areas having more than 80% of the total area under irrigation. These are also regions that lie on the Indus Basin which is the world's largest continuously irrigated land area [3]. According to Jägermeyr et al. [8], as of 2007, Pakistan had 19,270 Mha of irrigated area, almost all using surface irrigation systems for crop production. The irrigated area accounts for over 20% of the country's total area. In the study by Jägermeyr et al. [8], based on biophysical and technical irrigation system suitability parameters, it is assumed that rice is only grown by surface irrigation systems. In contrast, wheat and maize are grown by surface and more efficient sprinkler irrigation systems. Recent research by Razzaq et al. [32] on the economics of high efficiency irrigation systems in Pakistan, explains that currently there are a handful of areas in Punjab, where sprinkler and drip irrigation systems are used. Sprinkler systems are mainly installed to irrigate wheat while the drip systems are used for mango orchards. According to Muzammil et al. [33] about 50,000 ha in the Punjab province have

Table 1
Sub-regions used in this study and the districts within each sub-region.

	Defined Sub-Region	Districts
1	Baluchistan	Baluchistan
2	Khyber Pakhtunkhwa – North (KPN)	Malakand, Hazara, Mardarn
3	Khyber Pakhtunkhwa – South (KPS)	Kohat, Bannu, D.I. Khan, Peshawar, FATA
4	Azad Jammu and Kashmir (AJK)	Azad Jammu and Kashmir, Gilgit Baltistan
5	Sindh – East (Sindh-E)	Larkanna, Sukkur, Mirpur Khas
6	Sindh – West (Sindh-W)	Hyderabad, Karachi
7	Punjab – North (Punjab-N)	Rawalpindhi, Sargodha, Islamabad Capital Territory
8	Punjab – North East (Punjab-NE)	Gujranwala
9	Punjab – Central East (Punjab-CE)	Faisalabad, Sahiwal
10	Punjab – East (Punjab-E)	Lahore
11	Punjab – Central South (Punjab-CS)	Multan, Bahawalpur
12	Punjab – West (Punjab-W)	Dera Ghazi Khan

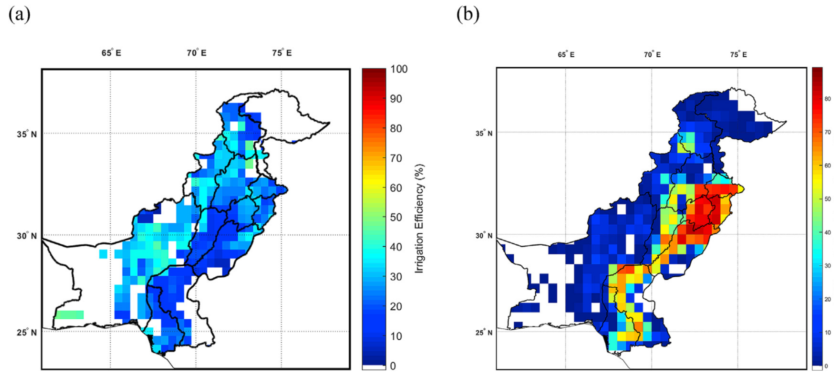


Fig. 2. Beneficial irrigation efficiency distribution in Pakistan for the crops rice, wheat and maize (a), and share of cell with surface irrigation systems in Pakistan (b).

been equipped with highly efficiency irrigation systems.

Fig. 3 presents the current water stress map for Pakistan. Water stress is the ratio of the water withdrawals to the renewable water resources available. Regions with water stress greater than 80% are areas where water withdrawals are much greater than the renewable water resources, and there is exploitation of fossil groundwater resources. In Pakistan, the northern regions, namely AJK, KPK, KPS and Punjab-N, have lower water stress. However, in the more populated sub-regions of Sindh, central and southern regions of Punjab, the water withdrawals exceed the renewable water limit. In the arid region of Baluchistan, the demand for water is less as the population is lower. However, the renewable water resources are also much limited, resulting in an overall high water stress.

When compared with Fig. 2 (b), it can be seen that areas with large extent of irrigation systems also suffer from high water stress levels. This endangers the future of Pakistan's agricultural sector, which supports the livelihoods of 43% of the population and the country's economic growth.

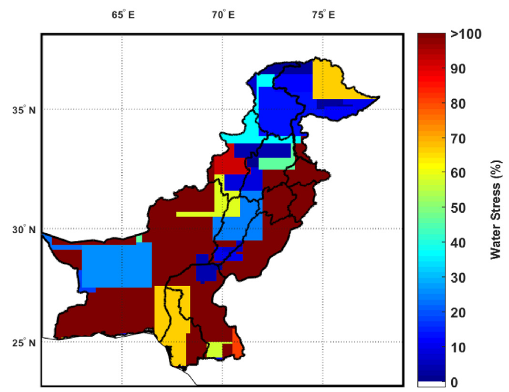


Fig. 3. Water stress in Pakistan for the year 2020.

3.3. *Irrigation efficiency scenarios for Pakistan*

Caldera and Breyer [26] presented three scenarios where the efficiency of the global irrigation sector was varied over time, under different assumptions, up to 2050. The Base scenario represents a business as usual case where the irrigation efficiencies of the existing sites, shown in Fig. 2 (a), are not projected to improve. According to Hanasaki et al. [34], the highest rate of increase in global irrigation efficiency has been only 0.3% per year, relative to the preceding year. Similarly, for Pakistan, Muzammil et al. [33] explain that while there have been efforts made to implement more efficient irrigation systems, the results are unremarkable. For this study, it was assumed that this trend will continue and that there would be no change to the current irrigation efficiency of Pakistan shown in Fig. 2 (a).

In the Irrigation Efficiency Push (IEP) scenario, a more optimistic future for Pakistan's irrigation sector was posited. Based on the scenario outlined in Caldera and Breyer [31], the irrigation efficiency of a region is increased based on the water stress for the given year. The minimum growth rate per year is 0.3%, while the highest possible growth rate is 1%. The relationship between water stress and irrigation growth rate is shown in Fig. 4 (a). Regions where the water stress is greater than 100%, the irrigation efficiency improvement rate is 1% per annum. Further details of this relationship is provided in Caldera and Breyer [26].

Fig. 4 (b) illustrates the assumed beneficial irrigation efficiency in the IEP scenario, for the year 2030, based on the growth rate presented in Fig. 4 (a). The improvements in irrigation efficiency relative to Fig. 2 (a) are moderate. The improvements in irrigation efficiency for the year 2050 are more stark, as shown in Fig. 4 (c).

In the Highest Possible Irrigation Efficiency (HPIE) scenario, as the name of the scenario suggests, it is assumed that all irrigation sites achieve an irrigation efficiency of 90% by 2050. At present, irrigation sites across North America, Europe and Israel are reported to have such high irrigation efficiencies through the widespread use of drip irrigation technology [8]. This is further supported by companies like Netafim who show that highly efficient irrigation systems can be used to grow thirsty crops such as rice and wheat [12,13]. It is assumed that by 2050 all sites will be able to achieve an irrigation efficiency of 90%. This is illustrated in Fig. 6 and represents the most optimistic scenario. By 2050, it is then assumed that highly efficient drip irrigation systems will be used to grow crops like rice and wheat in Pakistan.

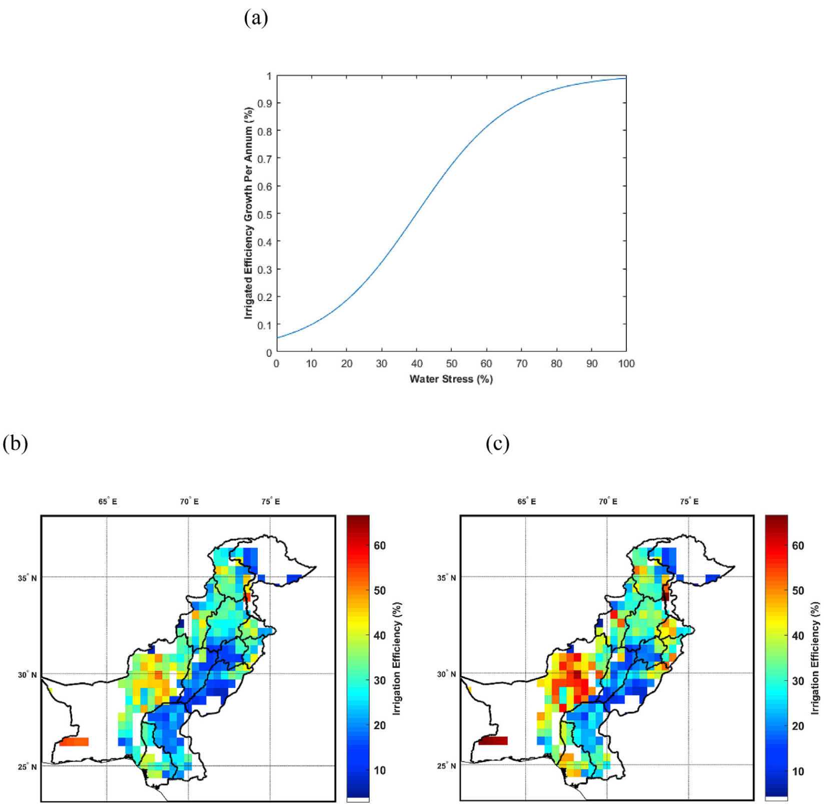


Fig. 4. Relationship between water stress and irrigation efficiency growth per annum in the IEP scenario (a), projected irrigation efficiency of Pakistan in 2030 in the IEP scenario (b), and projected irrigation efficiency of Pakistan in 2050 in the IEP scenario (c), axes on both are kept the same to aid comparison (c).

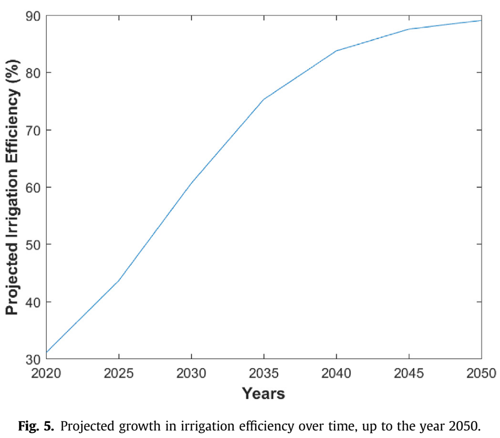


Fig. 5. Projected growth in irrigation efficiency over time, up to the year 2050.

After establishing the irrigation efficiency growth for the IEP and HPIE scenarios, the country's total desalination demand is projected. The total desalination demand for Pakistan includes the demands of the irrigation, industrial and municipal sectors. The desalination demand is a function of the total water demand and water stress. The higher the water demand and water stress, the greater is the need for desalination. Details of the method to establish the desalination demand for a region has been explained in Caldera et al. [22] and Caldera and Breyer [26]. Fig. 6 illustrates the total desalination demand of Pakistan for the time period from 2020 to 2050, for the Base, IEP and HPIE scenarios. Table 2 and Table 3 provide the desalination demand numbers and the corresponding total water demand numbers respectively. The decrease in desalination and water demand is due to the improvement in irrigation efficiency projected.

As of 2017, the total water withdrawals of Pakistan were estimated to be 5080 million m^3/day [3]. The World Bank [3] recently modelled different water security trajectories for Pakistan under different climate change and economic growth scenarios. Economic growth and population are the main drivers of increasing water demand in the future. However, climate change, without demand management further exacerbates the gap between water supply

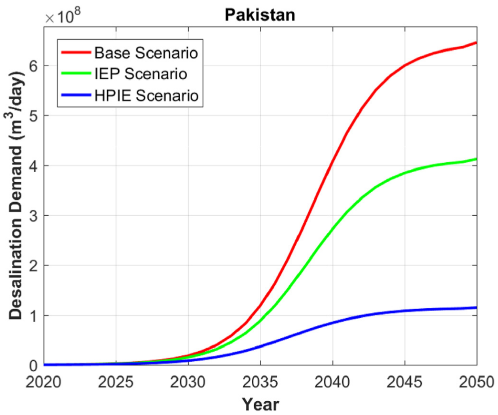


Fig. 6. Desalination demand projections for Pakistan, in the Base, IEP and HPIE scenarios.

Table 2
Desalination demand projections for Pakistan.

		2020	2025	2030	2035	2040	2045	2050
Base	10^5 m^3/day	2.69	17.2	111	649	2710	5710	6460
IEP	10^5 m^3/day	2.52	15.1	90.2	483	1840	3670	4120
HPIE	10^5 m^3/day	2.13	10.7	52.5	223	649	1050	1150

Table 3
Total water demand projections for Pakistan.

		2020	2025	2030	2035	2040	2045	2050
Base	10^8 m^3/day	7.07	7.83	8.59	9.36	10.1	10.9	11.7
IEP	10^8 m^3/day	6.85	7.35	7.78	8.21	8.59	8.94	9.26
HPIE	10^8 m^3/day	5.85	5.49	4.86	4.74	4.82	5.08	5.39

and demand. By 2047, it is expected that the total demand will exceed the total available water resources of the country, thus emphasising the need for stringent water management.

3.4. Setting up the energy transition

To meet the current and increasing future water demands, as shown in Tables 2 and 3, Pakistan will need to invest in more desalination infrastructure. The desalinated water will help meet the demands of the municipal, irrigation and industrial sectors. In this research, the aim is to analyse the possibility of meeting the energy demand of the desalination plants, for both potable water production and transportation, through RE-based systems. By 2050, it is expected that all desalination plants in Pakistan will be powered by 100% RE. The desalination system can be further integrated into the total energy system as carried out by Sadiqa et al. [35] and described within the framework of smart energy systems in Mathiesen et al. [36]. As explained in Mathiesen et al. [36], the integration of energy sectors enable the most cost effective and energy efficient 100% RE systems.

The LUT Energy System Transition model, which has been widely used for the energy transition analysis for many countries and regions, including Pakistan [35,37], is used to determine the energy transition pathway for the desalination sector in Pakistan as defined in this section. The LUT model is a linear optimisation model, designed in an hourly temporal and 0.45° × 0.45° spatial resolution. The objective of the model is to design a cost optimised energy system, where the energy demand for every hour is met through a portfolio of different RE technologies while accounting for relevant resource potentials in a high spatial and hourly resolution. Further details on the model are provided in the publications [26,38,39]. A critical comparison of the different energy system models available to study 100% renewable energy systems is presented in Prina et al. [40]and also framed in Hansen et al. [41]. Results of these models support policy makers with the establishment of viable energy strategies and help analyse alternative pathways that best meet specific requirements [42].

Fig. 7 illustrates the energy generation, storage and bridging technologies that comprise the version of the LUT model used throughout this work. The desalination energy demand includes that of the thermal and SWRO technologies. The thermal technologies included are Multiple Effect Distillation (MED) and Multi Stage Flash (MSF).

The electricity is generated by solar PV and wind power plants based on the RE resources. The power-to-gas (PtG) components and battery energy storage complement the electricity generation sources by ensuring cost optimal operation of the desalination plants. Power-to-heat (PtH) is used to generate heat for thermal desalination plants and stored in the thermal energy storage (TES). The hot heat burner (HHB) can be used to burn gas to produce additional heat if required. In addition, the steam turbine (ST) may generate electricity using the heat from the TES. The allocation of the technologies is driven by the total system costs that are a function of the financial costs, technical parameters and RE resource availability.

To meet the new desalination demand, MED stand-alone and SWRO plants are used by the model. This is due to the lower thermal and electricity demand of these technologies. MED stand-alone plants are installed based on the excess heat during the transition. Excess heat may be generated from the gas turbines and PtG units. Based on the availability of heat in the system and the cost of required heat generation, the model optimises the water production from MED stand-alone plants. MSF stand-alone plants are not installed after 2015. This is due to the higher thermal consumption compared to MED stand-alone plants. The MSF and MED cogeneration plants are phased out based on the lifetime of the plants. The key desalination and energy system financial and technical assumptions used in the model are provided in Appendix Table A1 and Table A2 respectively. Table A3 presents the carbon dioxide costs assumed over the transition period of this research.

The model also accounts for the electricity required for pumping the desalinated water from the desalination plant to the demand site. The weighted average pumping distances in both horizontal and vertical directions were estimated as in Ref. [26]. Fig. 8 provides an idea of the horizontal pumping distances for each of the sub-regions from the nearest coastline. In the case of Pakistan, the nearest coastline is the Arabian Sea. Therefore, the sub-regions Balochistan and Sindh have the shorter water transportation distances. These distances do not vary much between the years and scenarios.

