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Data-Driven Insights into Sustainable Energy Transition across Diverse Climatic Conditions: Evidence from Pakistan's Energy Sector

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ABSTRACT

The comprehensive quest of a sustainable energy transition has suited a defining challenge, as nations seek the data-driven insights that concurrently address climate change, economic growth, and energy security issues. The energy sector in Pakistan, like that of many other developing countries, currently faces similar challenges. Therefore, comprehensive data-driven research is required to find sustainable energy solutions. This research presents a method for gradual increase in variable renewable energy sources (VRES) and optimized retirement of fossil fuel power plants, ultimately to attain 100% integration of VRES till 2050 using H2RES modelling tool. The results demonstrate that 100% share of Pakistan's electricity demand can be met through energy storage technologies, flexibility options, endogenous investments into VRES, power to X technologies, etc. This research emphasizes the potential of H2RES model in achieving SGDs 7 and 13 targets as a template to provide a scalable framework for other developing nations facing similar power system issues, making it globally relevant.

KEYWORDS

Diverse climate zones, Energy planning, Flexibility options, Pakistan's energy sector, Power-to-X technologies, Sustainable energy transition, 100% VRES.

INTRODUCTION

The growth of sustainable development has necessitated a fundamental paradigm shift in both power and energy systems worldwide. Almost all nations are struggling to decrease their dependency on fossil fuels and shift towards variable renewable energy sources (VRES) to tackle the challenges of climate change, global carbon emissions, environmental degradation, energy supply insecurity, etc. The transition towards VRES involves overcoming significant challenges related to energy security, grid stability, and socio-economic impacts. For example, fossil fuel dependence remains a critical issue in Pakistan, contributing to an economic vulnerability due to reliance on imported energy. Similarly, the developing countries are also prioritizing the transition from conventional fossil fuels to VRES [1]. As these nations have broadly relied on fossil fuels-based energy generation, leading to economic challenges due to high dependence on energy imports.

To model the energy sector of these developing countries, many energy modelling tools and techniques are available in literature, H2RES has appeared as a vigorous optimization tool

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capable to analyse the energy sector with high-VRES penetration. The detail description of the H2RES model can be found in [2].

This software is chosen as a modelling tool for this research to assess and optimize the gradual transition towards 100% renewable based energy systems on exogenous and endogenous assumptions for these types of developing countries. The model uses Gurobi that is a strong mathematical optimization solver [3].

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The H2RES model is more focused on the renewable energy (RE) based energy systems and is used to transform fossil-fuel power systems into VRES energy systems [4]. Despite significant progress in understanding the potential of RE, there remains a gap regarding comprehensive transition plans tailored for long- and short-term implementation towards a sustainable energy transition paradigm. This research proposed detailed actions to be undertaken every 5th years, including the decommissioning of thermal power plants and the VRES installations.

To achieve this resilient, sustainable and robust RE system that has driven global research efforts towards the complete integration of VRES into local and national grids is depicted in the following literature. The authors in [5], critically analysed the potential of maximum VRES, and its key barriers. Currently, all the stakeholders are gaining interest in 100% VRES electricity these days. Many countries like Sweden, California, Norway etc. set their goals to achieve 100% VRES system till 2045 or 2050 [6]. The authors in [7] investigated and suggested the worth of a phased approach to decommissioning thermal power plants and adding VRES to reduce energy cost and maintain system stability. Even the first fossil energy company/industry named Wartsila, has also committed to 100% VRES till 2050 [8]. North Africa, European countries, and Australia have set their goals to establish 100 % VRES based grids [9]. However, there is little interest in developing 100% VRES-based energy supply systems in developing countries, including South, Southeast, and Northeast Asia, South and Sub-Saharan Africa, South America, and Eurasia [10].

The main reason is that in developing countries is a lack of research, less support from the decision makers, and almost no interest in future high renewable policies for developing high VRES based energy systems. However, on the other hand, the total research focuses on the developed regions, countries and nations and how to develop 100% RE supply system form the utility grid. Most of the research in developed countries focuses only on their regions, and there is no such interest or study in the literature that defines a clear paradigm for developing countries that are rich in renewable energy (RE) resources and have diverse climate zones [11]. Therefore, this research is helpful for the developing countries to set their clear goals, strategies and plan for the transition towards 100% clean, green and sustainable RE paradigm. Except for this literature review, several studies have been conducted to assess the potential of various renewable resources, including hydro, biomass, wind, tidal, geothermal, and solar [12].

The number of research papers that are based on 100% VRES system in the world according to google scholars are shown in **Figure 1** from 2010 to 2024. This research aims to overcome the gaps between literature and the study on developing 100% VRES system to establish an integrated framework to calculate a cost-effective pathway for 100 % energy transition for energy sectors in developing countries. One thing is most important when modelling the 100 % VRES system, the major challenge is demand and production balancing, otherwise the optimization reaches infeasible solutions. This research successfully handles this situation and properly addresses it. The research hypothesis is “Pakistan can achieve 100% VRES by 2050 through a phased, data-driven transition insight and integration of Power-to-X technologies using H2RES modelling tool”. The term 'data-driven' refers specifically to the use of high-resolution data used for collection procedure on renewable resource availability, and energy demand.

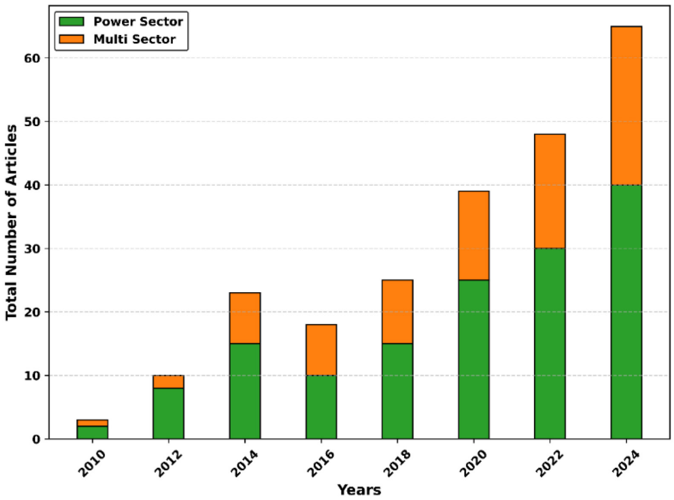

Figure 1. 100 % VRES research from 2010-2024

The novelty of this research work lies in the modelling of the power system considering diverse climatic conditions and resource availability. This research modelled the energy sector of Pakistan, provide a unique data driven transition roadmap using H2RES tool. A holistic view is developed to integrate Power-to-X technologies, sector coupling across industry, heating, and transport along with sectoral decarbonization. The framework is designed as scalable template for other developing countries with ample VRES, but limited transition planning.

The following sections of this research paper are established as Section 1 presented introduction. Section 2 presents research method, and complete data collection procedure, parameters settings to setup H2RES model. In section 3, the energy sector of Pakistan, its diverse climate energy zones and region considered are presented as case study. The results are presented in section 4. Discussion, limitations and future directions are in section 5. Lastly, the conclusion summarizes the key takeaways.

