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Review

An Overview of the Current Energy Situation of Pakistan and the Way Forward towards Green Energy Implementation

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Abstract: Pakistan has been facing energy crises for more than a decade as a result of its reliance on imported fossil fuels, circular debt, political instability, and absurd energy policies. However, the country has abundant renewable energy resources which, if harnessed, may help to effectively cope with ever-increasing energy demand. This review study investigates the country's economic and energy situations, energy crises, and energy sector performance. A critical analysis of studies conducted on Pakistan's energy planning since its independence in 1947 is, and policies announced to date are assessed. This review reveals that the economic situation of the country has remained severely stressed, and energy sector performance has been compromised over the years for various underlying reasons. The energy policy narrative in the early decades of the post-independence period focused on water resource management, whereas energy concerns were only realized in the late 1960s as demand grew. The first-ever energy and power planning study in Pakistan was conducted in 1967, and since then, various studies have been conducted to support the medium-term development plans of the government. These planning studies inspired further development, and in 1994, the first-ever electricity-focused power policy was announced by the government in response to industrial growth and subsequent electricity demand. However, this and subsequent policies were fossil-fuel-centric until 2006, when the government announced the first-ever renewable energy policy. This 2006 policy focused on increasing renewable energy penetration in the overall energy mix by setting specific targets. However, these targets have rarely been accomplished as a result of a lack of an effective planning paradigm, as most of studies have been conducted without sound demand forecasting and without considering renewable energy's potential to meet growing demand. As such, planning efforts based on proven methodologies/modeling tools and the undertaking of demand forecasts and renewable energy assessments are inevitable for countries such as Pakistan. Therefore, we suggest that sectoral energy demand forecasting, estimation of renewable energy potential with end use, and modeling of optimal penetration of renewable energy using energy modeling tools will be helpful to develop sustainable energy policies in Pakistan to eradicate the energy crisis.

Keywords: energy system; renewable energy modeling; energy policies; energy planning

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1. Introduction

Pakistan is situated between latitude 30° N and longitude 69° E. The total land area of the country is approximately 76 thousand km^2. The administrative units comprise four provinces (Punjab, Sindh, Khyber Pakhtunkhwa, and Baluchistan), one capital federal territory (Islamabad), and two autonomous territories (Azad Jammu and Kashmir and Gilgit-Baltistan. A map of the country is shown in Figure 1.

Figure 1. Map of Pakistan [1].

The diversity of Pakistan extends to its climatic, environmental, and socioeconomic characteristics, which change from region to region. A proportion of 38% of the total land area of the country is arable; major crops grown include rice, wheat, cotton, sugar cane, and maize, as well as a rich diversity of fruits. Pakistan is the world's fifth-most populous country, with a population of 203 million. According to the first census conducted in 1951, the official population of the country was 32.7 million. During the last four decades, the population of the country has increased at an average growth rate of 2.57%. At present, 36.44% of the population resides in urban areas. The population growth of Pakistan is considered to have slowed in recent years (2.4% average annual growth rate for the period of 1998–2018). The population of Pakistan, along with its annual growth rate, from 1975 to 2018 is shown in Figure 2.

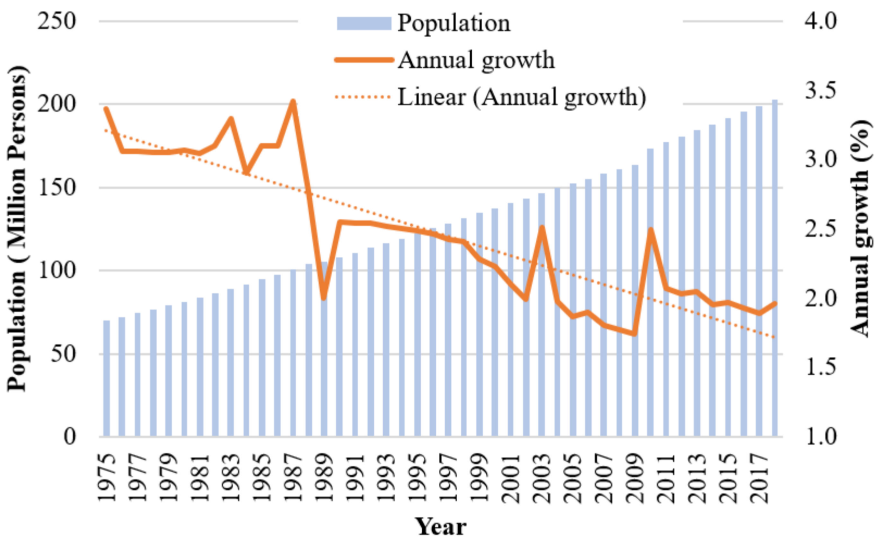


Figure 2. Population growth of Pakistan [2].