The levelised cost of water (LCOW) is calculated based on the below equation (1), also described in Caldera et al. [43]:

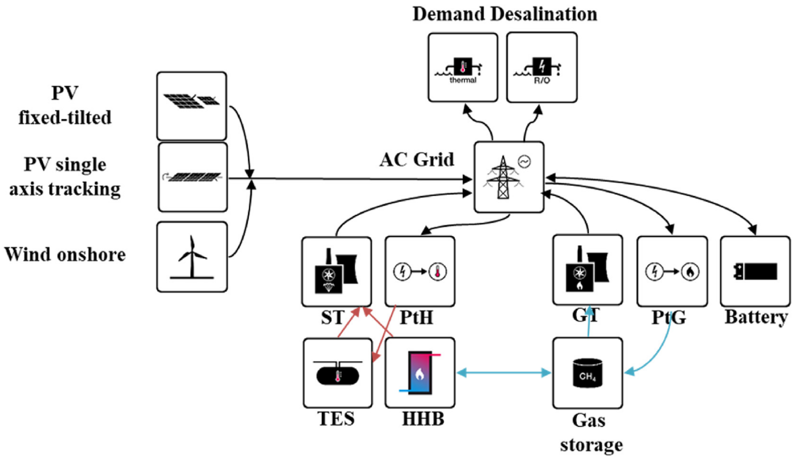


Fig. 7. Block diagram of the LUT Energy System Transition model used for analysis of energy systems to power the desalination demand [26].

$$LCOW_{desal} = \frac{\left(Capex_{desal}\cdot crf_{desal} + Capex_{water\ storage}\cdot crf_{water\ storage}\right) + opex_{fixed\ desal} + opex_{water\ storage}}{Total\ water\ produced\ in\ a\ year} + Opex_{var\ desal}\cdot SEC \tag{1a}$$

$$Opex_{var\ desal} = LCOE \tag{1b}$$

$$LCOT_{desal} = \frac{\left(Capex_{hpumps}\cdot crf_{hpumps} + Capex_{vpumps}\cdot crf_{vpumps}\right) + Capex_{pipes}\cdot crf_{pipes)} + opex_{fixedt}}{Total\ water\ produced\ in\ a\ year} + Opex_{vart}\cdot SEC_t \tag{1c}$$

$$LCOW = LCOW_{desal} + LCOT_{desal} \tag{1d}$$

Here, $\mathbf{capex_{desal}}$ is the capex of the desalination plant in €/(m^3·a) and $\mathbf{crf_{desal}}$ is the annuity factor for desalination plant. Total water produced in a year is in m^3, $\mathbf{opex_{fixeddesal}}$ is the fixed opex of the desalination plant in €/(m^3·a). $\mathbf{opex_{vardesal}}$ is the levelised cost of electricity (LCOE) and is in €/kWh. SEC is the specific energy consumption in kWh/m^3. The product of the LCOE and SEC is the energy cost of the desalination plant in €/(m^3.a). $\mathbf{capex_{waterstorage}}$ is the capex of water storage and $\mathbf{crf_{waterstorage}}$ is the annuity factor for water storage. $\mathbf{LCOT_{desal}}$ is the levelised cost of water transportation. $\mathbf{capex_{hpumps}}$ is the capex of the horizontal pumps in €/(m^3·a) and $\mathbf{crf_{hpumps}}$ is the annuity factor for horizontal pumps, $\mathbf{capex_{vpumps}}$ is the capex of the vertical pumps in €/(m^3·a) and $\mathbf{crf_{vpumps}}$ is the annuity factor for the vertical pumps. $\mathbf{opex_{fixedt}}$ is the fixed opex of the horizontal and vertical pumps in €/(m^3·a). $\mathbf{opex_{vart}}$ is the LCOE and $\mathbf{SEC_t}$ is the total energy consumption for water pumping.

4. Results

4.1. Impacts of irrigation efficiency on Pakistan's desalination demand

Fig. 9 compares the desalination demand and the total water demand for Pakistan in the years 2030, 2040 and 2050. By 2050, 55%, 45% and 21% of the country's total water demand is to be met by desalination plants in the Base, IEP and HPIE scenarios respectively.

Increasing the irrigation efficiency makes a significant dent in the water and desalination demand of Pakistan. However, the reduction in desalination demand is steeper than that observed for

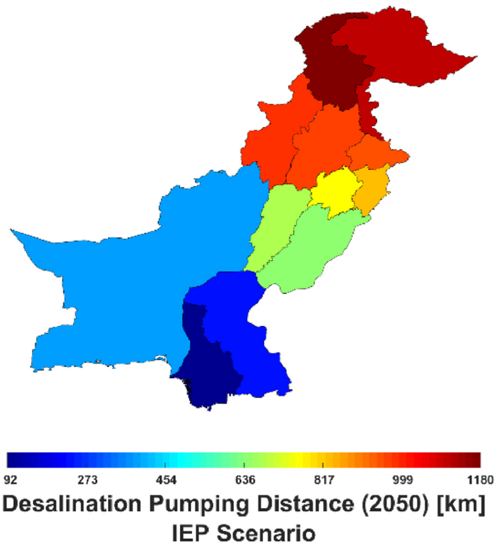


Fig. 8. Weighted average pumping distances for the sub-regions of Pakistan, in 2050, for the IEP scenario.

the total water demand. This indicates that most of the irrigation sites are in regions of high water stress, large water demand and therefore have the most need for desalinated water.

In the IEP scenario, the total water demand of the country is reduced by 9% and 21% in 2030 and 2050 respectively, relative to the Base scenario. In the HPIE scenario, a more significant reduction of 43% in 2030 and 54% in 2050 is observed. In fact, by 2050, the total water demand in the HPIE scenario is 5390 million m^3/day and is only 5% higher than the country's water withdrawals in 2017. In the Base and IEP scenario, the total water demand in 2050 is projected to increase by 130% and 82% respectively, relative to the total water withdrawals in 2017. Thus, the HPIE scenario, with the drastic increase in irrigation efficiency, offers the most effective way of managing the water demand increase in the country.

Fig. 10 (a), (b) and (d) illustrate the regional desalination demand projections for 2050 in the Base, IEP and HPIE scenarios. Fig. 10 (d) and (e) represent the decrease in desalination demand in the IEP and HPIE scenarios relative to the Base scenario, for the year 2050. The weighted average decrease in desalination demand across all sub-regions is about 30% in the IEP scenario and 80% in the HPIE scenario. In the northern sub-regions, there is almost a 100% reduction in desalination demand indicating that these regions are facing water stress due to irrigation.

Fig. 11 shows the desalination capacities modelled to meet Pakistan's desalination demand during the transition, up to 2050. SWRO desalination plants account for almost 100% of the capacities by 2050. Less than 1% of the total capacities are MED stand-alone plants. The installation of SWRO and MED stand-alone plants are optimised during the transition based on the least annualised total system costs. The MED stand-alone plants require significant amounts of heat which is not available at low cost in the energy system and therefore are not installed during the transition. A similar trend is also observed in the Base and HPIE scenarios.

4.2. *Energy transition pathway for Pakistan's desalination sector*

The energy transition pathway presents a least cost approach to ensure that the desalination capacities required are entirely powered by renewables by 2050. The figures that follow highlight the key aspects of this transition pathway.

Fig. 12 (a) illustrates the trend in the levelised cost of electricity (LCOE) during the energy transition in Pakistan, for the IEP scenario.The LCOE decreases from about 80 €/MWh in 2020 to 40 €/MWh by 2050. Up to 2030, fuel costs play a significant role in the final LCOE of the system and is eliminated from the system by 2050. The CO_2 emission costs adds on to the fuel cost and increases over time due to the increasing emission cost. In 2020, CO_2 emission cost of 28 €/tCO_2 is assumed and this increases to 150 €/tCO_2 by 2050. As the fuel cost decreases, the capital expenditures (capex) of the energy system becomes the largest contributor to the final LCOE.

The LCOE in the Base and HPIE scenarios follows a similar trend to that of the IEP scenario. Fig. 12 (b) compares the LCOE for the three scenarios in the years 2030, 2040 and 2050. The LCOE values diverge slightly in 2050. In the HPIE scenario, the final LCOE is estimated to be about 43 €/MWh, whilst the corresponding number in both the Base and IEP scenario is 39 €/MWh.

Fig. 13 (a) illustrates the electricity generation mix during the transition in the IEP scenario. The electricity generation for the

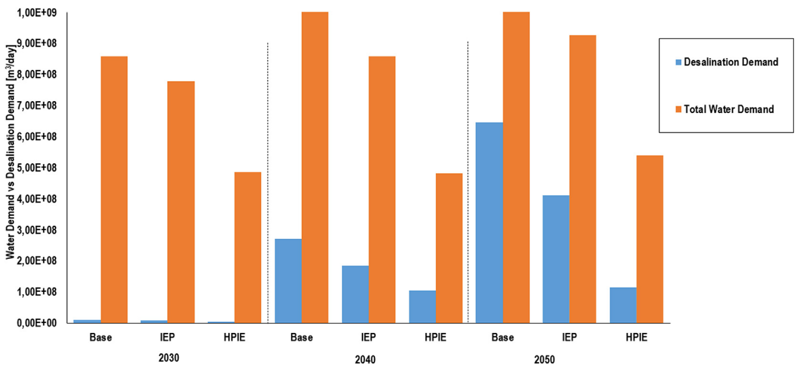


Fig. 9. Scenario comparison of desalination demand and total water demand for Pakistan in 2030, 2040 and 2050.

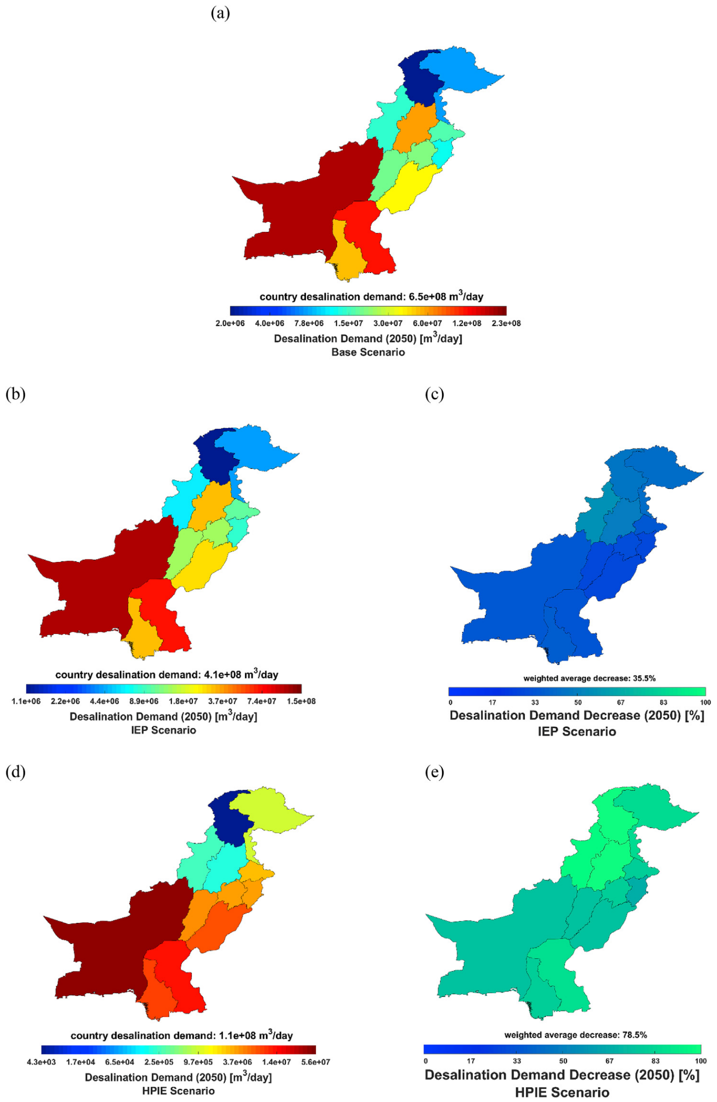


Fig. 10. Regional desalination demand projection for Pakistan in the Base scenario by 2050 (a), IEP scenario by 2050 (b), HPIE scenario by 2050 (d), regional relative decrease, to the Base scenario, in the desalination demand in the IEP scenario by 2050 (c), HPIE scenario by 2050 (e).

desalination sector increases drastically from less than 1 TWh in 2020 to 790 TWh in 2050 for the desalination sector. Solar PV contributes up to 99% of the total electricity generation in 2050. This highlights the fact that most desalination areas are also regions with plentiful solar resources. Fig. 13 (b) provides a comparison of the electricity generation mix in the Base, IEP and HPIE scenarios, for the years 2030, 2040 and 2050. The electricity generation falls by 83% in the HPIE scenario, relative to the Base scenario. Meanwhile, the corresponding electricity generation falls by 36% in the IEP scenario. Solar PV is the dominant electricity generation resource in all three scenarios throughout the transition.

The cumulative electrical power capacities required to operate the desalination plants in the IEP scenario are presented in Fig. 14 (a). Reflecting the dominant role of solar PV in the energy

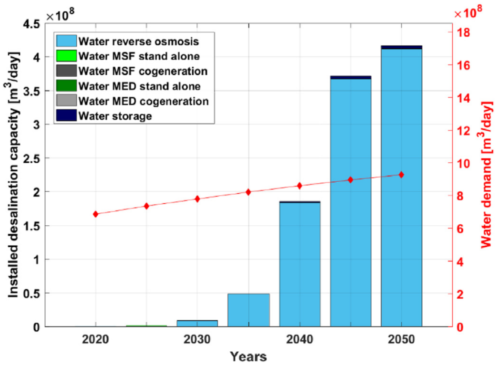


Fig. 11. Desalination capacities installed in the IEP scenario for Pakistan. The left y-axis presents the desalination capacity, and the right y-axis presents the total water demand.

transition, by 2050, 468 GW of solar PV is required. The total installed capacities by 2050 is 534 GW. OCGT capacities do not increase from 2040 onwards and account for the remaining 11% of the total capacities in 2050. However, as shown in Fig. 13 (a) OCGT plants account for less than 1% of the total generation by 2050. In the Base and HPIE scenarios, the total electricity generation capacities by 2050 are 835 GW and 151 GW respectively.

The land area in Pakistan available for utility-scale solar PV installations, excluding total agricultural land, forest land and urban area is approximately 440,851 km^2. This is based on the most recent data available via the FAOSTAT Land Use and World Bank databases [4,44]. The maximum power capacity potential of the land available can be estimated using the assumptions of standard irradiation conditions of 1000 W/m^2, 18% PV module efficiency and ground cover ratio of 50%. Of the total available area, 6% is assumed to be for solar PV as outlined in Bogdanov et al. [38]. During the transition period, the overall efficiency of new modules will improve as discussed by Vartiainen et al. [24]. The efficiency improvement is estimated to be roughly 0.4% pp/annum, leading to about 30% PV module efficiency in 2050. As such, by 2050, the total solar PV installation potential in Pakistan is estimated to be about 4000 GW, enabling the installation of the capacities presented in Fig. 14. Furthermore, agro-photovoltaics, where agricultural land is primarily used for crop production and has a secondary role of electricity generation, has been proven to increase the crop yield and land use efficiency in Germany [45]. Such systems in Pakistan will help mitigate competition for land between irrigation and electricity generation from PV.