RESEARCH METHOD

The research methodology focuses on leveraging the H2RES model and Gurobi solver for the 100% VRES transition planning by 2050. The H2RES model handles hourly energy, heating, and cooling demands, along with generation, inflow, availability factors, power plant internal data, imports, exports, etc., as input data. It provides an analysis of the variability and flexibility in the adoption of VRES technologies, storage, capacity expansion, retirement options, etc., to reduce operational and system costs annually. Additionally, its modular design facilitates the incorporation of storage technologies such as hydrogen and batteries, which are crucial for managing the variability of solar and wind generation. The model flexibility makes it particularly suitable for long-term planning in the energy transitions, ensuring the results both realistic and actionable manners. This model schematics can be found in [13] that illustrates the key components and operational flow, highlighting its role in enabling a sustainable energy future. The schematics shows heat generation part, dispatchable and non-dispatchable units, generation availability and flexibility options, secondary transformation and final demand sectors. The H2RES model incorporates various flexibility options, including energy storage systems (hydrogen, battery storage) and 'Power-to-X' technologies to balance the variability of renewable generation. Grid stability is maintained through the integration of these technologies, ensuring that energy demand is met even during periods of low renewable generation. The H2RES model, including the use of storage to handle peak demands and energy surpluses, thus maintaining system stability.

The H2RES optimization model incorporates capital costs are based on current market data projections for renewable technologies and energy storage solutions, while O&M costs are estimated from industry standards. Other than generation plant investment, the model considers the capital cost of investment into flexibility solutions which are factored into the model to ensure a realistic cost estimate for the energy transition to 100% VRES by 2050. All the costs are brought to the net present value.

GUROBI is an optimization software available for free academic use. It offers various algorithms, such as Barrier, SIMPLEX, and DUAL SIMPLEX, to efficiently solve large-scale optimization problems. H2RES, written in Python [14], utilizes GUROBI as its primary optimization solver [3].

Data Collection Methods

In the data collection phase of this research, we gathered the past 10 years of Pakistan's power demand data from national energy statistics, covering the period from 2010 to 2020. The data was then cleaned, normalized, and structured for use in training the ARIMA model, with a forecast horizon extending to 2050. After completing the forecasting, we presented the results to a representative of Pakistan's power system for validation and received technical approval. The final validated demand forecast was incorporated into the H2RES model, ensuring its accuracy and suitability for long-term renewable energy system analysis. The forecasted data achieved a deviation of less than 5% from official projection. The study also utilized a combination of primary and secondary data sources and complete layout of the research method can be seen in **Figure 2**. Energy consumption patterns, generation capacities, and fossil fuel plant's operational data for the year 2020 were also collected from Pakistan's national energy reports, government publications, and utility records [15–19]. First, the raw data is collected, and then useful information and related data is logged into the input files after using the ARIMA model where required before setup the H2RES model. Renewable energy potential data, including solar irradiance, wind speeds, and hydropower resources, were sourced from national and international RE databases, such as the Alternative Energy Development Board (AEDB) and the International Renewable Energy Agency (IRENA) [20–24]. Secondary data on energy storage technologies and cost projections were gathered from peer-reviewed literature and market reports [25, 26]. Data collection forms the backbone of this research, as the quality and reliability of input data directly impact the validity of the H2RES model's output. The study prioritizes gathering high-resolution temporal and spatial data on RE resources as these are critical for developing realistic energy scenarios found in [21]. Additionally, precise data on fossil fuel plant capacities, operational lifespans, and GHG emissions were sourced to ensure accurate decommissioning timelines found in [27]. The energy consumption patterns were integrated to project future energy demand and supply balances were found in [28]. These rigorous input data collection processes ensure the development of a robust and actionable transition paradigm tailored for Pakistan's unique energy landscape and infrastructure.

Transition Roadmap Development

The transition roadmap is developed by dividing the 2020-2050 timeline into seven (five-year) intervals. For each interval, it is to be analysed the impacts of decommissioning the specific fossil fuel plants and commissioning of new RE based generating systems. This transition roadmap is designed to ensure a gradual reduction in fossil fuel dependency while meeting the growing energy demand, maintaining grid stability, and the most important balancing the energy demand and supply requirements. Key considerations included the integration of energy storage solutions, such as batteries and hydrogen storage, and its optimization.

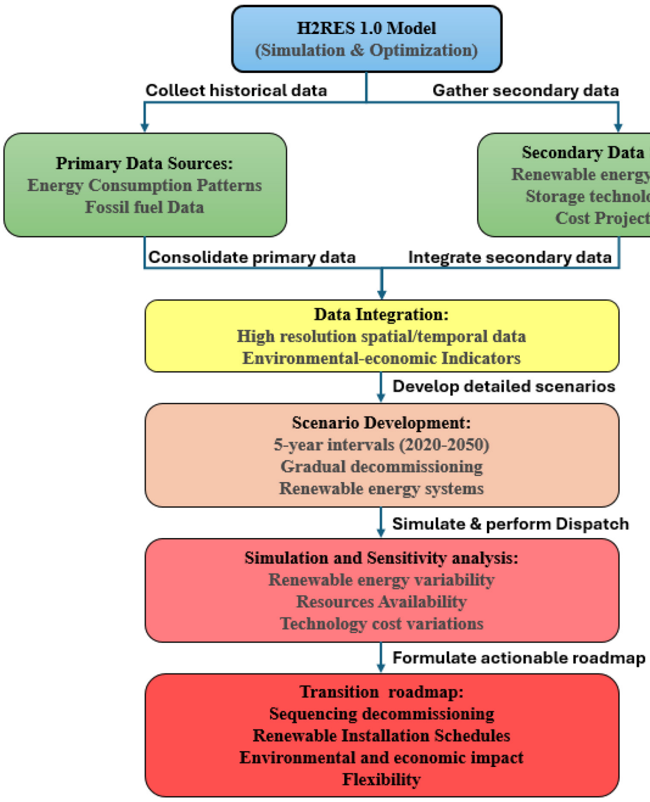

Figure 2. Flowchart of method

Mathematical Modelling: Objective Function and Main Constraints

The mathematical modelling of the H2RES model for the optimization and integration of VRES penetration, storage dynamics for energy carriers, capacity limits, hydrogen production, demand balancing, transformation, GHG emissions constraints, reduce total annualized operational and capital investment costs, etc. The modelling variables includes (fuel cell, hydro, heat, EV and stationary storage, etc.), H2 demand and storage, industrial demand, respect minimum and maximum output per generator type, meet demand, heat pump systems, CHP (generation, storage) constraints, meet cooling and heating demand, storage hydro dam (rump up/down) constraints and the objective function to minimize the total costs.

Eq. (1) displays a general representation of the objective function with all the parameters included:

$$\sum_{y}\sum_{p}\sum_{t} df_y \quad [C_{t,p,y}D_{t,p,y} + TC_{t,y}K_t Inv_{t,y} + R_{t,p,y}Ramp_{t,p,y}I_{p,y}Imp_{p,y} + CO_2Price_y CO_2Levels_{t,p,y}] \tag{1}$$

where: $C_{t,p,y}D_{t,p,y}$ – variable cost for dispatching a technology t, in period p, in year y; $TC_{t,y}K_t Inv_{t,y}$ – annualized capital cost (K_t) of technology t; $R_{t,p,y}Ramp_{t,p,y}$ – ramp up/down cost; $I_{p,y}Imp_{p,y}$ – import cost; $CO_2Price_y CO_2Levels_{t,p,y}$ – cost per unit of CO_2 emissions for each of the technologies.

The objective function consists of five types of costs, fuel and non-fuel costs, capital investment costs, operational ramps (up and down) costs, import cost per period, and the cost of CO_2 emissions and the detail of these costs and equation can be found in [29].

H2RES uses four constraints that are dispatch and technical constraints, storage constraints, demand constraints, and policy constraints. In the modelling, there are different parts like energy generation and reserve balancing (primary, secondary, ramp-up/ramp-down constraints), energy storage management (EV, hydro, heat pump), energy demand matching (meeting demand for electricity, heating, and cooling), CO_2 emission constraints (CO_2 emissions, carbon emissions limit), and cost minimization (including operational, import, investment, ramp-up/down, CO_2 emissions, storage and electrolysis costs).

CASE STUDY: PAKISTAN'S ENERGY SECTOR TRANSITION

Pakistan is considered as a case study with diverse climate zones and huge RE potential. Currently, the major source of electricity generation is based on the important fossil fuel that can be seen in **Figure 3**. Pakistan has huge potential of solar, wind, hydro, biomass and geothermal energy that can be seen in **Figure 4**.

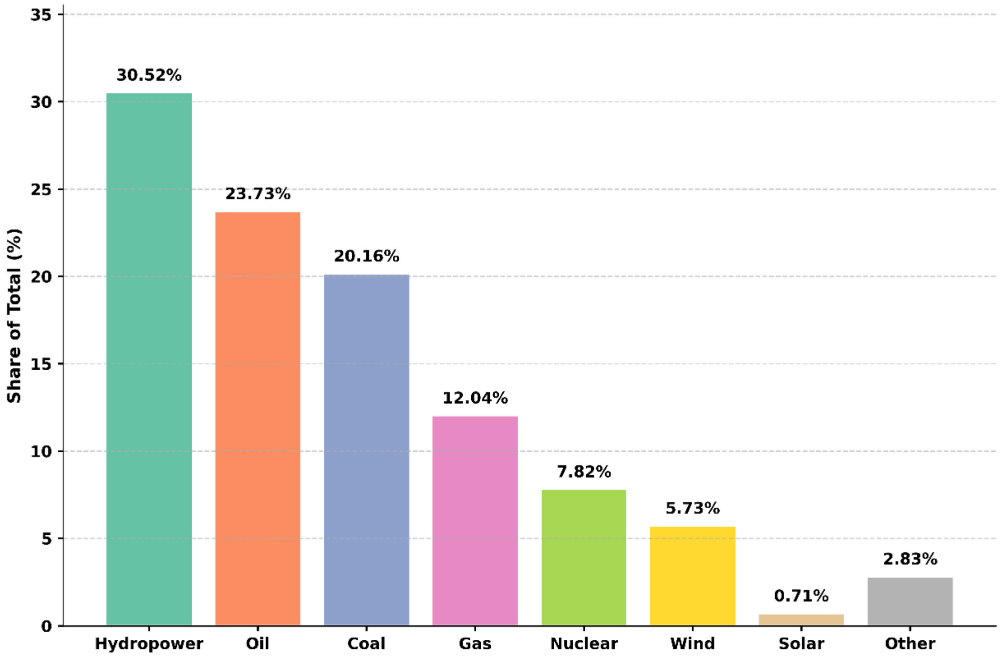

Figure 3. Current Pakistan Energy Mix Share [30]

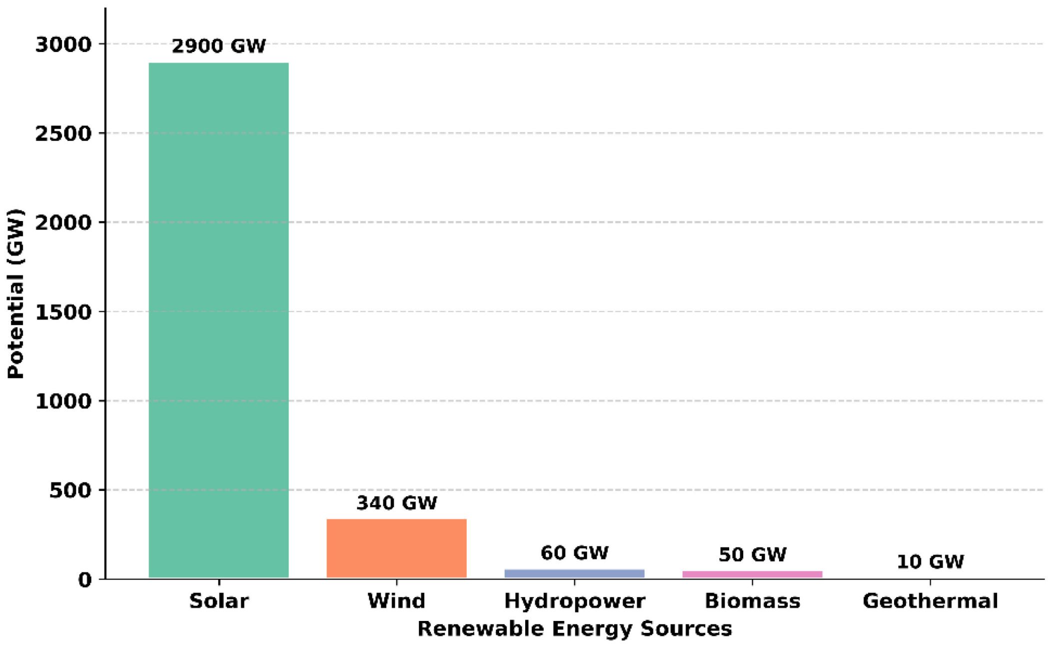

Figure 4. Available Abundant RE Potential in Pakistan [31]

The reigns of Pakistan's including all provinces and sub-regions, considered as case study, can be seen in **Figure 5**. In Pakistan, an average of 5 – 7 kWh/m² of solar irradiance daily and has an average wind speed typically around 2 to 7 m/s [5] [32, 33]. The monthly avg. solar radians data (kWh/m^2/month) and wind speed (m/s) potential in Pakistan of different reigns are shown in **Figure 6** and **Figure 7** [34].

Figure 5. Research Area Scope: Pakistan's all provinces and sub-regions as case study [35]

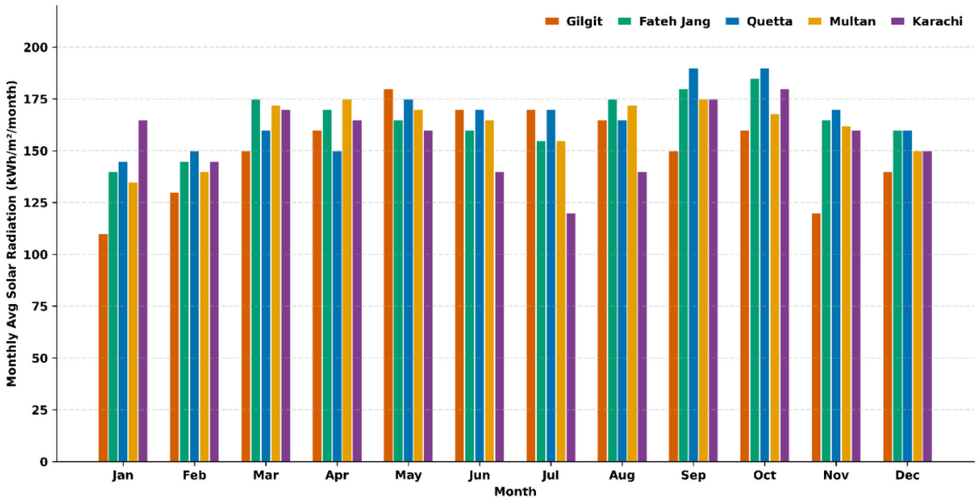

Figure 6. Pakistan Monthly avg. solar irradiance data (kWh/m^2/month) [35]