Storage capacities are installed during the transition to ensure that the desalination plants can be powered even during times of inadequate renewable electricity generation. Fig. 15 (a) presents electricity output from energy storage during the transition. Battery storage starts to play a dominant role in the transition from 2035

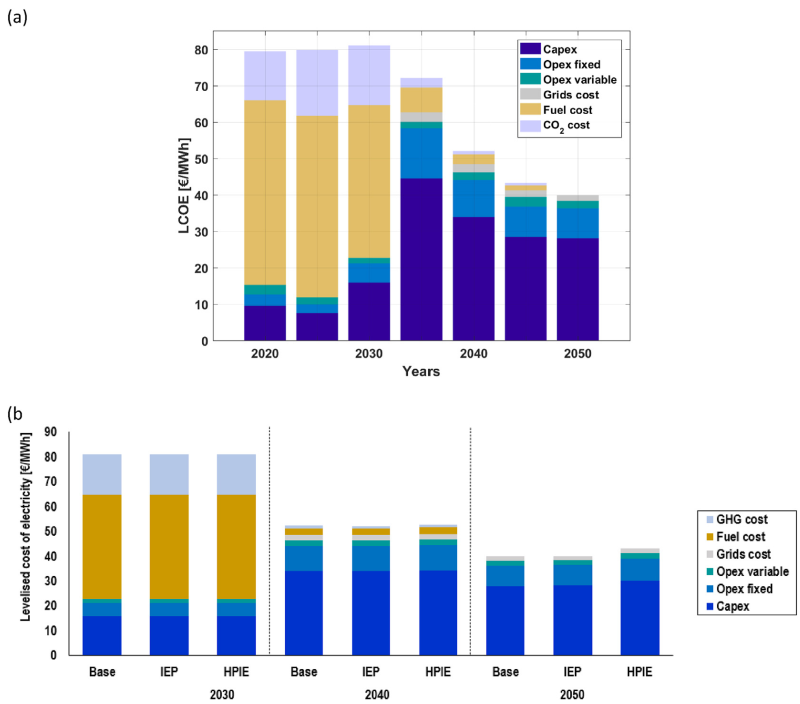
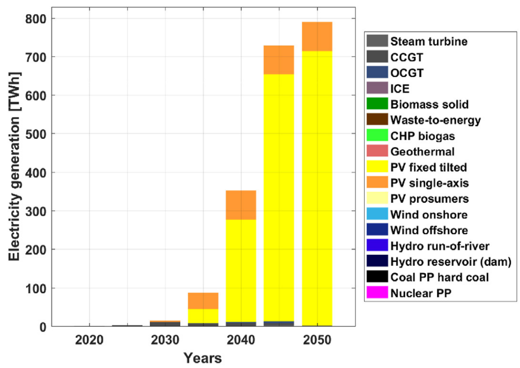


Fig. 12. LCOE breakdown for Pakistan's energy transition in the IEP scenario (a), comparison of LCOE in 2030, 2040 and 2050 for the Base, IEP and HPIE scenarios (b).

(a)



(b)

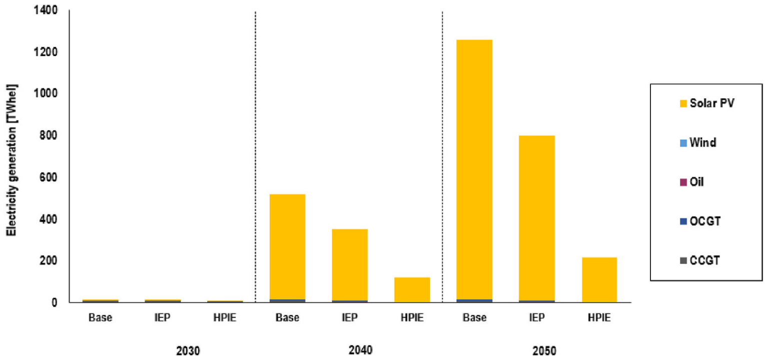


Fig. 13. Electricity generation for the desalination sector during Pakistan's energy transition for the IEP scenario (a), electricity generation mix in 2030, 2040 and 2050 for the Base, IEP and HPIE scenarios.

onwards. By 2050, battery storage output provides up to 60% of the total electricity demand in the IEP scenario. The same shares are found in both the Base and HPIE scenario by 2050. Gas storage also plays a limited role, accounting for 4% of the total storage output. Fig. 15 (b) shows that the storage output trends are similar across all scenarios.

Fig. 16 (a) presents the final weighted average LCOW for Pakistan during the energy transition in the IEP scenario and is determined based on Equation (1). The LCOW accounts for the cost of water production at the desalination plant, the cost of water storage and the water transportation from the desalination plant site to the demand node [26]. During the transition, the LCOW decreases from 0.94 €/m^3 in 2020 to 0.62 €/m^3 by 2050. As shown in Fig. 16 (a) the LCOW also includes the water transportation costs from the desalination plant at the coast to the desalinated water demand site. The decrease in LCOW is driven by the reducing cost of the SWRO plants and the electricity cost. The reduction in LCOE relative to the LCOE in 2020 occurs from 2035 and this is also reflected in the cost of water production. The transportation costs include the capital and operational expenditures of the pumps and pipes. The increase in horizontal transportation costs can be attributed to the fact that over time more regions inland are expected to suffer from worsening water stress. This increases the horizontal pumping costs.

The LCOW trends for all the three scenarios are similar. In the Base and HPIE scenarios, by 2050, the LCOW is about 0.63 €/m^3 and 0.68 €/m^3 respectively. Fig. 16 (b) compares the LCOW for the years 2030, 2040 and 2050. The capex shown includes the cost of the desalination and water transportation components. The opex variable comprises the cost of electricity and other variable costs. The opex fixed includes the fixed operational costs of both the desalination and water transportation components.

Fig. 17 captures the behaviour of water storage for every hour of every day in the year 2050, in the IEP scenario. Water storage is available during the transition to allow for flexibility in the energy system. However, the capacity of water storage required is 4.0 million m^3 and accounts for less than 1% of the total desalination demand in 2050. The SWRO plants continue to operate on an almost baseload capacity, whilst flexibility is provided at a lower cost by solar PV and battery storage. The fluctuations in water storage is due to the small capacity of the MED stand-alone plants in the system by 2050. Due to the low heat in the system, MED stand-alone plants are operated at less than half the baseload capacity and water storage is used to replace the small fraction of

(a)

(b)

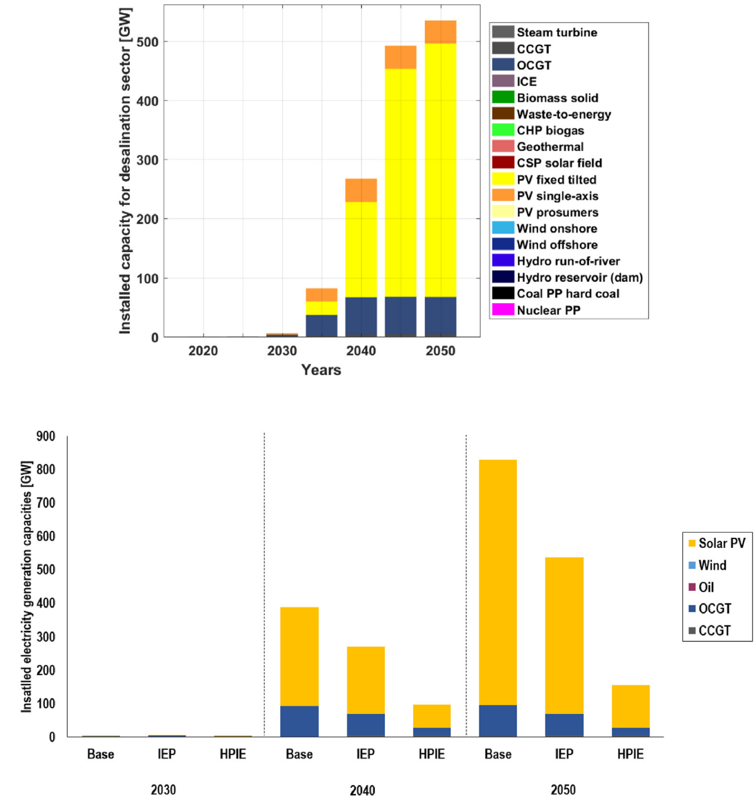


Fig. 14. Electricity generation capacities in the IEP scenario (a), comparison of electricity generation capacities in the Base, IEP and HPIE scenarios (b).

water from the MED plants. Similar observations are also made for the Base and HPIE scenarios.

Fig. 18 (a) and Fig. 18 (b) compares the cumulative desalination capex and cumulative system capex during the transition of Pakistan's desalination sector respectively. The desalination capex account for all components of the desalination infrastructure including water transportation and storage. Fig. 18 (b) accounts for the components of the energy system installed during the transition. Because of the improved irrigation systems, the total desalination and system capex by 2050, in the HPIE scenario, is 80% and 70% less than the Base and IEP scenarios respectively. Table 4 provides an overview of the total investments required and the annualised costs by the years 2030 and 2050 of the energy transition in the desalination sector.

5. Discussion

The World Bank's [3] study on Pakistan's water sector clearly highlights that Pakistan cannot continue in a business as usual scenario if the country wants to ensure economic growth and improved livelihoods for the population. Despite being endowed with local water resources and glacial water storage, Pakistan is reported to be one of the top ten, most water stressed, countries in the world. The study conservatively estimates that Pakistan loses 12 bUSD per year, or 4% of the country's GDP, due to water related issues such as deficient water supply, droughts and floods. The report recommends several initiatives to help Pakistan ensure water security. Seawater desalination together with improved irrigation systems, better groundwater recharged systems and water recycling are presented as means to augment the local water supply. The main reasons against using desalination in Pakistan are the high energy demand of and capital investments required for such water facilities.

In this research, the relationship between RE-based seawater desalination and improved irrigation systems is evaluated for the case of Pakistan. First, the impacts of increasing the country's water productivity through better irrigation systems and the subsequent impacts on the water stress, total water and desalination demand are assessed. In the Base scenario, where there is no projected increase in the irrigation efficiency, the total water demand and desalination demand are estimated to be 11,600 million m^3/day and 6460 million m^3/day. As described in Caldera et al. [22] the desalination demand is calculated as a function of water stress and total water demand. Reports by the Action on Climate Today [46] and the

(a)

(b)

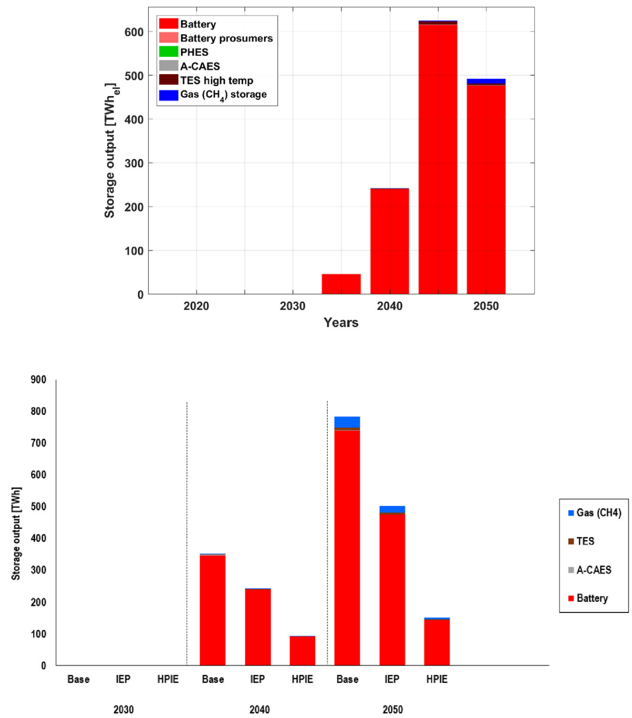


Fig. 15. Storage output in the IEP scenario (a), comparison of storage output in the Base, IEP and HPIE scenarios (b).

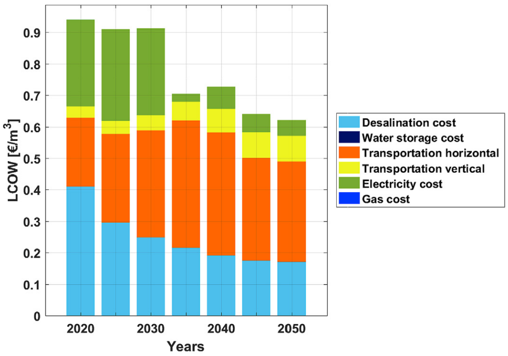
World Bank [3] explain that Pakistan will not have enough local water resources to meet the country's demand in 2047.

The results of this research show that in the most optimistic HPIE scenario, where the irrigation efficiency is increased to 90% by 2050, Pakistan's total water demand can be reduced by 54% relative to the total water demand in the Base scenario. In the moderate IEP scenario, where the irrigation efficiency increases at a maximum annual rate of 1% and minimum annual rate of 0.3%, the total water demand decreases by 21% relative to the corresponding value in the Base scenario. The FAO [7] estimated Pakistan's total annual renewable water resources to be 246 billion m^3. Based on the results, only in the HPIE scenario, with an irrigation efficiency of 90%, can Pakistan ensure that the total water demand does not exceed the country's annual renewable water resource. In the HPIE scenario, the 2050 annual water demand is approximately 197 billion m^3, whilst in the Base and IEP scenarios, the water demands are 427 and 338 respectively by 2050. The IEP scenario does not show a drastic change in the water demand due to the relatively lower improvements in irrigation efficiency. This can be observed in Fig. 5 where the maximum beneficial irrigation efficiency increases from 50%, in 2030, to 60% in 2050 in the Indus Basin. In contrast, in the HPIE scenario, all regions are expected to achieve an irrigation efficiency of 90%.

The overall change in the demand for desalination was more significant across the scenarios compared to the change in the total water demand. In the HPIE scenario, the total desalination demand in 2050 decreased by 82% relative to the corresponding value in the Base scenario. Meanwhile, in the IEP scenario, the corresponding decrease was 36%. The sharp decrease in desalination demand highlights the fact that the desalination demand in Pakistan is driven by the irrigation sector which lies in water stressed regions. Across all three scenarios, the largest desalination demand was found for the Sindh, Punjab and Baluchistan regions. However, due to the high concentration of irrigation sites in Sindh and Punjab, the total desalination demand shares of these regions decreased in the HPIE scenario relative to the Base scenario. Sindh and Punjab regions accounted for 60% of the desalination demand in 2050 in the Base scenario, but decreased to 50% in the HPIE scenario.

According to the GWI Desal database [15], 80% of Pakistan's desalination plant output, estimated to be 150,530 m^3/day, is used for industrial purposes. Only 10% is used to meet the municipal water needs, with the largest desalination plant for municipal purposes located in Karachi, in the Sindh region. However, according to the World Bank [3], the largest increase in future water demand is expected to come from both the municipal and industrial sectors. Desalinated water is not used for the irrigation sector due to the higher perceived costs of the potable water. In addition, water for irrigation requires further post-treatment to ensure that the minerals, such as boron or magnesium, are at levels that are suitable for the irrigation of the crops. Burn et al. [47] explain that farmers in Australia currently are not willing to pay more than 0.68 €/m^3 for irrigation water. In Spain, where at least 12% of the

(a)



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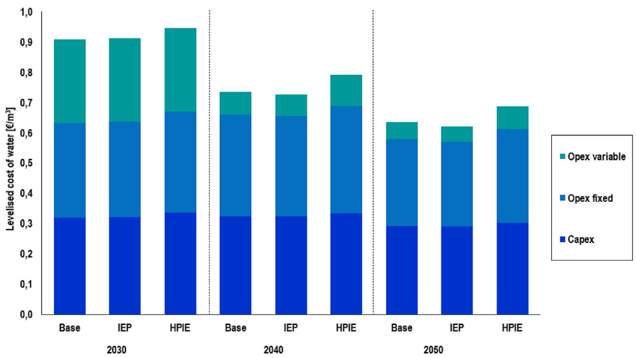


Fig. 16. Levelised cost of water (LCOW) during the energy transition for Pakistan in the IEP scenario and the components that make up the LCOW (a), comparison of the LCOW for the years 2030, 2040 and 2050 in the Base, IEP and HPIE scenarios.

desalination plants are used to supply irrigation water [15], water costs less than 0.3 €/m^3 allow all types of crops to be grown with profit [48]. Meanwhile, water costs greater than 0.6 €/m^3 are considered to be feasible for greenhouse grown crops. As such, desalinated seawater is reported to be used mainly for high value crops such as vegetables, fruits and flowers. According to Burn et al. [47], the use of desalinated water resulted in an increase in yield of fruits such as banana and oranges in Spain. At present, the resource is not used for the irrigation of rice, cotton or sugar [47]. The FAO (no date) reports that in most countries, except in the wealthier OECD countries, the full costs of supplying water to the irrigation sector is never recovered. In Pakistan, farmers are estimated to pay about 0.013 USD/m^3 for their irrigation water [49] (FAO, no date). However, as the cost of using conventional water resources increase due to factors such as diminishing surface water and groundwater resources, seawater intrusion and pollution, seawater desalination becomes an attractive option for farmers [50]. Villar-Navascues et al. [48] explain this to be the case in Spain, where farmers use desalinated water to overcome the supply deficit from water transfer projects. Similarly, the ACT (2015) report explains that in Pakistan, for some water stressed regions, water is brought in by trucks at much higher costs. Turner et al. [51] model the adaptation of the global agricultural sector throughout this century as non-renewable groundwater resources are constrained. The results show that by mid-century, wheat production in Pakistan will cease and instead move to places with more abundant non-renewable groundwater resources like China and the Arabian Peninsula. The results show that ultimately agricultural production will keep shifting to places with cheap and abundant groundwater resources until all resources are depleted.