H2RES Model: Main Input Parameters

The H2RES model, main input parameters are policy parameters, technological change parameters, decommissioning parameters, vehicle-to-grid (V2G) parameters, etc. These parameters are set to achieve 100% RE in Pakistan. The parameters and scenarios considered can be seen in **Table 1** and **Table 2**, respectively. H2RES can include policy constraints in the form of a minimal required share of RE sources (100% in our case) in electricity generation as well as in the maximum amount (zero in our case) of CO_2 emissions. For the purposes of this research, both constraints are used. The CO_2 limit in the model is closely followed and respected to zero in all sectors by 2050. **Table 2** shows the parameters of electricity generation technologies for Pakistan energy sources that are used in building the processes of the model.

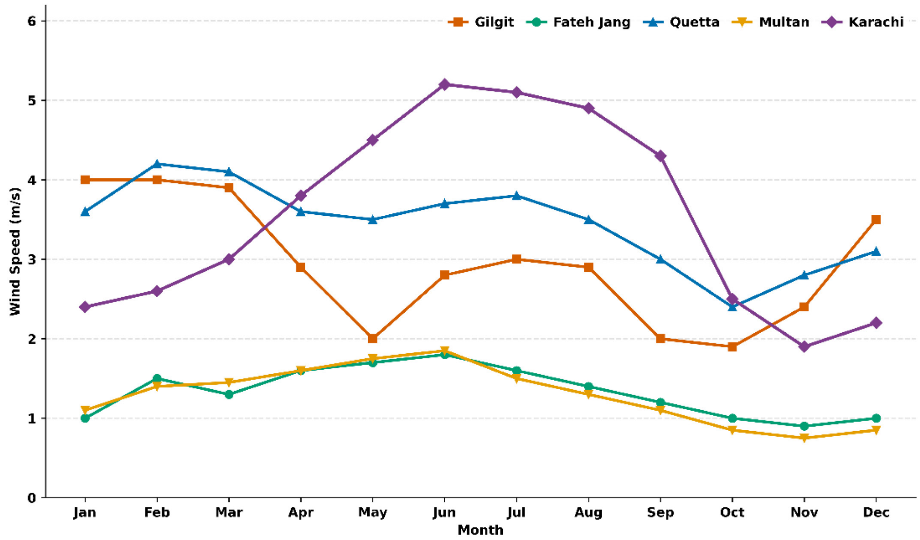

Figure 7. Pakistan Monthly average wind speed (m/s) [35]

Table 1. H2RES Scenario Description

Scenario	Conditions	Description
rps_inv	True	Enforces the H2RES constraints.
carbon Limit	True	Indicates if a carbon emissions limit should be enforced (required for 100% RES).
res_inv	True	Enables the investments into RES generations.
hydro_storage	True	Determines if hydro storage systems are modelled (important for balancing renewables).
exports_dat	True	Indicates whether to consider export data in the model.
ceep_limit	True	Enforce CEEP limit.
NoResToHeatInv	True	If True, then heat pumps are not invested into.

Table 2. Parameters of Energy Conversion [18]

Parameters	Hydro	Solar	Wind	Waste and Biomass	Nuclear	Natural Gas	Coal	Furnace/ Diesel Oil
Max. Availability	73	18	35	80	85	70	75	88
Life Span in Years	75	25	25	20	60	30	40	35
Land Use Acres/MW	315	43	70	12.5	12.71	12.41	12.21	12.44
Fuel Cost (US-Cents/kWh)	0	0	0	6	3	7	6	14.13
Emission (Grams/kWh)	0	0	0	750	0	545	915	596

Roadmap for Transition to 100% VRES by 2050

The results of this research provide a detailed step-by-step roadmap for Pakistan energy sector to transform towards 100% VRES by 2050. The findings outline specific actions to be taken every five years and the systematic installation of RE systems, ensuring a balanced and sustainable energy transition. During this initial phase from 2020 – 2025, the focus is on laying the foundation, and infrastructure development. The second phase from 2025 – 2030 emphasizes expanding RE capacity and modernizing the grid. The phase from 2030 – 2035 marks a significant shift toward RE dominance and expanding battery energy storage systems along with deployment of solar PV, and wind power projects. In the phase 2035 – 2040, renewables account for most of the energy generation and implement advanced smart grid technologies to optimize energy distribution and management along with retirement of nuclear power plants. The energy sector approaches its final stages of transition during the 2040 – 2045 phase. Leaving minimal reliance on fossil fuels, expanding renewable capacity and scaling hydrogen and battery storage to ensure grid stability. The final phase achieves from 2045 – 2050 the target of 100% RE generation by complete elimination of fossil fuel plants from the energy mix, RE installation, and electrification of transportation and industrial sectors using renewable energy. This phased approach to decommissioning fossil fuel plants and systematically increasing RE capacity can achieve Pakistan's goal of 100% VRES by 2050.

RESULTS

This section presents an energy transition pathway of Pakistan's energy sector using H2RES model to analyse the future trajectory from 2020 to 2050. The results cover electricity generation trends, Power-to-X utilization, RE capacity investments, heating sector transformation, industrial fuel consumption, etc. The optimization results highlight the gradual shift from fossil fuels to VRES, emphasizing the increasing role of solar, wind, and energy storage technologies. A detailed analysis of projected trends observed in electricity generation, energy sector transformations, and technological advancements, illustrated through graphical representations.

Figure 8 presents the total power generation mix from 2020 to 2050 after the interval of every 5-years. The results indicate a gradual transition from fossil fuel generation to VRES energy, particularly in solar and wind power production. While coal, diesel, oil, gas, and nuclear generation maintain a presence in earlier years, their contribution declines over time, reflecting a shift towards cleaner and greener alternatives. The model predicts a significant rise in RE deployment post-2030, demonstrated the increasing commitment to sustainable energy solutions of Pakistan. Hydropower and nuclear energy remain stable contributors till 2035, ensuring a balanced energy mix. After 2040, nuclear plants will be shut down and majorly replaced by renewables. As the overall electricity generation capacity is projected to grow steadily, aligning with the country's rising energy demand. These findings highlight the feasibility and necessity of integrating renewables into the power grid to enhance energy security and reduce carbon emissions.

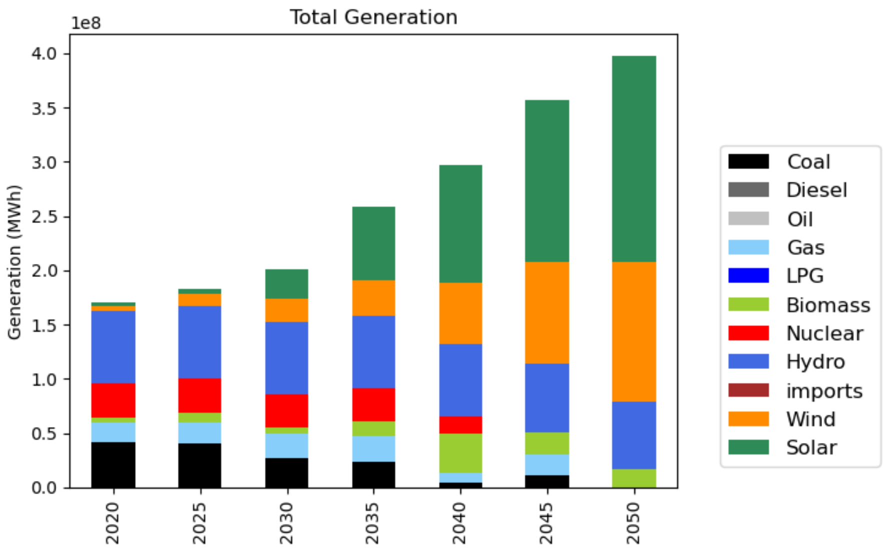

Figure 8. Generation by fuel per year

Figure 9 illustrates the hourly distribution of electricity generation over the course of a year, categorized by fuel type and technology. In the start, the fossil fuel generation is dominated. To provide the base load stability, hydropower energy is continuously present in the system. The results emphasize the feasibility of transitioning towards a balance, sustainable and low-carbon power system, aligning with Pakistan's long-term energy policies and decarbonization goals.

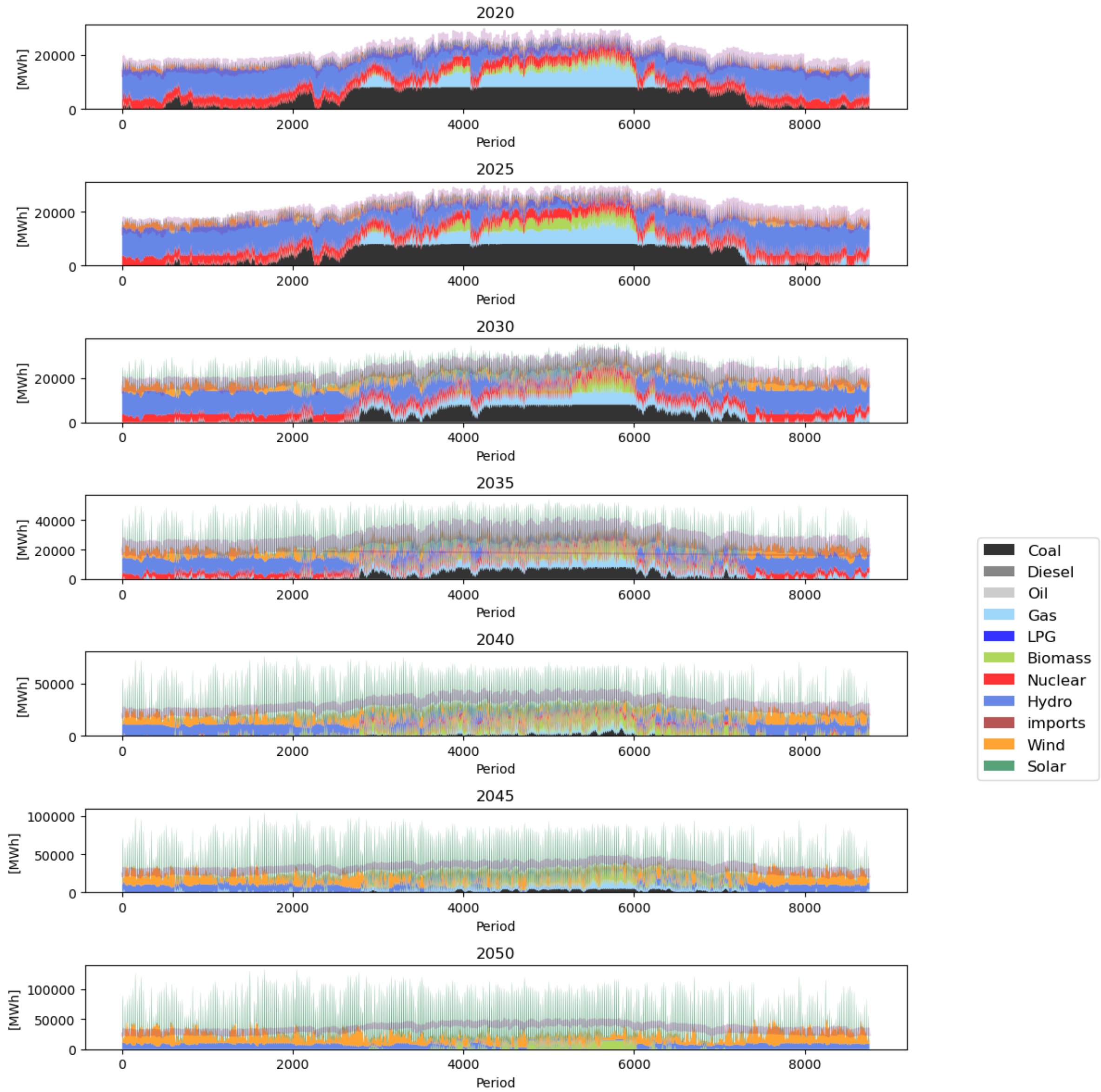

Figure 9. Electricity Generation by year and fuel/technology

Figure 10 depicts the projected "Power-to-X" exploitation on an hourly basis from 2020 to 2050. The possible power-to-X options include heating, hydrogen generation and EVs, while over the period heating demand decreases. Across various timeframes, the extra amount of RE converted into other available options and stationary energy storage systems. In the start as can be seen that power to heat and EVs preside, that revealed the dependence is primarily on electrification for transportation and heating. After 2030, the significance of VRES contributions to start replacing the energy mixed generation based on conventional sources. The instability due to renewable production is mitigated by hydrogen generation and using large energy storage options. The discharge of stored energy indicates that it will take part in the demand and supply balance and stabilize the fluctuations effectively. Also, during 2040 to 2050, the key components to stabilize the grid will be hydrogen and storage options as can be seen in the flexibility options. The results show that the significance of advancement in storage technologies and sector coupling to allow a high share of VRES system. Long term decarbonization in Pakistan will be based on the shifting of transport and heating on electrification and hydrogen-based storage options.