In this research it is shown that by 2050, a 100% RE-based seawater desalination sector will enable water security to all sectors of Pakistan at a LCOW of approximately 0.68 €/m^3. This cost includes the cost of water transportation and is similar across all scenarios, as shown in Fig. 16. In fact, water transportation can contribute up to 50% of the final cost of desalinated water in

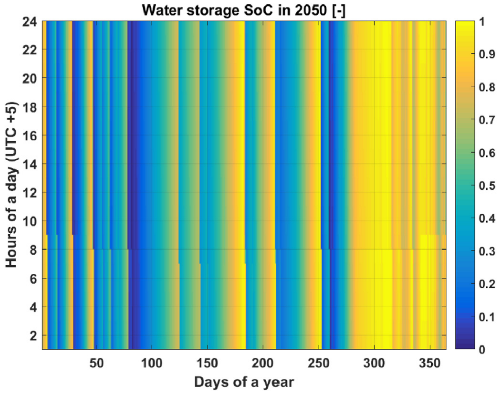


Fig. 17. Water storage state of charge (SoC) in the IEP scenario for 2050. The total water storage capacity in 2050 is 4.0 million m^3.

Pakistan. The reduction in the LCOW is driven by the decreasing cost of SWRO plants and the cost of electricity generation. The capital cost of SWRO plants is projected to decrease at a learning rate of 15% [25], and is estimated to be 415 €/(m^3/day) by 2050. In addition, due to the energy transition, the average LCOE for Pakistan drops to 40 €/MWh by 2050, from 80 €/MWh in 2020. Solar PV and battery storage are the main drivers of the decrease in electricity costs during the energy transition. By 2050, in the IEP scenario, the total installed solar PV capacity required is 467 GW, while supplying 99% of the total electricity generation. The capex of single-axis tracking PV and fixed-tilted PV are assumed to be 183 €/kW and 166 €/kW by 2050, based on the respective learning rates [24,52]. In the Base scenario, by 2050, a total of 736 GW of solar PV is required. In contrast, in the HPIE scenario, a total of 126 GW of solar PV is required due to the lower desalination demand and thus, energy demand. Battery storage supplements the operation of the solar PV plants and meets 60% of the total electricity supply. Afanasyeva et al. [53] validated the yield output of the LUT model with the software PVsyst for several locations with different climatic conditions. The maximum deviation between the calculated yields for single-axis tracking PV was found to be 4% highlighting the accuracy of the yield calculation of the LUT model on a global scale. For the duration of the transition, the PV plant yield is calculated in the LUT model using an 85% performance ratio. However, PV module degradation that may occur over time will slightly reduce the average annual yield and thus slightly increase the cost within a 5%−10% error bar, while the initial yield may be higher using best equipment. The low cost electricity generated through the combination of solar PV and battery storage enables the continual operation of the SWRO plants, ensuring lower water production costs by 2050. Water storage is found to account for less than 1% of the total desalination demand in 2050 and is not used to enhance the flexibility of the system. This is due to the fact that desalination plants are still more capital intensive than solar PV and battery storage. Therefore, the low-cost option is to run the SWRO plants at higher full load hours and using battery storage to provide flexibility in the system as described in Caldera and Breyer [54]. In contrast, in systems where energy storage is not considered, SWRO desalination systems behave in a flexible load and allow for the integration of increased shares of renewable energy. This aspect has been discussed by Novosel et al. [55] for the case of Jordan, while for the same case country Azzuni et al. [56] have found high full load hours for SWRO plants with enabled flexibility of battery storage.

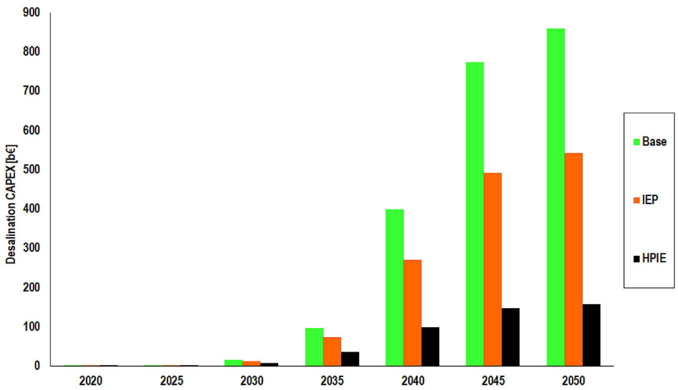
The results show that regardless of the water demand management option chosen for the irrigation sector, RE-based seawater desalination can be used to secure Pakistan's water supplies. However, by implementing water demand management strategies in the irrigation sector, Pakistan can ensure a more sustainable and cost efficient water strategy as shown in Fig. 16 and Table 4. The annualised costs in the IEP scenario and HPIE scenario, by 2050, are 40% and 80% relative to the Base scenario, respectively.

Razzaq et al. [32] advocate for the increased role of high efficiency irrigation systems in Pakistan due to the increasing depletion and contamination of groundwater resources that meet 60% of the country's agricultural demand. According to Razzaq et al. [32], the main reason that farmers in Pakistan are reluctant to adopt drip irrigation systems are the high capital investments and they are unaware of the benefits of much higher yield, lower fertilizer requirement and water savings potential. The World Bank report on the utilisation of Pakistan's water resources, highlights the need to improve water productivity, measured in USD/m^3, of the irrigation infrastructure to ensure economic gains. The direct gains to the economy from irrigation are estimated to be at 22 bUSD per year, but the sector's contribution to the country's GDP is decreasing whilst accounting for the largest share of the country's water withdrawals. With deciding factors such as arable land area cropped and groundwater almost fully used, increasing water use efficiency is vital to sustain Pakistan's irrigation sector. Furthermore, in order to ensure food security within the country, Pakistan has to increase grain production by more than 5 million tonnes per year relative to current production rates. This will require a seismic shift in the way water is managed within the sector. By investing in improved irrigation systems in the country and securing water supply, Pakistan can both secure its own food security and boost its economy [3]. In the next phase of the research, the cost of upgrading to high efficiency irrigation systems in Pakistan can also be incorporated. This will allow to determine the costs of the RE-based water supply and improved irrigation infrastructure for the country. In addition, the water that may be recovered from the basin, when surface irrigation systems are used, must also be accounted for to verify the efficiency of the irrigation system.

The transition to a RE-based energy system will also allow Pakistan to overcome the water withdrawals currently required to cool the fossil-based and nuclear power plants in the country. According to Lohrmann et al. [57], Pakistan's power plants withdrew 2.7×10^8 m^3 of freshwater in 2015. However, after the country transitions to a 100% RE-based system by 2050, the total water withdrawals for the power sector was found to be reduced by 95%. Thus, the energy system transition will further enable Pakistan to better manage existing renewable water resources.

Several studies on the energy transition pathways for neighbouring countries facing water shortage issues such as Iran [58], Jordan [56] and Saudi Arabia [59] further support the results observed in Pakistan. In these countries with abundant solar resources and high desalination demand, the declining costs of solar PV, battery storage and SWRO plants enable the continuous reduction of desalinated water costs. Shahzad et al. [60] discuss the ongoing research into hybridisation of desalination technologies that can increase performance, reliability and recovery. For instance, a RO and thermal base multi-evaporator adsorption system is modelled to drive down the total electricity consumption to 1.76 kWh/m^3 while increasing brine recovery to 80%. These developments may help drive down the cost of water production even further.

(a)



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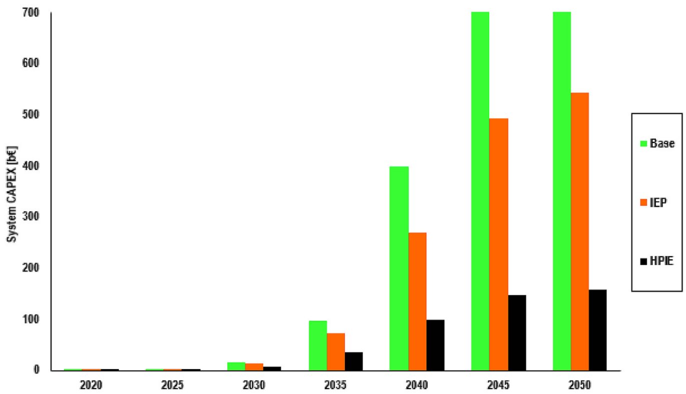

Fig. 18. Desalination capex comparison for the Base, IEP and HPIE scenarios (a), system capex comparison for the Base, IEP and HPIE scenarios (b).

Table 4
Comparison of the total capex (system and desalination) and annualised costs for the Base, IEP and HPIE scenarios.

	2030	2050
Total Capex	b€	b€
Base	28	1557
IEP	23	988
HPIE	14	286
Annualised Costs	b€	b€
Base	5	190
IEP	4	119
HPIE	2.5	36

The results of this research illustrate the water saving potential, subsequent impacts on water stress and desalination demand projections if Pakistan switches to high irrigation efficiency systems. In addition, the results demonstrate how Pakistan can ensure that the desalination demand of the country, for three scenarios with different irrigation water management strategies, can be powered by 100% renewables by 2050. The results provide insights into how the policies outlined in the national water policy [27] may in fact be implemented to the benefit of the country.

6. Conclusion

Seawater desalination has been mentioned as an option to augment Pakistan's water supply. However, the high costs, energy consumption and generation of greenhouse gas emissions, has thwarted the uptake of desalination in the country. Meanwhile, the country's overall irrigation efficiency is estimated to be at 30% and thereby driving the high water withdrawals of the sector. Several researchers have already recommended the upgrade of these older systems to higher efficiency sprinkler or drip irrigation systems.

In this research, the water savings potential of upgrading the current irrigation infrastructure to sprinkler or drip irrigation systems, across three scenarios was analysed. It was observed that increasing the country's overall irrigation efficiency to 90% by 2050, results in an 54% and 80% reduction in total water and desalination demand, respective to a business as usual scenario. However, in a more moderate scenario, where the maximum increase in irrigation efficiency is 1% per year, the 2050 total water and desalination demand are reduced by 21% and 40% respectively.

For all three scenarios, the energy transition pathway was modelled to determine how Pakistan could ensure that the country's desalination sector was powered by 100% RE by 2050. Solar PV and battery storage are the key drivers of the energy transition of the SWRO desalination sector. This is because of the low costs of these energy technologies and the fact that water stressed regions are usually places with plentiful solar resources. The final 2050 LCOE for Pakistan, in all three scenarios, was about 40 €/MWh. The corresponding 2050 LCOW was 0.6 €/m^3 and includes the cost of water transportation. This is still higher than the subsidised costs some farmers pay for irrigation water. However, literature still supports this to be an affordable cost of water for irrigation, particularly considering that conventional water resources are diminishing, and the corresponding production costs are increasing.

This research illustrates how Pakistan can assuage the country's growing water crisis by investing in improved irrigation systems and tapping into the abundant low-cost electricity generation potential of solar PV in the country. In conjunction with the rapidly decreasing costs of battery storage, SWRO desalination plants can be operated to ensure that potable water is provided at affordable costs to all sectors in Pakistan.

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

Table A.1
Technical and financial parameters of the seawater desalination technologies from 2020 to 2050 [26].

			2020	2025	2030	2035	2040	2045	2050
Sea Water Reverse Osmosis	Capex	€/(m^3·day)	960	835	725	630	550	480	415
	Opex fix	€/(m^3·day)	38	33	29	25	22	19	17
	Energy consumption	kWh/m^3	3.6	3.35	3.15	3	2.85	2.7	2.6
	Lifetime	years	25	30	30	30	30	30	30
Multi Effect Distillation – Thermal Vapor Compression	Capex	€/(m^3·day)	1200	1043	906	787	687	600	519
for stand alone	Opex fix	€/(m^3·day)	13.2	15.6	18	21.6	24	24	24
	Thermal energy consumption	kWh_{th}/m^3	51	44	38	32	28	28	28
	Electrical energy consumption	kWh_{el}/m^3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Lifetime	years	25	25	25	25	25	25	25
Multi Effect Distillation – Thermal Vapor Compression	Capex	€/(m^3·day)	1437	1437	1437	1437	1437	1437	1437
for cogeneration	Opex fix	€/(m^3·day)	47.4	47.4	47.4	47.4	47.4	47.4	47.4
	Thermal energy consumption (Total gas input required for water and electricity)	kWh_{th}/m^3	168	168	168	168	168	168	168
	Electrical energy consumption	kWh_{el}/m^3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Lifetime	years	25	25	25	25	25	25	25
Multi Stage Flash	Capex	€/(m^3·day)	2000	2000	2000	2000	2000	2000	2000
for cogeneration	Opex fix	€/(m^3·day)	100	100	100	100	100	100	100
Gain Output Ratio: 8 Power-to-Water: 2.25 kW/(m^3·day)	Thermal energy consumption (Total gas input required for water and electricity)	kWh_{th}/m^3	202.5	202.5	202.5	202.5	202.5	202.5	202.5
	Electrical energy consumption	kWh_{el}/m^3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Lifetime	years	25	25	25	25	25	25	25
Multi Stage Flash	Capex	€/(m^3·day)	2000	2000	2000	2000	2000	2000	2000
for stand alone	Opex fix	€/(m^3·day)	100	100	100	100	100	100	100
Gain Output Ratio: 8	Thermal energy consumption	kWh_{th}/m^3	85	85	85	85	85	85	85
	Electrical energy consumption	kWh_{el}/m^3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Lifetime	years	25	25	25	25	25	25	25
Piping	Capex	€/(m^3·a·km)	0.053	0.053	0.053	0.053	0.053	0.053	0.053
	Fixed Opex	€/(m^3·a·100 km)	0.023	0.023	0.023	0.023	0.023	0.023	0.023

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			2020	2025	2030	2035	2040	2045	2050
	Lifetime	years	30	30	30	30	30	30	30
Vertical Pumping	Capex	€/(m^3 · h · m)	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	Fixed Opex	€/(m^3 · h · m)	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Energy consumption	kWh/(m^3 · h · 100 m)	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	Lifetime	years	30	30	30	30	30	30	30
Horizontal Pumping	Capex	€/(m^3 · h · km)	19.26	19.26	19.26	19.26	19.26	19.26	19.26
	Fixed Opex	€/(m^3 · h · km)	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Energy consumption	kWh/(m^3 · h · 100 km)	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Lifetime	years	30	30	30	30	30	30	30
Water Storage	Capex	€/m^3	65	65	65	65	65	65	65
	Fixed Opex	€/m^3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	Lifetime	years	30	30	30	30	30	30	30

Table A.2
Technical and Financial Assumptions of key energy system components used in the energy transition from 2020 to 2050 [39].