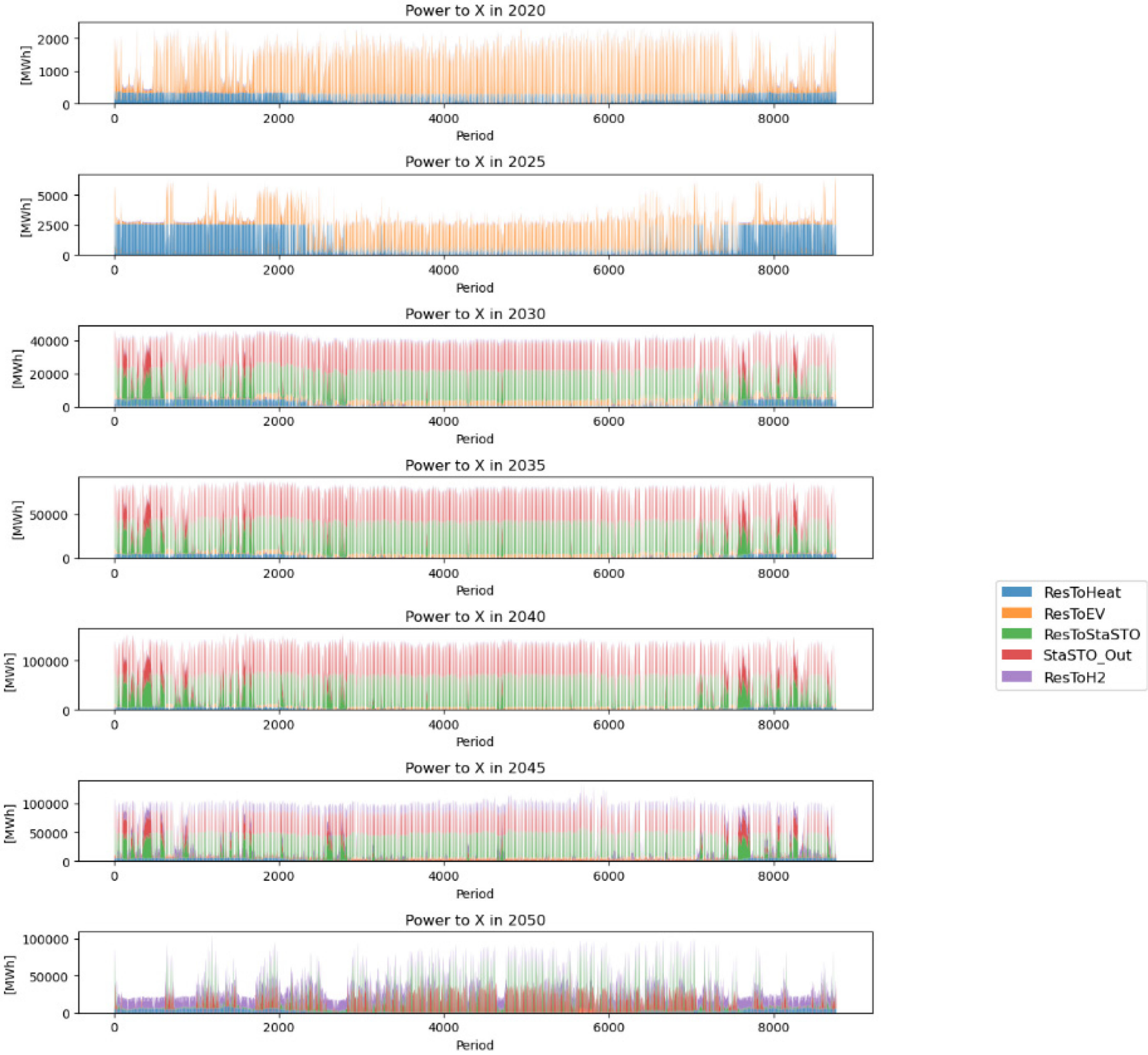

Figure 10. Power-to-X options/Flexibility Options

Addition to total capacity investment across various regions of Pakistan in VRES can be seen in **Figure 11**. A clear addition in the investment of solar and wind energy with substantial growth is observed particularly in Karachi, Gharo, and Faisalabad areas. In the start the investment in solar energy is dominant in most of the reigns like Balochistan and Southern Punjab showing a huge solar irradiance potential in Pakistan. After 2035, the coastal areas such as Jhimpir, Karachi and Gharo are the most favourable for wind corridors. These areas are full of wind energy potential throughout the year. The model starts investment, and it rapidly accelerates after 2030. At national level, most of the distribution companies emphasize the installation of solar energy systems, that accentuate national-level pledge to support large-scale VRES integration. The total capacity investment in renewables particularly in solar and wind power generation in terms of MW for different rich areas of Pakistan can be seen in **Table 3**.

Figure 12 illustrates the envisioned individual heating generation transition mix that elaborates the contribution of different heating technologies like oil, gas, bio, and electric boilers, air to water heat pumps. A significant decrease in gas and oil boilers and then the electric boilers dominate after 2030 indicates that the dependence on fossil fuel reduced and will reach zero in 2050 while the trend shifts towards renewable and electrification-based solution for individual heating generation. This is the evidence in decarbonization of heating sector and electrification of heating systems. It is also observed in the heating generation graph that the heat pumps are not dominant over the boilers is due to the reason that the peak loads are much higher than average, so the utilization is low and therefore HPs are not economical. Moreover, heat pumps also required huge capital cost, elongated payback period, and in existing infrastructure of Pakistan, there exists numerous integration challenges.

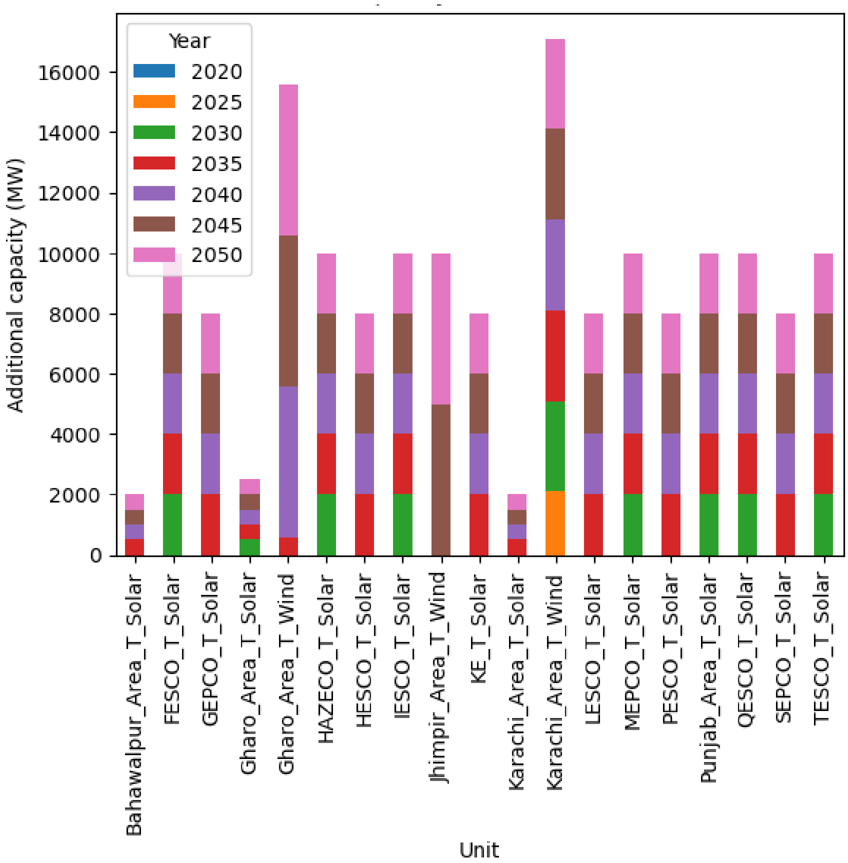

Figure 11. Addition to Total Capacity Investment in VRES (Mega Watt)

Table 3.Capacity investment in renewable (Solar, Wind) systems (MW)