Name of component			2020	2025	2030	2035	2040	2045	2050
PV optimally tilted	Capex	€/kWp	432	336	278	237	207	184	166
	Opex fix	€/(kWp a)	7.76	6.51	5.66	5	4.47	4.04	3.7
	Opex var	€/(kWh)	0	0	0	0	0	0	0
	Lifetime	years	30	35	35	35	40	40	40
PV single-axis tracking	Capex	€/kWp	475	370	306	261	228	202	183
	Opex fix	€/(kWp a)	8.54	7.16	6.23	5.5	4.92	4.44	4.07
	Opex var	€/(kWh)	0	0	0	0	0	0	0
	Lifetime	years	30	35	35	35	40	40	40
Wind onshore	Capex	€/kW	1150	1060	1000	965	940	915	900
	Opex fix	€/(kW a)	23	21.2	20	19.3	18.8	18.3	18
	Opex var	€/(kWh)	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	25	25	25	25
Water electrolysis	Capex	€/kW	685	500	363	325	296	267	248
	Opex fix	€/(kW a)	27	20	12.7	11.4	10.4	9.4	8.7
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
	Lifetime	years	30	30	30	30	30	30	30
Methanation	Capex	€/kW	421	310	278	247	226	204	190
	Opex fix	€/(kW a)	16.8	12.4	11.1	9.9	9.0	8.2	7.6
	Opex var	€/(kWh)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
	Lifetime	years	30	30	30	30	30	30	30
CO_2 direct air capture	Capex	€/kW	411	301	228	201	183	165	154
	Opex fix	€/(kW a)	16.4	12.0	9.1	8.0	7.3	6.6	6.1
	Opex var	€/(kWh)	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	Lifetime	years	30	30	30	30	30	30	30
CCGT	Capex	€/(kW_{el})	775	775	775	775	775	775	775
	Opex fix	€/(kW_{el} a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4
	Opex var	€/(kWh)	0	0	0	0	0	0	0
	Efficiency	%	58	58	58	59	60	60	60
	Lifetime	years	35	35	35	35	35	35	35
OCGT	Capex	€/(kW_{el})	475	475	475	475	475	475	475
	Opex fix	€/(kW_{el} a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25
	Opex var	€/(kWh)	0	0	0	0	0	0	0
	Efficiency	%	43	43	43	43	43	43	43
	Lifetime	years	35	35	35	35	35	35	35
Battery. Li-ion	Capex	€/(kWh_{el})	234	153	110	89	76	68	61
	Opex fix	€/(kWh_{el} a)	3.28	2.6	2.2	2.05	1.9	1.77	1.71
	Opex var	€/($kWh_{throughput}$)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	Efficiency	%	94	95	96	97	99	99	99
	Lifetime	years	20	20	20	20	20	20	20
Thermal Energy Storage (TES)	Capex	€/(kWh_{th})	40	30	30	20	20	20	20
	Opex fix	€/(kWh_{th} a)	0.6	0.45	0.45	0.3	0.3	0.3	0.3
	Opex var	€/($kWh_{throughput}$)	0	0	0	0	0	0	0
	Lifetime	years	25	25	25	30	30	30	30
Gas storage	Capex	€/kWh_{th}	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Opex var	€/(kWh)	0	0	0	0	0	0	0
	Lifetime	years	50	50	50	50	50	50	50

Table A.3
Natural Gas and CO_2 cost projections [38].

		2020	2025	2030	2035	2040	2045	2050
Natural Gas	€/MWh_{th}	22.2	30	32.7	36.1	40.2	40.2	40.2
CO_2	€/tCO2	28	52	61	68	75	100	150

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Gender vulnerabilities in low carbon energy transitions: a conceptual review

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Abstract

Low carbon energy transitions are of paramount importance to achieve climate goals. These transitions are not only technical and economical, but also deeply social and gendered. In this paper, we reviewed the academic literature to understand: firstly, what gender vulnerabilities have been discussed in the literature and how they have been embedded in structural dynamics. Secondly, what socio-cultural and socio-economic drivers may lead to these gendered vulnerabilities? Based on content analysis, four key themes emerged from this literature survey: *land use change, gender-neutral energy policies, access to resources*, and *green practices, gender, and culture*. These four themes indicate that there are several enabling mechanisms arising from social and structural inequalities, indicative that vulnerabilities ought not to be considered in isolation, but in relationship with others. We also explored dimensions of vulnerability (exposure, sensitivity, adaptative capacity) based on Carley *et al* (2018 *Nat. Energy* **3** 621–7) to contextualise components of vulnerability in relation to gender. The main finding suggests considering further intersectional approaches to low carbon energy transitions, emphasising acknowledging, and lessening societal inequalities.

1. Introduction

Low carbon energy transitions are an essential aspect of carbon mitigation commitments, as noted in the Paris Agreement and supported by the Sustainable Development Goals (especially SDG 5 and 7) (Nick 2003). These low carbon energy transitions could risk marginalising those whose livelihoods and lands are compromised—making it crucial to identify and explore risk factors to alleviate potential vulnerabilities in order to achieve a just energy transition (Sovacool 2021, Tsagkari 2022). Until recently, energy transitions research has expanded into multiple contemporary dimensions, such as techno-economic feasibility (Das *et al* 2018, Bhat *et al* 2019), integration of low carbon technologies (Raven *et al* 2016), developing value chains and business models (Richter 2012), yet neglecting dimensions such as gender and social inequalities (Farla *et al* 2012, Geels *et al* 2017, Chlebna and Mattes 2019). It is therefore necessary to establish which economic sectors, socio-demographic groups, and regions may be most at risk for marginalising vulnerable communities and individuals (Williams and Doyon 2019). More recent low carbon energy transitions literature has begun to consider gender vulnerabilities as a part of their research, indicating that in the past decade academics and practitioners have begun to seriously consider energy transitions as inherently gendered (Fernández-Baldor *et al* 2014, Fernández-Baldor *et al* 2015, Lazoroska *et al* 2021, Tsagkari 2022). This paper draws on recent literature on low carbon energy transitions to identify the gender vulnerabilities that could emerge or are already emerging during the energy transition process.

Most low carbon energy transition (LCET) literature is focused on technological and economic feasibility of energy projects, with gender only recently becoming a category of analysis (Johnson *et al* 2020). However, the literature is now considering how LCETs impact infrastructures, such as biomass plants and the building of new hydropower plants. Especially in the Global South, local landscapes change to accommodate large-scale energy projects, engendering social inequalities and women's access to resources. Scholars generally overlook gender dimensions in local case studies of new energy systems concerning electricity generation and land-use for transportation biofuels, which exposes new and existing vulnerabilities (Sovacool *et al* 2015, Lieu *et al* 2020). Policy and social inequality studies conclude that there is a noticeable lack of gender representation in the workforce and decision-making concerning low carbon energy projects development and implementation (Boyd 2002, Lieu *et al* 2020, Mang-Benza 2021). Our analysis therefore focuses on considering the potential future of LCETs and its effects on gender vulnerabilities from a system-level perspective. System change is the emergence of new patterns of organisational and system structures (UNDP 2022). We acknowledge the relevance of climate change studies to discerning present-day vulnerabilities (Terry 2009, Djoudi *et al* 2016) and the complex linkages between energy and gender (IRENA 2019, Pueyo and Maestre 2019, Feenstra 2021). This content analysis is concerned with identifying vulnerabilities from when a future transition occurs and what types of gendered vulnerabilities may be revealed from these transitions. Despite the rising amounts of gender analysis in energy, climate change, and energy transitions studies (Pearl-Martinez and Stephens 2016, Clancy and Feenstra 2019), literature on gender and low carbon energy transitions relating to electricity generation, biofuel production, and green policies are currently gaining more scholarly attention, making it a fruitful point of analysis (Johnson *et al* 2020).

In this study, we examine how gender vulnerabilities are analysed in low carbon energy transition literature. An initial 8155 articles were identified, after removing non-peer reviewed articles and initial screening of titles and abstract, articles were selected for the detailed review. We found no papers exist which review literature on gender vulnerabilities and low carbon energy transitions. As stated by (Fernández-Baldor *et al* 2015, Hill *et al* 2017, Ahlborg 2017), there is little emphasis on the formal gender assessment and inclusion of gender-based analysis of how low carbon energy projects and solutions might consider existing injustices and how such vulnerabilities manifest into future potential risks. Our review argues that there is a need to conduct gender-based analysis alongside environmental and social assessments when low carbon energy projects are planned and implemented.

The article is structured in the following manner: section 2 provides definitions for the terminology used throughout the review, section 3 discusses the methodology used to review the literature and research objectives. Section 4 discusses the gendered vulnerabilities observed in literature and their future implications for gender in low carbon energy transitions. Section 5 concludes the review with potential future directions of further studies.

2. Definitions

This conceptual literature review aligns itself with theories on gender and vulnerability, utilising definitions of *vulnerability* and *gender* found in gender and climate change studies. In the sections below, we define the terminology present throughout the review.

2.1. Vulnerability

Vulnerability as a term has numerous definitions dependent upon disciplinary context (Brooks 2003). Within climate change studies, it is used to describe and define different groups negatively impacted by environmental degradation (Brooks 2003). This study utilises the definition of vulnerability according to the Intergovernmental Panel on Climate Change (IPCC). It defines vulnerability as 'the propensity or predisposition to be adversely affected' which 'encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' (Field *et al* 2014). We utilise Carley *et al*'s (2018) vulnerability assessment framework to assess low carbon energy transition vulnerabilities in relation to gender. They (Carley *et al* 2018) define vulnerability in relation to policy exposure, in this case the IPCC, as 'where and when these policies go into effect (*exposure*); the susceptibility of different communities to the impacts of these policies (*sensitivity*); and the capability of communities to attenuate, cope with or mitigate the negative effects (*adaptive capacity*)'. As the literature surveyed in this paper is not solely based on policies, we expand this definition to include case studies.

2.2. Gender

By *gender* we imply socially constructed differences that translate into inequalities and hierarchies traditionally performed by women and men, whilst acknowledging that gender is a multifaceted and complex term (Johnson *et al* 2019). More recent conceptualizations in the scientific literature fundamentally integrate the wider notion of social equity, which captures the intersectional nature of gender (Stienstra *et al* 2016, Robinson 2019). In our article, we consider the term 'gender vulnerabilities' as encompassing the IPCC definition of vulnerability with an additional emphasis on gender.

2.3. Gender vulnerability

Enarson (2012) argues that 'as a primary factor of social organisation, gender shapes the social worlds within which disaster occur', making gender a vital category of analysis also in low carbon energy transitions. In climate change literature, it is well understood that adverse impacts of climate change disproportionally affect different genders according to their respective vulnerability and adaptive capacity (Freedman 2019). Hence, gender vulnerability is understood as 'the characteristics of a women and men and their situation influencing their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard' (Reid *et al* 2012, McGann *et al* 2016). Climate change is inherently related to disaster risks and risk assessment, as disasters reflect the social divisions which already exist in society. Low carbon energy transitions, which will be impacted by continued and worsened climate change, will need to ensure that the social divisions already existing are not worsened.

3. Literature review methodology

Content analysis is a research method used to identify patterns, themes, and trends in the content and to make inferences by systematically identifying the attributes of the content (Neuendorf 2016, Fell 2017). This method involves coding and categorizing the content, and then using statistical techniques to analyse the results by paying attention to objectivity, reliability, and replicability. (Fell 2017) provides an example by applying it in context of energy services. The sub-sections further provide the details on literature collection for this study, inclusion and exclusion criteria, and some quantitative details of the content.

3.1. Research objectives and search strategy

We conducted a conceptual review that seeks to synthesise the scientific knowledge that can help us better comprehend the essential concepts and arguments. Our research objectives are two-fold: first, how do different articles discuss gender vulnerabilities and, secondly, what types of evidence is utilised to identify gender vulnerabilities related to low-carbon energy transitions. To fulfil these objectives, a search of the literature was conducted in July and in October 2021 using the Scopus database. We also performed searches in December 2022 on Scopus for the years 2021–22 with the same search string. We developed a search string with 'OR' and 'AND' operators. The search string was the combination of the terms (1) low carbon energy transitions (2) gender and (3) vulnerabilities. We aimed for specificity in our searches, aiming to exclude terms not relevant for our focus. For example, we combined 'solar' with 'power', 'photovoltaics', 'PV', 'concentrated' (as in concentrated solar power), 'home system', and 'industry'; to ensure that our searches do not include the related topics outside our research scope. Moreover, we added different qualifiers—such as 'group', 'people,' and 'community', to make our search more inclusive around gender equity issues. Further searches were performed with Scopus were limited to the English-language literature. Table 1 shows the search strings used for the literature review. Additional searches were undertaken to include the terms that were not included in initial search. These terms include green practices, energy justice, injustices, and inequalities.

3.2. Initial screening and eligibility criteria

All the articles gathered in the systemic search were screened for eligibility with title and abstracts, and finally the full text was screened with predefined eligibility criteria (section 3.2.1). The screening was done by the researcher and no software was used. Articles screened on title and abstract are listed in additional file 1. Gender vulnerabilities related to low carbon energy technologies were considered in terms of their influence on education, health, employment, poverty, social and economic class, poverty land ownership, access to resources and markets, which consist of all the major dimensions found in the article screening process.

To analyse the articles selected for review after full text screening, basic information was extracted from each article and put into a coding framework. We utilised content analysis to quantitatively categorize the articles to understand which themes were most frequently occurring. Structured analysis approach was undertaken because we wanted to search for topics which were not the main themes of the papers. Characteristic details of the papers, geographical location, type of energy technology/source or policy and type of impact were assembled in an excel sheet (additional file 2). Figure 1 shows the screening and selection process of articles found in searches. Initially, there were 8155 articles after the searches. After the exclusion of non-peer reviewed and non-English articles, 5401 articles were left. After an initial screening of titles, keywords and abstract, 147 (additional file 1) articles were shortlisted for detailed full-text screening. After full-text screening 65 (additional file 2) articles were selected for review. Articles were shortlisted based on predefined criteria (section 2.2).

3.2.1. Inclusion and exclusion criteria

During the screening of the papers, we used the following exclusion and inclusion criteria to decide which papers fit our search criteria (see figure 1).

Inclusion criteria: (1) Studies of use/adaptation/management of low carbon energy transitions; (2) topics which had an explicit link to gender, vulnerabilities, and new energy systems; (3) only peer-reviewed literature was selected. (4) No restriction regarding country, area, and date of publication.

Exclusion criteria: (1) We filtered out the studies whose primary and/or secondary focus was not

Table 1. Search string.

Database	Date	Search strings
Scopus (title, keywords, abstract) (advance document search option was used)	July and October 2021	(((“sustainable energy” OR “low carbon” OR renewable*)) AND ((development OR energy OR power OR electricity OR generation OR industry)) OR ((solar* AND (power OR photovoltaics OR pv OR concentrated OR “home system*” OR industry))) OR ((wind* AND (power OR electricity OR turbine* OR industry))) OR ((geothermal AND (power OR electricity OR industry))) OR (hydropower*) OR ((biomass AND energy) OR bioenergy OR biofuel* OR agrofuel* OR “mini grid*”) OR ((geothermal AND (power OR electricity OR industry)))) AND ((transit* OR transform* OR change* OR shift* OR pathway* OR polic* OR strateg*)) AND ((“social impact*” OR “social outcome*” OR “socioeconomic* OR vulnerability”)) AND ((gender* OR women* OR men OR girl* OR boy*))
Additional searches Scopus (title, keyword, abstract)		(Gender AND just AND energy AND transitions) (Gender AND renewable AND energy inequalities) (Gender AND low AND carbon AND energy AND energy AND justice AND vulnerab*) (Gender AND vulnerab* AND low AND carbon AND transitions)

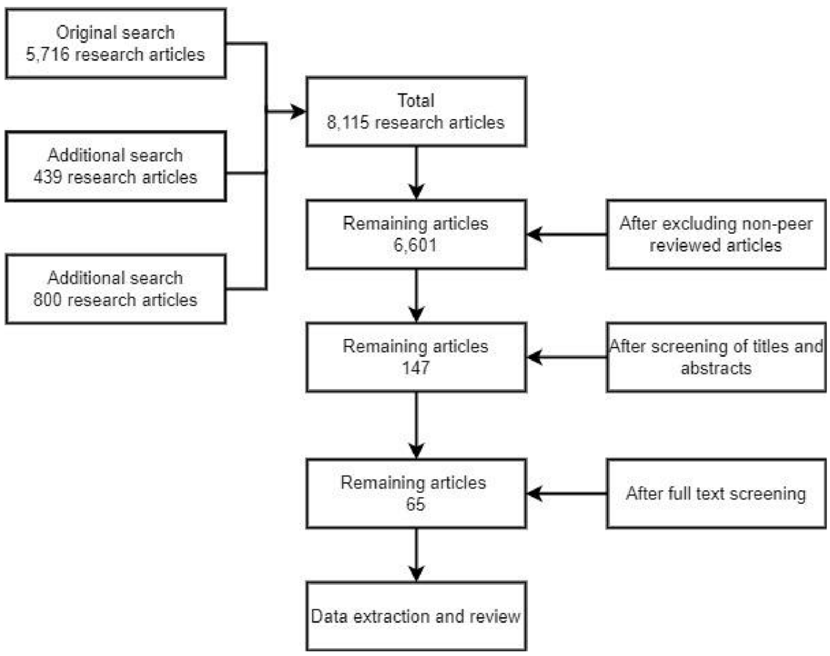

Figure 1. Flow chart diagram of process of articles shortlisting.

the relation between gender and low carbon energy transitions; (2) gendered and non-gendered positive impacts of technology implementation were not analysed as review is focused on vulnerabilities of low carbon transitions; (3) hypothetical studies (computer simulations and modelling studies) and literature reviews were not included as the review is focusing on current and future large-scale energy projects and policies. Focus of this study is to map gendered vulnerabilities emerging from development of structure of low carbon transitions that lacks in modelling studies; (4) studies on the willingness and attitude towards low carbon energy transitions were excluded as they are tangential to system-level studies; (5) studies focusing on technical performance were not included. (6) Non-English-language publications were excluded.

Figure 1 shows the screening process and the numbers of articles at every stage of screening. It should be noted that only 0.8% of the total articles were selected for the full-text review. Papers related to climate change, ecosystem management, and health and food safety appeared in the search terms in large quantities because of their close connection with low-carbon transition themes. Cooking was also a prominent theme, found in 7% of articles surveyed, indicating that this is an important research area in gender and energy research. These papers were excluded from review since they did not focus on vulnerabilities pertaining to LCETs on a system level. Non-peer reviewer literature contains books, book chapters, editorials, letters, conference papers. This literature was mostly related to climate change, environmental sustainability, environmental management, environmental justice, livelihood, and poverty.

3.3. Limitations

It is important to acknowledge the limitations of the approach adopted in this review. Although it was anticipated that the search sample would include a wide range of energy studies, it is not claimed to be representative. Additionally, since all of the searching and screening was done by the first author, it is possible that certain cases were overlooked that another researcher would have identified or interpreted differently. However, given that the shortlisting and screening process in this instance consisted mostly of recording individual words and phrases, very little subjective interpretation was necessary, and it is therefore unlikely that this factor had a significant impact on the conclusions drawn.

Furthermore, it is probable that some works that engage profoundly with the idea of gender vulnerabilities (for example, cookstoves technologies) been excluded from this study since the search terms are more focused on the electricity and systematic level change. We acknowledge that the gender aspects of the clean cooking technologies are so profound and already been studied at an extensive level (Kshirsagar and Kalamkar 2014, Urmee and Gyamfi 2014). Other limitations of this review is the exclusion of grey literature and multiple databases (Dave Singh *et al* 2021). There are several publications on gender and low-carbon transitions in the grey literature, such as reports from non-governmental and international organizations, policy briefs, and position papers from governments. The majority of this work reflects normative methods to gender mainstreaming in energy policy from non-governmental organizations (NGOs) and financial bodies. To be able to critically evaluate and synthesize the main concepts and arguments in examined literature, however, we decided to focus for this review on peer-reviewed academic papers.

4. Results

4.1. Countries and areas

The 65 articles analyse 118 case studies in 48 different countries. In some articles (Behrman *et al* 2012, Terrapon-Pfaff *et al* 2018), there was no mention of a particular country but the geographical areas, so it was not possible to geographically represent these articles with the country scale representation. The majority of the studies analysed the Asian region (15 articles; Terrapon-Pfaff *et al* 2014, Dharmawan *et al* 2020), Africa (15 articles) and North America (13 articles; Winther *et al* 2017, Sovacool *et al* 2020) while 13 articles are related to countries from Global North (Chalifour 2010, Lieu *et al* 2020). Almost all the case studies analysed rural areas with few exceptions (see for example, (Axon and Morrissey 2020, Lieu *et al* 2020, Lazoroska *et al* 2021)).

4.1.1. Energy sources frequency

Figure 2(a) shows the percentage of studies that discussed various LCETs within the literature. Solar energy technologies (PV, thermal, lighting, cooking, and heating) received the most attention with approximately 35% of the literature, followed by biofuels with 34%, and hydropower with approximately 17% of the literature coverage. Increasing land use area for biofuel and hydropower is vital for transitioning to low carbon energy, but the potential impact of other renewable energy (RE) technologies on land use (solar, wind, hydro) remains under-explored. Small-scale decentralised solar energy project case studies are predominantly featured in the articles because solar home system mini-grids and microgrids offer women critical roles in the selling and purchasing of these systems, which is reflected in the literature concerning rural electrification in the Global South (Gray *et al* 2019). Solar technologies are often cheap, small, and inexpensive to install for easy energy access in areas lacking nation grid access (Ulsrud *et al* 2011, Urpelainen 2014, Bhattacharyya *et al* 2019). Wind power projects received little to no attention (mentioned only in two articles (Turkovska *et al* 2021))

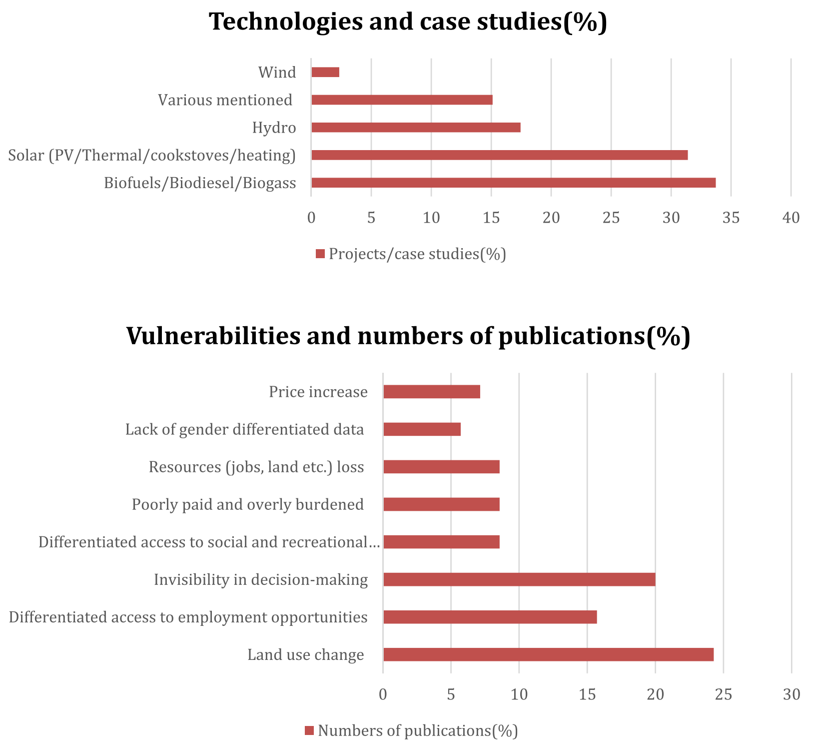

Figure 2. (a) **Technologies and case studies:** Number of case studies that examine each energy technology ('Various mentioned' = carbon taxes, green practice-based policies, electric transportation, household technologies) (b) **Vulnerabilities and number of publications:** Number of publications that address a particular gender vulnerability. (*Note:* percentages are mutually exclusive because one publication may deal with more than one vulnerability).

in review literature. One possible explanation could be the absence of gender analysis in studies related to wind, though the literature is emerging on social impacts of the wind farms (Mueller and Brooks 2020).

Figure 2(b) represents the vulnerabilities covered by the percentage of literature. Land use change related impacts are covered by more than 28% of the literature, whilst the social and economic exclusion and uneven distribution of employment opportunities are covered by more than 18% of the literature. Other negative impacts are job losses, overburden with domestic/household tasks, and price increases. Here, job losses refer to loss of income from the development of energy projects and employment opportunities refers to new opportunities emerge from implementation of low carbon energy projects.

4.2. Previous conceptual work

Main themes emerged from the content analysis of the literature are land, access, resources, practices, and policies in relation with energy and gender (see table 2). In order to categorize these different topics, we merged them in four main themes: *land use change, gender-neutral energy policies, access to resources*, and *green practices as gendered*. These four themes suggest that there are a number of enabling mechanisms arising from social and structural inequalities. This is indicative that vulnerabilities should to be considered not in isolation, but in relationship with others (see figure 3 and table 2). One of the main limitations of rendering the surveyed literature into categories is the overlapping nature of social and structural inequalities which are bolstered especially in the Global South. Pre-existing gender inequalities and social hierarchies may marginalise women's access to land and resources when new energy projects are begun (Gay-Antaki 2016, Tsagkari 2022). This may further exclude women from decision making processes, and this absence from creating carbon market policies and decision-making practices limits women's capacity to gain financial benefits from low carbon energy projects (Gay-Antaki 2016). On a holistic level, low carbon energy projects are predominantly employing men and male know-how, as Science, Technology, Engineering, and

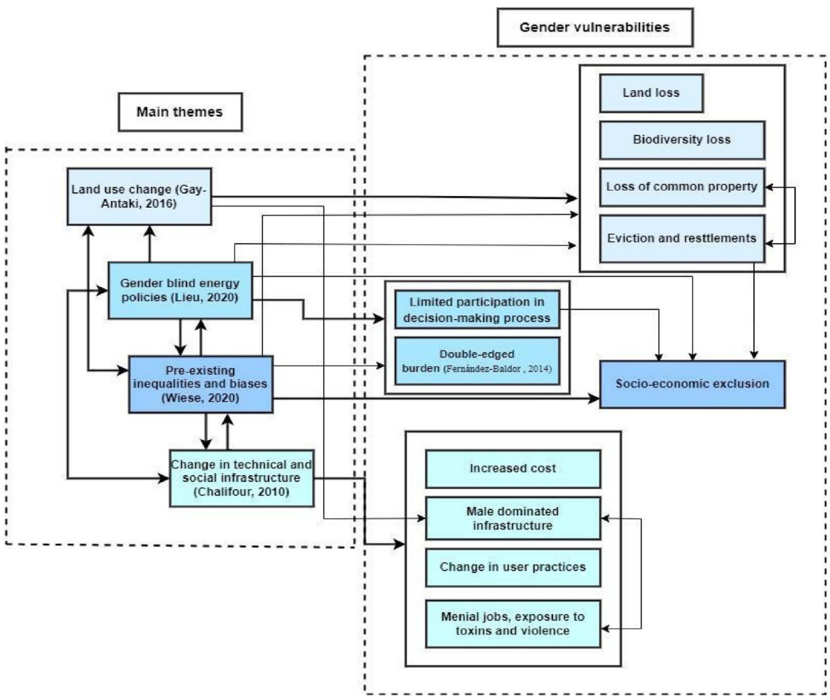

Figure 3. Main four themes colour-coded by theme and their projected gender vulnerabilities.

Mathematics (STEM) related energy sectors and industries continue to be deeply gendered spaces (Boyd 2002). The literature further highlights that energy project planning and execution has often weakened women's abilities to influence or participate in projects, as projects may reinforce existing unequal social hierarchies and reliance on men's technical know-how and skills (Boyd 2002, Lazoroska *et al* 2021, Shrestha *et al* 2021). It is important to consider not just the direct link of vulnerabilities to different enabling mechanisms, but also their complex mutual linkages and relationships. The next section highlights the mechanisms and context by which vulnerability risk factors are expected to arise during low carbon energy transitions.

4.2.1. Land endowment, resettlement, and low carbon energy transitions

Land use change emerged as the dominant topic in reviewed literature, where more than 27% of the reviewed literature concerned this impact. The surveyed literature focused mainly on the Global South, covering loss of land, migrations, and loss of livelihood (Dauvergne and Neville 2010, Hunsberger 2015, Selbmann and Ide 2015, Chigbu *et al* 2019, Bielig *et al* 2022). With the exception of a few papers (Fernández-Baldor *et al* 2014, Hill *et al* 2017, Ahlborg 2017), there was little emphasis on formal gender assessments and inclusion of gender-based analysis of how low carbon energy projects and solutions might consider existing energy injustices and future potential vulnerabilities.

The pattern observed in reviewed literature shows that policies, practices, and projects involving land use change and land deals tend to overlook the interests, rights, and demands of women. As a result, they not only aggravate the pre-existing gendered inequalities, but also limit the available resources, creating gender vulnerabilities (Liu *et al* 2011, Schoneveld *et al* 2011). A common strand in many papers is the focus on changes in forest spaces and common land loss, as these changes could impact men and women differently depending on the existing pattern of responsibilities and control (Corbera *et al* 2007, Dauvergne and Neville 2010, Behrman *et al* 2012, Obidzinski *et al* 2012, Yenneti *et al* 2016, Dharmawan *et al* 2020, Gebreyes *et al* 2020, Stock and Birkenholtz 2020). Some papers (Behrman *et al* 2012, Stock and Birkenholtz 2020) also focus on the differential gender impact of the land enclosure (enclosure of open land that prevents the common grazing and other activities) for low carbon energy

Table 2. Gendered vulnerabilities emerged from different studies and their relevance with the four themes.

Discussed low carbon scenario or outcome/ energy production method	Vulnerabilit(y/ies) emerging from studies	Categorisation of vulnerability	References
Tree plantation and conservation to reduce carbon dioxide levels in Bolivia.	Debate driven by men. Women have menial and low paid jobs. Minimum to no influence in decision making process. Women exclusion from project decision making, implementation and design process. Women reproductive work being used as subsidy. Blindness to gendered resource management.	Inequalities in decision making process. Access to resources and gender division of labour.	(Boyd 2002, Corbera, *et al* 2007, Gay-Antaki 2016)
Biomass plantation and expansion in different countries for biofuels (Indonesia, Ghana, Malaysia, Brazil, Mexico, Zambia, Mozambique, Tanzania).	Loss of available at: resources with the rise of monoculture plantation and forest conversion. Loss of land after resettlements. Exclusion of women from negotiation and consultation process while transferring the land rights during land acquisition process (land deals). Food insecurity (Women usually manage the household food supply). Gender differentiated ability to recover from losses. Changes in farming activities (decreased availability of land). Lower wage and worse working conditions for women. Plantations expansion accompanied by increase in commercial sex cafes. Food crops replaced by cash crops make women vulnerable to resources and land loss.	Access to resources. Land endowment and resettlements.	(Dauvergne and Neville 2010, Vermeulen and Cotula 2010, German *et al* 2011, Schoneveld *et al* 2011, Behrman *et al* 2012, Obidzinski *et al* 2012, Gasparatos *et al* 2013, Popp *et al* 2014, van Eijck *et al* 2014, Chigbu 2019, Dharmawan *et al* 2020)
Nuclear power in France, net metering policy in UK and solar power projects in Germany were developed to address climate change.	In all three cases single mothers were more affected by increase in price.	Green practices are gendered.	(Sovacool *et al* 2019)
Hydropower plant in Lao village and Hongjiang and Wanmipo hydropower stations in Chinawas built to produce clean power and electricity.	Decisions are more influenced by men. Loss of livelihood and resources. High cost of electricity and household's reduced access to land and food.	Land endowment and resettlements. Access to resources. (Land use change, Resettlements and displacements, Water regime change). Men also lost their jobs and forced to work as wage-labourer. Increase in work for women.	(Hill *et al* 2017, Weeratunge *et al* 2014, Gebreyes *et al* 2020, Zhao *et al* 2020)

(Continued.)

Table 2. (Continued.)