Units	2020	2025	2030	2035	2040	2045	2050
Bahawalpur Area Solar	0.0	0.0	0.0	500.0	500.0	500.0	500.0
FESCO Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0
GEPCO Solar	0.0	0.0	0.0	2000.0	2000.0	2000.0	2000.0
Gharo Area olar	0.0	0.0	500.0	500.0	500.0	500.0	500.0
Gharo_Area Wind	0.0	0.0	0.0	565.45	5000.0	5000.0	5000.0
HAZECO Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0
HESCO Solar	0.0	0.0	0.0	2000.0	2000.0	2000.0	2000.0
IESCO Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0
Jhimpir_Area Wind	0.0	0.0	0.0	0.0	0.0	5000.0	5000.0
KE Solar	0.0	0.0	0.0	2000.0	2000.0	2000.0	2000.0
Karachi_Area Solar	0.0	0.0	0.0	500.0	500.0	500.0	500.0
Karachi_Area Wind	0.0	2100.03	3000.0	3000.0	3000.0	3000.0	3000.0
LESCO Solar	0.0	0.0	0.0	2000.0	2000.0	2000.0	2000.0
MEPCO Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0
PESCO Solar	0.0	0.0	0.0	2000.0	2000.0	2000.0	2000.0
Punjab_Area Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0
QESCO Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0
SEPCO Solar	0.0	0.0	0.0	2000.0	2000.0	2000.0	2000.0
TESCO Solar	0.0	0.0	2000.0	2000.0	2000.0	2000.0	2000.0

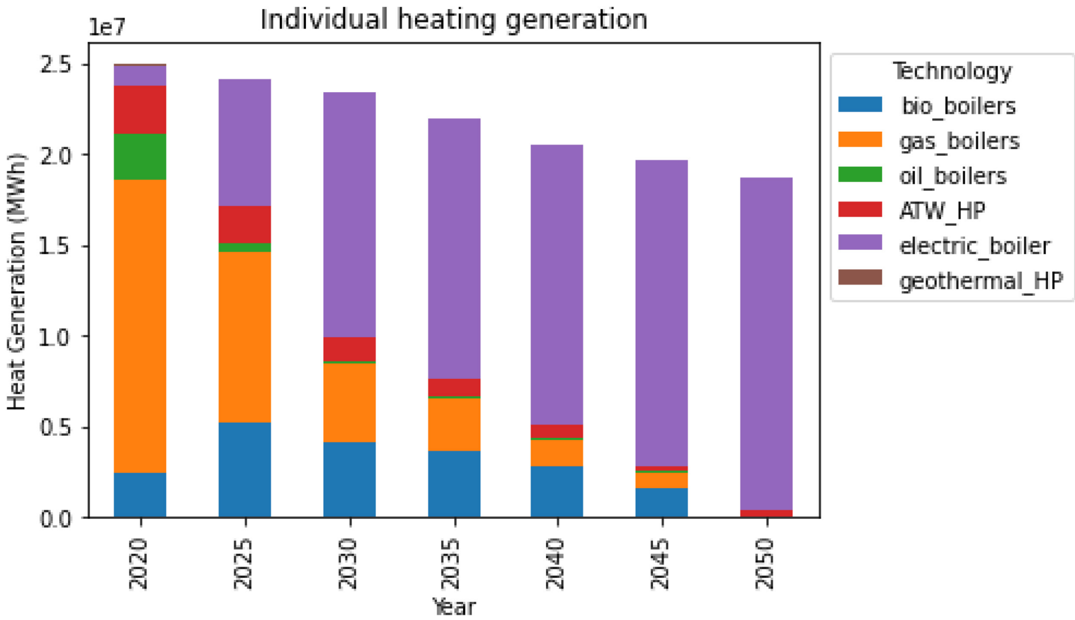

Figure 12. Individual heating generation

Figure 13 illustrates the evolution of industrial fuel consumption from 2020 to 2050 on an hourly basis. The figure highlights the transition in fuel usage within the industrial sector as in the early years (2020 – 2030), gas and oil remain the dominant fuels for industrial processes, with coal contributions. However, by 2035, a noticeable transformation begins as hydrogen starts replacing conventional fuels, marking an early stage of industrial decarbonization. By 2040, the share of hydrogen increases significantly, reducing reliance on gas and oil, enabling a strong industrial decarbonization trend. By 2050, hydrogen becomes the dominant energy source for industrial energy consumption since hydrogen is only carbon neutral option. The results emphasize the critical role of hydrogen in achieving a zero-carbon industrial sector.

The critical excess of electricity production (CEEP) is 8.34 % in 2050 due to the model uses hydrogen generation and storage systems to balance out the variations in energy generation as can be seen in **Table 4**. The generation closely follows the demand and does not generate excessive amounts of CEEP. It displays the generation of CEEP expressed in [TWh] energy along with the percentage of total electricity demand. The results for H2RES display very low CEEP generation until 2040 where it starts to rise to maximum value of 8.34 % for the year 2050. Generation of CEEP is not limited as H2RES model is using hydrogen generation and storage systems, especially in industry sector to balance out the variations in energy generation. **Table 5** clearly represents the CO_2 emissions from 2020 – 2050 from power, heat and industry. The CO_2 emissions in the heat sector rise sharply to 23.7 Mt in 2025, primarily due to continued fossil fuel use for heating before the adoption of electrified heating systems and renewable-based solutions. After this period, emissions decrease in line with the transition to a low-carbon energy system, reaching zero by 2050.

The overall results highlight Pakistan's gradual transition towards a 100% VRES energy system by 2050. Power-to-X integration will increase significantly by 2030, with hydrogen and energy storage technologies playing a key role in balancing the grid. Investments in solar and wind capacity expand across multiple regions, ensuring widespread renewable adoption. In the heating sector, electric resistive heaters replace gas and oil boilers, supporting decarbonization efforts. Industrial fuel consumption shifts from gas and oil to hydrogen, marking a critical step toward low-carbon industrialization. These results emphasize the urgent need for infrastructure development, policy incentives, and technological advancements to facilitate a sustainable energy transition in Pakistan to achieve long-term SDGs.

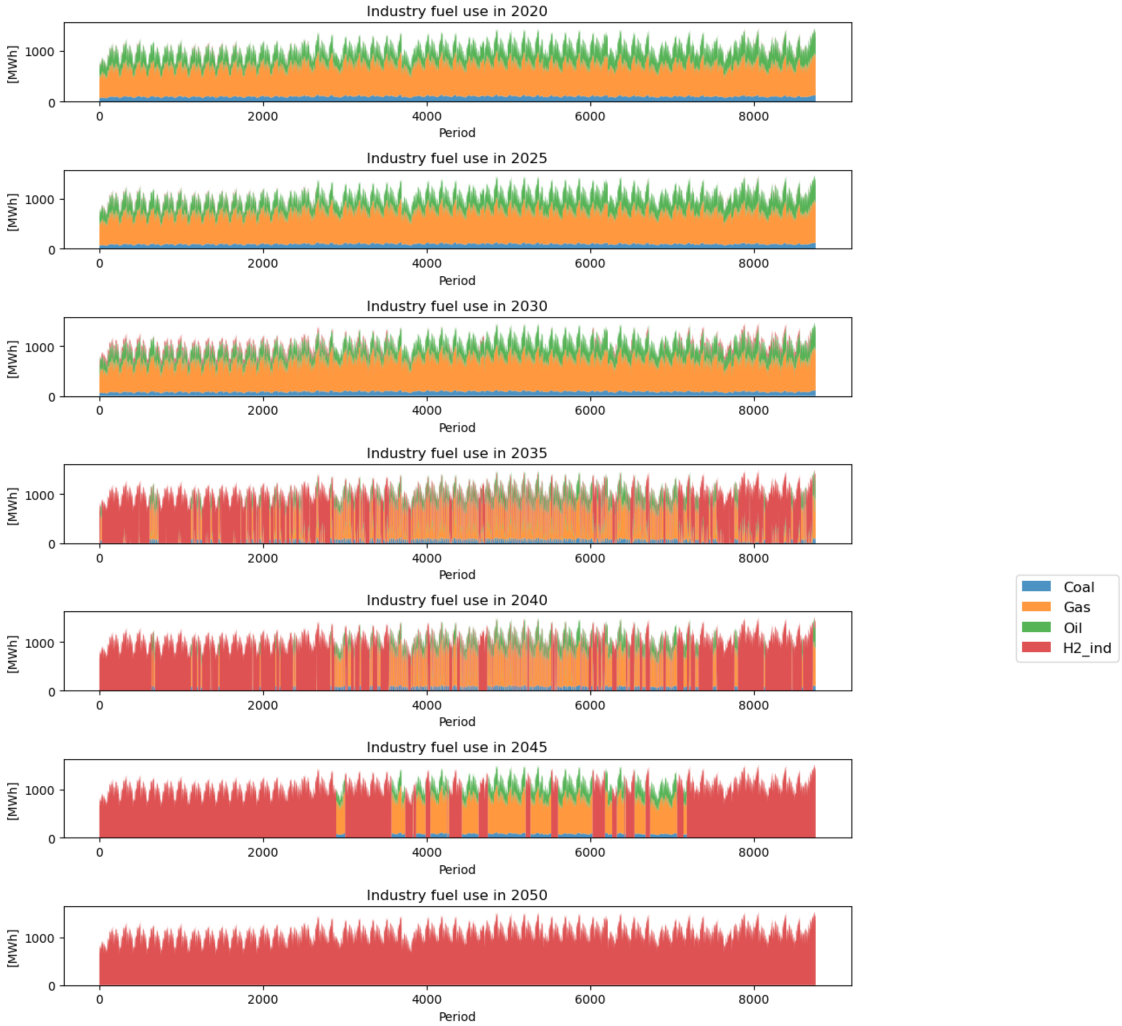

Figure 13. Industrial fuel use or Energy supply in Industry

Table 4. Critical Excess of Electricity Production

Year	2020	2025	2030	2035	2040	2045	2050
CEEP (TWh)	0.0	0.0	0.014598	2.830	10.929	28.858	34.833
CEEP (%)	0.0%	0.0%	0.01%	1.02%	3.46%	7.52%	8.34%

Table 5. CO_2 Emissions (Use millions of tonnes [Mt])

Year	2020	2025	2030	2035	2040	2045	2050
CO2_power	44.55	24.26	12.24	16.98	14.06	10.27	0.00
CO2_heat	4.68	23.7	1.05	0.73	0.38	0.21	0.00
CO2_industry	3.06	3.05	2.93	1.33	1.03	0.95	0.00

DISCUSSION, LIMITATIONS AND FUTURE DIRECTIONS

The proposed roadmap is for developing countries, such as Pakistan, to transition their energy systems to 100% VRES by 2050. It offers a comprehensive and structured approach to achieving energy sustainability while addressing the technical, economic, and environmental challenges associated with large-scale VRES integration into the existing energy system. By leveraging Pakistan's abundant solar, wind, hydropower, and biomass potential, the roadmap highlights the technical feasibility of energy transitions. Drawing from the experiences of countries like Denmark and Germany, early investments in energy storage and smart grid technologies have proven to enhance the resilience of RE systems. Comparatively, Pakistan energy transition plan incorporates these insights while adapting to its unique geographic and diverse climate zone conditions. The transition to 100% VRES promises long-term benefits, including reduced dependence on fossil fuel imports, lower energy production costs, and job creation in RE sectors. Although the initial phases demand significant capital investments in infrastructure and RE plants, case studies from China and India reveal that these costs are offset over time by declining technology costs and the absence of fuel expenses [36]. Pakistan can ease the financial burden of this transition by leveraging international financing mechanisms, such as green climate funds and RE loans. The roadmap is transformative, aligning with global climate goals, such as the Paris Agreement, and positioning Pakistan as a leader in sustainable energy transitions in South Asia. By phasing out fossil fuel plants, the country can achieve significant reductions in GHG emissions, air pollution, and water consumption, particularly benefiting urban areas affected by smog and pollution. Similar transitions in Sweden and Norway have demonstrated these environmental benefits, including improved air quality and public health outcomes [37]. Comparing Pakistan's transition roadmap with global efforts highlights both challenges and opportunities. Developed countries like Germany and Denmark have benefitted from robust policy frameworks, advanced technologies, and financial resources, enabling them to achieve significant RE integration. In contrast, Pakistan faces hurdles such as policy inconsistencies, weak institutional capacity, and limited financial resources. However, emerging economies like India and Brazil offer closer parallels, showcasing successful examples of VRES integration through targeted policies, public-private partnerships, and international collaboration [38]. The study's findings emphasize the importance of localized approaches to energy transitions, with context-specific solutions tailored to unique socioeconomic and geographic challenges in Pakistan. By drawing on the experiences of countries like Morocco and addressing localized challenges, Pakistan can accelerate its transition to 100% VRES by 2050. The reduction in fossil fuel dependency will lower GHG emissions, helping the country meet its commitments under the Paris Agreement to fulfil the sustainable development goals 7 and 13. Additionally, the development of RE projects will create thousands of jobs in construction, operations, and maintenance, contributing to economic growth and energy security. The transition to 100% VRES in Pakistan required strong policy frameworks to support the integration of VRES. Comparative policy benchmarking shows that countries like Germany and Denmark have successfully implemented policies that incentivize VRES investments and infrastructure development. Lessons from these countries can guide Pakistan in adopting similar strategies, such as feed-in tariffs, green finance mechanisms, and carbon pricing to accelerate the transition.

The limitations of this research work and the future directions are also part of discussion:

1. The open source H2RES model makes the decision only on long term optimization by taking the intact planning period.
2. By developing the myopic version of H2RES model, the decision-making approach will change to short term. It will make the real time adjustments which are more feasible to practical.
3. This study does not consider tidal and geothermal energy sources and does not incorporate in the input data files.

CONCLUSION

The main objective of this research work is to develop a sustainable energy transition paradigm for the developing countries. Pakistan with its abundant RE potential, climatic diversity, and increasing energy demand is chosen as a case study. To create an optimal balance between generation and energy demand for the period 2020 – 2050 after every 5-years internal, H2RES model is used. The research concluded that by transforming the Pakistan energy sector into 100% RE system is economically favourable, technically feasible and environmentally transformative. The proposed model provides a roadmap for decommission of power plants, retiring of nuclear plants, installation of VRES. For large scale investments in VRES infrastructure, advancement in technologies, energy storage technologies, flexibility options, and generation of hydrogen are clearly highlighted. By adopting this proposed roadmap, Pakistan can achieve SDG_7 (Affordable and Clean Energy) and SDG_13 (Climate Action) targets. These research directions provide actionable insights to support a successful, adaptive, and inclusive energy transition.

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