Dam construction to produce electricity with low carbon emissions.	Women were pushed to work outside the home because of economic situation but they also have to work at home because of societal norms of division of labour.	Access to resources and gendered division of labour. Land loss. Increase in work for women.	(Aiken and Leigh 2015, Castro-Diaz *et al* 2018, Shrestha *et al* 2019, Aung *et al* 2021, Sikka and Carol 2021)
Micro-hydro power plants Ethiopia were built to generate power	Women challenges, needs and uses were insufficiently addressed. Difficulties in diversifying the income for women and poor men. Gender differentiated access to opportunities and benefits (Education, health etc). Exclusion from decision making spaces at community level.	Inequalities in decision making. Access to resources.	(Wiese 2020)
Renewable energy-based electrification.	Ignoring the gender analysis in project design and implementation. Extra work for women. Men extend their leisure time, but women usually involve themselves in income generation activities like knitting. Lack of participation from women in project related activities due to care giving responsibilities.	Inequalities in power and decision making. Access to resources and gendered division of labour.	(Fernández-Baldor *et al* 2014)
Construction of mega solar energy projects in India to mitigate climate change.	Loss of livelihood (trees, firewood etc) from the land acquisition for solar park. Culture of masculinities in STEM fields. Social and economic exclusion of women. Exclusion from decision making process.	Land use change. Access to resources and gendered division of labour. Inequalities in decision making.	(Yenneti 2016, Terrapon-Pfaff 2019, Stock and Birkenholtz 2020)
Different solar communities and housing association was investigated in link with justice and gender-energy nexus.	Absence (lack of presence) of women in decision making bodies.	Inequalities in decision making process.	(Lazoroska *et al* 2021, Welton and Eisen 2019)
Development of solar projects for clean electricity generation (Morocco, Kenya, some analysis in global south).	No consideration for women employment. Gender blind energy policies.	Access to resources. Inequalities in power and decision making.	(Terrapon-Pfaff *et al* 2014, Terrapon-Pfaff *et al* 2018, Ryser 2019)
Energy production activities at household level in Norway and UK (solar prosumers).	Technology being considered as masculine domain. Less women in STEM fields. Gender and social differentiation neglect in policies.	Access to resources and gendered division of labour. Inequalities in decision making.	(Standal *et al* 2020, Sovacool 2021)
Carbon marketing	Market-oriented development approaches accentuate the existing gender social norms.	Unequal access to resources and embedded patriarchy.	(Lehmann 2019)

(Continued.)

Table 2. (Continued.)

Carbon or environmental taxation policies	Gender analysis is absent from policies. Men travel longer distances and use more fuel. Distributional impact borne more heavily on women than men. Lack of coping strategies because of care giving responsibilities. Unequal division of decision-making power at household level.	Inequalities in power and decision making. Green practices are gendered.	(Chalifour 2010)
Policies about low carbon energy transition.	Dominant male perspective in low-carbon energy transition policies. No gender analysis in energy transition in policies (Kenya). All male expert panel (Spain)-exclusion of diversity.	Inequalities in power and decision making. Gender invisibility in policies. Unequal access to resources and embedded patriarchy.	(Lieu *et al* 2020, Maduekwe and Factor 2021, Tsagkari 2022)
Conceptualization of power in energy transitions.	Already existing power relation predominates. Lack of access to resources for women translates into lack of opportunities.	Unequal access to resources.	(Creutzig *et al* 2015, Ahlborg 2017, Sovacool 2021)
Policies to promote green practices.	No consideration for women in policies designed to promote low-carbon lifestyle.	Green practices are gendered. Differential impact of energy efficiency on women.	(Wang 2016, Kawgan-Kagan 2020)
Mining of minerals to create energy storage batteries	Women marginalised in the community, forced to prostitution to make a wage. Mineral jobs, low wage and health risks.	Green practices are gendered.	(Sovacool *et al* 2019)
Wind power development in Brazil and Mexico was developed to produce renewable electricity.	Social and economic exclusion of women. Decisions are more influenced by men.	Land use change. Unequal access to resources. Inequalities in decision making.	(El Mekaoui *et al* 2020, Turkovska *et al* 2021, Bielig *et al* 2022)

projects. Afforestation or reforestation projects are being implemented as a carbon capture strategy from atmosphere (IEA 2020). An article (Stock and Birkenholtz 2020) explains how the women who depend on forest resource are more likely to be affected by loss of firewood, land for grazing and farming, water and medicinal plants in case of land enclosure for solar energy project. Besides firewood collection, households also depend on many other resources produced by forests like mushrooms, locust bean trees, charcoal production, raw material to make local handicrafts, which also provides a significant proportion of women's cash income. Few studies (Boyd 2002, Corbera *et al* 2007, Gay-Antaki 2016) draw attention to the lack of power in decision-making activities, even though women were primarily responsible for tree plantation in reforestation and management projects. It is evident from literature that there are significant differences in the vulnerabilities and expectations between different genders that may be traced back to social dimensions, such as gender inequalities, traditions, and social roles (Skutsch 2005).

The possibility of increased competition and demand between biofuels and the food sector could perpetuate the food security issue, especially in places where land and resources, such as water, could be diverted to biofuel production which had been previously preserved for staple crops (Popp *et al* 2014, Dauvergne and Neville 2010, (Dompreh *et al* 2021). Schoneveld *et al* explains that changes in existing land use toward monoculture plantations engendered intensive vegetation clearing and the loss of traditional ways of farming and forest resources (Schoneveld *et al* 2011). The change in patterns of power and control likely to result in the marginalisation of women, who not only grow crops for household consumption but to gain additional cash income (Vermeulen and Cotula 2010, Behrman *et al* 2012, Stock and Birkenholtz 2020). Structural transformation and modernization of the agricultural system owing to the increase in demand for biofuels could lead to insecurity of agricultural commodities, biodiversity loss, differentiated access to resources and increase in food prices. In agricultural production systems found in rural communities, pre-existing gender norms and social hierarchies determine the control over resources, division of labour, and the mechanisms of decision making. These changes could affect women and other vulnerable groups in a number of uncharted ways (Vermeulen and Cotula 2010, Laura *et al* 2011, van Eijck *et al* 2014). Behrman *et al* (2012) draws attention to women's limited access to customary land rights and secure land tenures, emphasising their limited access to nonland inputs, such as fertilisers, pesticides and external services to improve the land and crops conditions. The authors underscore the importance of continued research on gender equitable large-scale land deals (Behrman *et al* 2012). Land related transformations that create opportunities for women may have a positive impact, but if resources are taken away from women, it will negatively impact the welfare of women and their families even if there are financial gains for men (Schoneveld *et al* 2011, van Eijck *et al* 2014). The access to resources and rights represents the ways in which inequalities materialise. The understanding of different resource users and resource managers in relation with different productive spaces and how they are associated with resources is crucial for a just LCT.

Migrations, resettlements, and land loss as a result of low carbon energy projects, alters the fabric of a community by changing the dynamics of the power relations and gender norms. The changing land infrastructure and land deals for LCE projects results in eviction and resettlement of the local population that could have important gendered implications (Obidzinski *et al* 2012, Aiken and Leigh 2015, Hill *et al* 2017, Zhao *et al* 2020). Hill *et al* (2017) examined in a study on Vietnam that migrated communities as a result of low carbon energy projects, settled into the areas that are unsuitable for farming, which forces the migrated population into wage labour or illegal work. These resettlements results into reconstruction of gender relation, culture and livelihood (Lin 2001, Mutopo 2012, Zhao *et al* 2020). Women-headed households also have difficulties in mobilizing labour and material to build houses in resettled areas. Studies by (Mehta 2009, Hill *et al* 2017) argue that following the settlements, a number of gendered impacts were found, such as erosion of women's influence in households, losing the land rights and loss of opportunities as a result of exclusion from official consultations. Furthermore, social norms prevent women from engaging in alternative livelihood options like timber harvesting and wage labouring. Sikka and Carol (2021) draws attention to impacts of displacement on men. They found that in case of migrations of tribal and indigenous people, women were more adaptable, whilst men struggled to reconstruct their lives and renegotiate masculinities upon resettlement.

The concept that the household unit will share the benefits and losses of resettlements equally is flawed (Skinner 2018), as different household members will be affected differently by land loss, resettlement, employment opportunities, and additional assort that accompany the migrations and resettlement. Gender analysis in understanding the vulnerabilities that land use change causes is critical as men and women have different social roles, rights and opportunities. Land use analysis should be more inclusive and should shift focus from agriculture to common land use. Thus, societal and systematic factors play a critical role in determining the degree to which the benefits of the low carbon energy transitions could be reaped by different genders.

4.2.2. Gender inequalities in power and decision making

Exclusion and inequality in decision making processes emerged as the second most debated topic in the reviewed literature, where approximately 17% of the literature directly addressed the gender blindness in LCE policies and project implementation, and around 18% of the studies discussed the disproportionate access to employment opportunities. Although energy policies are often considered gender neutral, in that they benefit all genders equally, the decision makers are predominantly men (Feenstra and Özerol 2021). This influences women's access to social and economic opportunities with pre-existing social norms and gender representation in STEM fields. Although most of the articles are concerned with the Global South, a few articles address the issue from a Global North perspective (Lieu *et al* 2020, Lazoroska *et al* 2021).

Although the importance of gender equality is widely acknowledged in climate mitigation strategies of the Paris Agreement and in SDGs, deep-rooted power dynamics of gender, inequality in resource access, and exclusion from decision making process are making the implementation more challenging (Ahlborg 2017, Zhao *et al* 2020, Buechler *et al* 2020). Many articles indicate that gender blind policies, projects and strategies, alongside local practices and norms, are likely to hinder women's access to energy and produce perpetuate a system largely dominated by men (Boyd 2002, Terrapon-Pfaff *et al* 2014, Ahlborg 2017, Winther *et al* 2018, Shrestha *et al* 2019, Terrapon-Pfaff *et al* 2019, Lieu *et al* 2020, Lazoroska *et al* 2021). Some papers (Boyd 2002, Ahlborg 2017) argue that the reason for limited emphasis on the gender dimension could partly be attributed to the pressures emerging from technical requirements and translation of technical designs into functional system configurations. Consequently, this tends to create certain sets of ideas about energy consumption and users in which men are doing the productive work and women occupy the household (Winther *et al* 2018, Terrapon-Pfaff *et al* 2019). The analysis of the literature on gender perspectives in energy policy making, highlighted the central need to question why there was an overwhelming absence of not only gendered voices but empowered, gendered and diverse voices in energy transitions. Part of the answer is patriarchal underpinnings of sustainable developments and climate change mitigation agendas. For instance, energy transitions have strong emphasis on techno-economic transition which is dominated by the visions and scenarios largely developed by influential groups—often led by men (Kronsell 2013).

There is an established link between energy justice and policy making, but the discussion of gender in context of low carbon energy transition literature is often limited to sustainable energy poverty, employment and adaptation of efficient and clean energy cookstoves (Terrapon-Pfaff *et al* 2014, Wang 2016, Terrapon-Pfaff et al 2018, 2019, El Mekaoui *et al* 2020). However, in recent literature, gender has been explored from the perspective of power and politics in energy transition (Ahlborg 2017, Lieu *et al* 2020) because the power dynamics between genders can lead to exclusion and inequality in decision making process. The long standing unquestioned social norms, practices and discourses have reinforced unequal power relations between genders in decision-making spaces (Lieu *et al* 2020). Patriarchal approaches toward decision-making and pre-existing inequalities in social infrastructure could limit the potential effectiveness of LCE policies and projects (Boyd 2002). Some studies suggest that women have limited to no stake in decision-making and felt excluded from the processes at national, local and community levels (Boyd 2002, Lieu *et al* 2020, Lazoroska *et al* 2021).

The dilemma of these carbon mitigation policies is to operate through common property whilst upholding the existing unjust and discriminatory decision-making system. Studies shows that neither in the context of project implementation, nor at community level meetings, was there any evidence to improve the socio-political and economic integration of the women in decision-making (Ahlborg 2017, El Mekaoui *et al* 2020). RE programs are usually not gender mainstreamed and do not incorporate plans to address the gender issues in implementation of the projects explicitly (Ahlborg 2017). Many carbon mitigation projects like other development projects focused on some of the women's practical needs, such as, health, education and food production but ignored the strategic needs to empower women, challenge the gender biases and bring greater gender equality (Boyd 2002, Corbera *et al* 2007). This shows the limited capacity of environmental management projects and practices to effect the local structure of non-recognition of the gender needs in carbon mitigation projects (Boyd 2002). Similar pattern of dominance, control, and experienced subordination has been observed in electricity generation and distribution systems which involves the practice. General patterns of the electrification process have a tendency to reproduce the inequalities related to gender and class (Wiese 2020).

Overall, the literature indicates that there is not only a lack of representation of women in decision making processes, but also a lack of consideration of women's needs as energy consumers. Disproportionate representation of gender concerns the question of numbers and capabilities of men, diversity of the visions and actors represented (Lieu *et al* 2020, Wiese 2020). Underrepresentation of one gender accentuates attention towards specific storytellers and their perspectives whilst overlooking how gendered energy transition could be demonstrated. The absence of equal representation of gender, particularly women's needs and demands in decision making processes, perpetuates dominated technical culture, excludes the social and gender perspective, and prioritises the technical expertise and knowledge that lies in the hands of male technical experts (Lieu *et al* 2020). These pitfalls contribute into reinforcing pre-existing inequalities, vulnerabilities and unequal power structures, whilst also indicating that this could be the product of the emerging structure of energy transitions. The narrative constructed around the LCE transitions and climate mitigation actions centre on technological solutions simultaneously reflecting the dominating political and policy agendas.

4.2.3. Unequal access and gender division of labour: embedded patriarchy

Although low carbon energy transitions present alternative financial and community participation opportunities, it was observed in numerous studies that low carbon energy transitions also putting women in disadvantageous positions when it comes to paid jobs, accessing resources, and livelihood survival approaches, therefore creating gender vulnerabilities (Boyd 2002, Creutzig *et al* 2015, Castro-Diaz *et al* 2018, Dharmawan *et al* 2020, Stock and Birkenholtz 2020, Sovacool 2021, Tsagkari 2022).

Modern household electricity and heat use, particularly decentralised solar and bioenergy, are more frequently credited to have a positive influence on gender equality in rural contexts by lowering women's workload, allowing them to use daylight to pursue other activities, such as alternative income opportunities and engaging in community work (Baruah 2017, Terrapon-Pfaff *et al* 2018). Stock and Birkenholtz (2020) conducted a study in an Indian solar park, claim the opposite. The enclosure of land for the solar park has not only increased the time of low caste women to collect water but also denied their access to firewood. Some researchers (Fernández-Baldor *et al* 2014, Wiese 2020) have examined other ways in which men and women reap the benefits disproportionately from the implementation of low carbon energy technologies. The pattern observed in the literature shows that new energy technologies merely shift the inequalities, rather than eliminate them (Fernández-Baldor *et al* 2015, Lehmann 2019, Stock and Birkenholtz 2020). For example, a study conducted in Peru shows that men extend their leisure time by playing instruments or by watching TV whilst women use their time to increase their family's income by knitting, sewing or in completing other household chores (Fernández-Baldor *et al* 2014). Standal *et al* (2020) argue that the economic, cultural, social and symbolic resources to which individuals have access and different social fields they move within are the important enablers and obstacles to interact with the technologies. Societal differentiation along the gender lines, in which modern technology is perceived a masculine domain, creates a barrier for most women from fully benefited from technologies (Standal *et al* 2020).

The development of the low carbon energy infrastructure to mitigate climate change transforms the resource access, management and control and regional economy. This change translates into gendered inequalities in employment, labour market, and at household level. Many case studies in the reviewed literature show that in climate change mitigation, forestry, and biofuels plantation projects, there is a gendered division of labour: women performing menial tasks whilst men perform more highly-skilled labour (Boyd 2002, Corbera *et al* 2007, Behrman *et al* 2012, Fernández-Baldor *et al* 2014, Gay-Antaki 2016, Axon and Morrissey 2020, Dharmawan *et al* 2020, Sovacool *et al* 2020). In these projects women are increasingly hired as daily waged casual labour and lack the security that comes with permanent contracts. Female workers are mostly involved in collecting mainly weeds and firewood, cleaning and cooking activities, transporting, processing, and trading (Sovacool *et al* 2020).

Poor working conditions, inadequate access to social protection, and unpaid household work have particular implications for vulnerable women. These socio-economic inequalities accentuate gender vulnerabilities due to lack of access to education, mobility, and decision-making spaces (Lazoroska *et al* 2021, Shrestha *et al* 2021). Studies argue that access to electricity alone does not necessarily translate into women's (and men's) economic and political empowerment, such as (Wiese 2020), but rather calls for a need to coordinate energy interventions with other development objectives that target women's empowerment, such as access to credit or education to enhance social equality (Winther *et al* 2017, 2018, Standal *et al* 2020).

4.2.4. Green practices, gender, and culture

The smallest theme of the four analysed the way in which sustainable lifestyle, sustainable consumption policies, and low carbon energy projects underestimate the complexity of everyday life (e.g. Different genders have different roles and so the different energy consumption patterns). The policies, to promote sustainable lifestyle and their implications, usually ignore asymmetric power dynamics in households (Chalifour 2010, Shrestha *et al* 2019, Kawgan-Kagan 2020). These policy interventions to modify individual lifestyles by changing the consumer's choices and attitude increase women's household work and exacerbate gender inequalities (Wang 2016). These plans to promote green practices, which is the practice of creating the structure and habits of consumers that are environmentally responsible, excessively focused on technical and economic dimensions but ignored the social and gender dimensions of change. Policy makers assume that people will be willing to change practices if they are well informed about environmental risks. These policies consider consumption as an individual choice and ignore the fact that individual choices are often affected by the socio-economic position, gender, and culture (Owens *et al* 2004). Wang (2016) argues that gender is invisible in these policies as it might be more difficult for the women to change their behaviour and switch to less carbon intensive transportation because of their caregiving activities related to children or elderly family members.

In addition to the burden of purchasing new equipment, the powers of making decisions about switching to low carbon energy technologies are also gendered; decision making powers in a joint household with male and female members is often disproportionately distributed (Chalifour 2010). Women who work at home have more energy needs during the day, and some may have a partner who might share the cost, but in the case of single parenthood, these costs are difficult to avoid or share—and women are far more often single parents than men (Chalifour 2010, Sovacool *et al* 2019). Moreover, the price increase through carbon taxes related to low carbon energy technologies can have gender differentiated impacts since women make up a disproportionate share of low-income population (Chalifour 2010). Additionally, women's work as caregivers and lack of power over decision-making in relation to energy also restricts their ability to adapt to increased prices (electricity, heating) even in same financial circumstances as men (Chalifour 2010, Sovacool *et al* 2019, Hu 2020).

Another important vulnerability related to low carbon energy mitigation policies is spatial and temporal externalization of harmful impacts, which could have many critical gender implications. A study by (Stock and Birkenholtz 2020) emphasises that low carbon energy projects should be seen as the part of process of entrenching postcolonial ideas of gender and race within the narrative of nation building and international development interventions. Similarly, a study in Morocco claims that acquisition of land by the government drew on colonial strategies (Ryser 2019). Policies in the Global North to address climate change can deepen the gender injustices and pattern of domination in the Global South.

Low carbon energy transitions necessitate plantation expansion for biofuels and mining camps for mineral extraction, for electric vehicles, heat pumps, and storage technologies. Yet, they are marginalising women and reproducing the patterns of patriarchal control and gender inequalities. These plantation, mining, and RE projects sites were also accompanied by an increase in prostitution (Ryser 2019, Sovacool *et al* 2020). In general, sex workers are among the most vulnerable groups to violence and poverty as most of them are internal migrants and have fewer social connections and support (Behrman *et al* 2012). An increase in prostitution also increases the risk of sexually transmitted diseases in the community. Women in these mining sites, particularly the sex workers, faced the risk of contracting contagious diseases spread by the miners (Sovacool *et al* 2020). Women face the same kind of toxins and chemicals, but perform menial tasks. These toxins, with all other diseases, also put women at abnormally high risks of spontaneous abortions, stillbirths, and premature births (Sovacool *et al* 2020). Although these gendered impacts of mining practices are of paramount importance the research to date on the subject is restricted and there is no in-depth analysis in literature. Women's needs and biological differences are not systematically studied and have been overlooked. The paper by (Dehghani-Sanij *et al* 2019) considers the environmental devastation caused by mineral mining, yet they only briefly discuss the human aspects. Therefore, the links between low carbon energy transitions, gender vulnerabilities, and transition materials require further research.

5. Future research paths

Based on the conceptual review approach, we reviewed 65 peer-reviewed articles, which collectively advances our understanding of the disproportionate distribution of the benefits and burdens of low carbon energy transition and their relation to social and political inequalities for different genders. The low carbon energy transition literature on gender vulnerabilities is limited in scope as identified by the number of relevant articles. Four main themes were emerged from the content analysis of the research papers: *land use change, gender-neutral energy policies, access to resources*, and *green practices, gender and culture* as described in (section 3, figure 3). We have also identified several research gaps in the current literature and directions for future. In LCET research, gender is slowly emerging and little attention has been paid to power, social, and political relations and their synergies.

5.1. Discussion

The analysed literature challenges the prevalent energy system narrative to treat the energy transition as gender neutral, when in practice evidence shows that the distribution of benefits and opportunities for men and women continues to be unequal (Skutsch 2005, Wang 2016, Wiese 2020). Literature also shows how different enablers and potential vulnerabilities are complexly intertwined into each other and in some cases reinforcing one another's impacts. There are pieces of evidence that suggest that if not managed carefully, this energy system change may generate new social justice challenges and vulnerabilities, whilst possibly failing to address the already existing drivers of inequality in the energy market and larger socio-economy (Stock and Birkenholtz 2020, Sovacool *et al* 2020).

Whilst the energy transition literature focuses on the decarbonization of economic activities, it should be emphasized that broader changes in energy distribution and recovery result in new socio-spatial inequalities (Gay-Antaki 2016). Energy policies and decision-making practices are generally considered as technocratic processes and inclusion of gender dimensions is often limited to the electricity access and poverty issues (Clancy and Feenstra 2019, Robinson 2019). Understanding the power inequalities associated with energy transitions can make them a fertile ground to explore justice and equality issues.

Two factors were identified: first, the energy policy and implementation debates are dominated by politics, scientists, and bureaucrats; secondly, sociological thinking is unlikely to produce generalisable conclusions that policy makers favour (see for example, Shove 1998). A technological and/or economic approach limits the range of actors involved and their perspective in the energy transition which could lead to unfair outcomes (Geels *et al* 2017). Advocacy groups argue that the change to clean and low carbon energy resources and technologies should also herald equal employment and work policies for women as well as strong recognition of the women's reproductive roles (IRENA 2019). The gender aspect has not been perceived with the same level of attention by already established stakeholders and politicians regarding the energy transition's economic and technical aspects. Most of the literature on social justice and gender equality regarding LCE transitions is from the field of social science (Williams and Doyon 2019). The main challenge for the future research is how this conceptual thinking should be incorporated and embedded into the quantitative techno-economic debate that dominates the energy policy spheres.

The access to new opportunities that arises from the implementation of the low carbon energy projects are also gendered, as girls and women lack information and resources that might be more prominent in the rural context (Fernández-Baldor *et al* 2015). As Behrman *et al* (2012) observed, women who were responsible for selling crops in the local market have difficulties in reaching the commercial markets because of male dominated infrastructures of the markets and villages are situated away from these markets (Behrman *et al* 2012). Although the access to new large-scale (neo-liberal) markets is an important subject, but there is a lack of critical reflection in literature. There is also a need for gender disaggregated data to raise awareness on gendered implications of energy projects and to identify the remedies for vulnerabilities. Furthermore, it is also a continuous need to further our understanding of women's energy activities and concerns along with the structures that constrain women, particularly in the rural context, from access and use of energy services and participation on the household and community level.

In many countries, women's access to land and productive resources is already tenuous due to gender discriminatory laws and social practices. These pre-existing gender inequalities, disproportionately affect women, particularly rural and indigenous women, to the compounded effects of both climate change and the RE policies and projects implemented on their land and territories to reduce global GHG and diversify the energy system ('Wind farm in Mexico': 2020). The gendered impacts of climate change and the energy responses to address this crisis are often the result of intersectional gender discrimination in land rights, women's and girls' lack of participation in key decision-making processes, as well as their care-giving roles ('Renewable Energy & Gender Justice' 2020). Furthermore, women are overrepresented amongst the world's poor and are often more dependent on land and other natural resources to sustain their livelihoods. To be gender-equal, just, and in harmony with human rights, policies and political frameworks addressing the energy transition should avoid land dispossession for women and other marginalized groups. To ensure a meaningful and just transition, low carbon energy projects must recognise that useful participation of all genders is crucial in the conservation of natural resources and protection of environment.

5.2. Future path: vulnerability and intersectionality

This study aligns itself with theories of gender and vulnerability in climate mitigation literature to analyse the vulnerabilities in literature. Low carbon energy transitions will have implications for notions of gender equality and justice due to their differentiated vulnerability to such change (Fisher and Mohun 2015). Vulnerability is an evasive concept whose definitions varies across disciplines. Growing body of literature is trying to capture the multidimensionality and complexity of the concept (Brooks 2003). The widely used IPCC definitions of vulnerability are in disagreement with one another (Brooks 2003) and this difference further illustrates, whether the vulnerability is determined by the internal characteristic of the system, or if it also depends on the likelihood of the system to experience a particular hazard or probability of particular undesired outcome. Based on the studies analysed, there may be a need for more inclusive definition of gender vulnerability and related terms such as sensitivity, adaptive capacity, adaptation, and risk. A more explicit definition may help researchers, policy makers and NGOs to comprehend the impacts of energy transition on weakest members of the society. In our paper, we understand vulnerability as the integration of the inherited characteristics of the system and probability of occurrence of an event that could result into undesired outcomes.

Whilst the literature on vulnerability assessment of low carbon energy transitions is growing, gender as a component of the vulnerability dimension is missing. The framework of the vulnerability scoping diagram (Coletti *et al* 2013, Carley *et al* 2018) is being widely adopted in literature to analyse the vulnerability of energy transition across its three dimensions (sensitivity, adaptive capacity and exposure) and various components of these dimensions in different geographic locations (Kortetmäki and Järvelä 2021, Raimi *et al* 2022). The absence of gender from assessment frameworks limits the scope of analysis and at the same time make gender invisible in literary discourses. To address the gap, we analysed the identified vulnerabilities according to framework presented in (Carley *et al* 2018). Although (Carley *et al* 2018) focused on one policy and the vulnerability which arose from it, we analysed the vulnerabilities according to the three dimensions (figure 4) (exposure, sensitivity, adaptative capacity) since reviewed literature aimed to address gender in climate mitigation research from contrasting perspectives. Through this grouping exercise, we may see that articles consider specific sectors, but rarely consider gender vulnerability as having spatial dimensions. Although studies deal with sensitivity towards the potential hazards and exposure of the population but little to no attention has been paid to adaptive capacity. Capacity to adapt and respond to change is determined by access to resources and information and that the ability to diversify the livelihood options (Djoudi *et al* 2016, Thomas *et al* 2019). These factors are determined by the social identities and positions where gender is the key element of these identities. Vulnerability also depends on the social and spatial differentiation even within the same gender.

Intersectional approaches consider the impact of policies amalgamated with asymmetric power relation based on identities at various levels. The failure

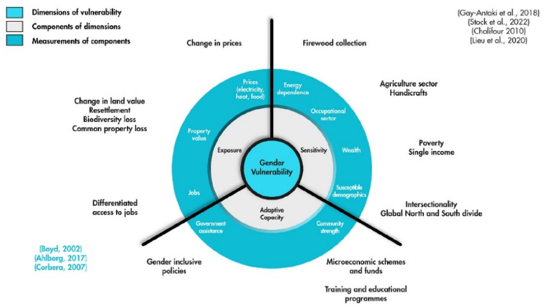

Figure 4. Gender vulnerability scoping diagram based on. Adapted from Carley *et al* (2018), with permission from Springer Nature.

to recognize and consider the complexities in energy interventions could results into short-term success, failed efforts and unplanned consequences (Djoudi *et al* 2016, Smith 2016, Cassese 2019). Although literature on intersectionality, gender, and energy is growing, but conceptualising gendered inequalities and how they interact with inequalities of ethnicity, race, class, and age continues to be critically understudied in low carbon energy transitions literature (Sahrakorpi and Bandi 2021). In the reviewed literature, only one study (Stock and Birkenholtz 2020) addressed that how land enclosure for solar power plant generated the inequalities that cut through gender, caste, and class. Another dimension of energy transition is introduction of technologies, skills, machinery, and policies in developing world. An article (Mollett and Faria 2013) raise the argument that the introduction of low carbon energy technologies should be seen as the part of long historical process of continuing the legacies of postcolonial ideologies of gender and race. To understand the consequences of these processes, new literature must focus on the intersectionality of the social and spatial positioning of people and energy systems.

5.3. Future path: gender inclusive policies, projects and practices

We identified the various gaps that could open new avenues for future research on the relationship between low carbon energy transitions and vulnerabilities. Low carbon energy policies and frameworks often fail to contemplate how changing energy infrastructure and development projects might impact the land and property rights of men and women differently (Burton *et al* 2005). Although, energy policies are assumed to be gender neutral, policy decisions have implications in terms of gender equality, and thus policies intended as gender neutral may turn out to be gender blind in their outputs. Therefore, the process of decision making should consider the roles and responsibilities of different genders (Lazoroska *et al* 2021). Large scale low carbon energy projects rarely adopt any strategy to prevent human rights abuses related to land acquisition, change in electricity generation, and distribution infrastructure (Stock and Birkenholtz 2020, Zhao *et al* 2020). This is a particularly common issue in RE projects (dams, hydro, wind farms, and solar installations) located in rural areas in developing countries where state institutions tend to lack the means and resources to enforce regulations ('Renewable Energy & Human Rights Benchmark' 2020).

Studies often do not critically access the double domination faced by women, a naturalised domination by asymmetric power relation between men and women and from these policies and practices. The role gender plays in green practices is critically understudied, which limits how we may understand vulnerability in the context of green practices (Wang 2016). The gender aspects of energy transitions need to be explored into further work, and the research community needs to put considerable dedication. The dearth of literature highlights more work is required on the differential effects of low carbon energy solutions on men and women, and further rigorous empirical work would be beneficial. Future research ought to incorporate gender-disaggregated data on time use, opportunities for income generation, and prior conditions (such as land ownership) and should examine the change over the course of the project. In addition to incorporating gender aspects, empirical research work and case studies also need to include intersectionality in their analysis by looking at a variety of other factors—including age, marital status, geographical location, and ethnicity. These aspects may impact whether local people will profit from low carbon energy transitions and if some individuals or groups are more likely to benefit than others.

Moreover, the idea that the diffusion of modern technologies and markets in the developing world can optimize production to produce environmental and social benefits should perhaps be critically re-assessed based on historical and societal realities (Robbins 2004). The development of green revolution technologies took place in developed countries that were later distributed, to increase agricultural production, around the world. Shiva explains how these technologies have resulted in extensive environmental, social and gendered issues (Shiva 2016). Shiva also raised the concerns about the lack of gender discourse in climate mitigation debate (Shiva 1988). She argued that climate mitigation is engaging in the debate lead by men, who are providing technical solutions to ecological problems. Yet, they have little understanding of women's concerns and interests (Boyd 2002). The more general assertion that superior environmental knowledge originates in the Global North for transfer to the Global South is problematic, reproducing as it does authoritarian colonial knowledge relations and *a priori* omitting the environmental practices of indigenous and local communities (Robbins 2004). Therefore, an intersectional perspective on gender, power relations and LCT can bring issues of overlapping inequities to the fore in the analysis of efforts to mitigate climate change through introducing low-carbon energy technologies.

6. Conclusion

This conceptual review analysed how gender vulnerabilities are discussed in low carbon energy transitions literature and what mechanisms may be causing vulnerabilities in the future. Recent trends indicate that gender is becoming a mainstream concern in low carbon energy transition literature. The aim was to map not only the existing literature, but also to provide insights into potential literature gaps and future studies on gender and low carbon energy transitions. Land use change, gender-neutral energy policies, access to resources, and green practices are gendered emerged as the main key themes concerning electricity generation. The studies analysed mainly focused on solar, biofuels, and hydropower as the main technology case studies, with 43 articles focusing on the Global South, 13 articles considered the Global North, and the rest considered global issues. When gender vulnerability was utilised as a tool of analysis, it was heavily featured in papers concerning land use change, differential access to employment, and invisibility in decision making. Through categorisation of the main strands of research, it became apparent that a number of enabling mechanisms from structural and social inequalities were not being addressed by case study projects nor provided adequate focus in the literature. It was also observed that low carbon energy transition projects relating to electricity pay little attention to gendered issues nor provide tools or plans to mitigate potential vulnerabilities. Through employing Carley *et al* (2018) framework to analyse gender vulnerabilities, we presented a number of research areas that are under-researched. The major finding from mapping gender vulnerabilities was that the adaptive capacity, compromises of government assistance and community strength, was often not found within the literature. Therefore, future research ought to consider how low carbon energy transitions are adapted in communities through a gendered dimension. For example, women have little access to the benefits from LCET electricity projects, with local men being offered better employment and waged positions. These results add to the rapidly expanding field of energy research on energy transitions and LCET, indicating the growing importance of the necessity to consider socio-technical systems in addition to the technological or economic dimensions of these transitions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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