Energy is an essential commodity of modern-day economies. The technologies involved in its production and consumption have, therefore, attained increasing importance. The provision of a clean, affordable, and reliable supply of energy in various forms is deeply intertwined with sustainable development and energy security. However, such ambition could only be achieved with a maximum of renewable energy in the overall energy mix. In the meantime, the growth of energy demand is exponentially increasing, encouraging energy planners and policy makers to address this challenge. It was reported that the global primary energy supply increased by 66% from 1990 to 2019, whereas electricity consumption surged to approximately 130% during the same period [3]. However, much of this energy demand is fulfilled using fossil fuels, which are key contributors to greenhouse gases (GHGs), which cause climate change. Oil and coal are the leading fossil fuels, representing a share of approximately 57% of the global energy supply [3]. The United Nations Secretary General reported a chronicle of climate chaos, outlining the effects of worsening heat waves, melting ice, and torrential rains around the world in his opening remarks at the COP27 climate summit. He also reported that Earth is fast approaching tipping points that would make climate chaos irreversible [4]. Apocalyptic floods in Pakistan, extreme heatwaves from Europe to China, the devastations caused in Belize by storm Lisa, and torrential floods in St. Lucia require climate-resilient global policies. Therefore, it is urgently necessary to consider renewables such as wind, solar, biomass, and small hydro generation to meet the ever-increasing demand. In this context, over the past decade, growth in renewable energy conversion technologies has increased the penetration of these resources. However, the improved share of renewables for power generation and other uses is not at par with the growth in the demand and is insufficient in developing economies. Therefore, it is challenging for developing countries to meet the increasing energy demand and ensure energy security.

(i). Problem statement

Poor economic conditions, scarcity of fossil fuel resources, uneven energy planning, and political instability are key daunting challenges faced by developing countries in cope responding to energy demand, although the majority of developing countries are blessed with substantial renewable energy resources. In such situations, reliance both on conventional energy resources and conformist energy planning could be helpful for these countries. As such, energy planning and policies considering optimal penetration of renewables in the overall energy mix is inevitable to attain the goal of sustainable development and energy security. Pakistan, like many developing countries, has been gripped by severe energy crises for nearly two decades. Electricity shortfall in the country alone has paralyzed production and even resulted the shutdown of industries, contributing to worsening unemployment. The country's limited indigenous oil and gas resources are rapidly depleting, and the harnessing of coal and renewable energy sources is a slow process. Pakistan has plentiful indigenous energy sources; however, with a population of over 200 million and rapid growth during the last twenty years, poor planning and a lack of proper governance has instigated a severe energy crisis. Therefore, electricity utilization per capita in the country is only 452 kWh, which is about one-quarter of the average global consumption. In summers, owing to very high temperatures and extreme humidity in lower regions of Pakistan, the electricity demand increases beyond generation/transmission capacity, causing load shedding of 8–12 h in city areas and 12–18 h in countryside areas. The demand for natural gas has also increased more than the supply capacity; therefore, large-scale consumers, mainly power plants, industry, and the transport sector are limited during winter to ensure provision to domestic and commercial consumers. The energy deficit has led to the shutdown of thousands of industries, or their industrial production has been adversely affected, compromising the standard of living of a large number of families, with a major impact on the economy and a very serious loss to the overall GDP growth of the country of approximately 10%. If this energy deficit is not addressed in the near future, Pakistan's energy crisis might develop into a national energy security risk.

In order to meet growing energy demand, governments and academics worldwide are undertaking extensive energy planning exercises, using energy modeling to support energy policy formulation. Such efforts aid in the analysis of policy options under different scenarios and at different levels. Various researchers have also greatly emphasized the use of energy modeling as the most efficient and appropriate approach to undertake energy planning and policy analysis.

Both conventional and renewable energy resources have been considered in various developed countries at the government level and by researchers at the academic level as part of integrated energy planning, using energy modeling to meet the demand [5]. However, integrated energy planning and energy policy formulation in the context of developing countries such as Pakistan lack consideration of renewable energy resources and appropriate application of energy modeling.

It is also pertinent to mention that Pakistan is blessed with enormous renewable energy resources. Estimation of these resources on a scientific basis had not been undertaken until recently [6]. In order to tap these renewable energy sources, multiple efforts in renewable energy modeling are essential to estimate their realistic potential and their diffusion in the long run.

Various energy planning approaches are now rely on computer-based energy modeling tools which include, the Energy and Power Evaluation Program (ENPEP), Market Allocation (MARKAL), the Low Emissions Analysis Platform (LEAP), the Model for Energy Supply Systems And their General Environmental Impact (MESSAGE), and Energy PLAN. These are well-recognized energy modeling tools used for energy planning at various levels, as they offer data arrangement and a framework for testing hypotheses and reflect the complete energy system. Energy planning can be undertaken using these or other energy modeling tools that offer variety of analytical features in terms of regions, technologies, and specific objectives, along with their constraints.

(ii). Study contributions

In this systematic literature study, we review all the energy carriers; in the case of Pakistan, only a few studies have been conducted, mainly in academia, wherein energy modeling has been used but without considering the indigenous renewable energy resources of the country. The outcome of this research is anticipated to facilitate the energy planners and policy makers in considering maximum utilization of renewable energy resource penetration in the overall energy mix of Pakistan in the long run. The aim of this paper is to undertake a detailed review of the current status of the energy sector of Pakistan, as well as planning studies undertaken and policies announced to date. Based on our extensive review, an energy planning framework is suggested to eradicate the energy crisis with maximum penetration of renewable energy in the overall energy mix of Pakistan.

(iii). Paper structure

This thesis is organized into six main sections as follows.

In Section 2, we present an analysis of the current energy situation of Pakistan, taking in to account the energy supply, sectoral primary energy consumption, and electricity generation by source, and devise reasons for the energy crisis in Pakistan. In Section 3, we review the institutional structure of Pakistan's energy sector, as well as energy planning and modeling studies undertaken to date, and present an analysis of power and energy policies announced by the government. In Section 4, we investigate the renewable energy potential of Pakistan and related studies undertaken for estimation of the country's renewable energy sources. In Section 5, we summarize issues related to current energy planning policies of Pakistan. In Section 6, we propose a triple-helix model of research issues and knowledge gaps.

2. Energy Situation and Challenges of Pakistan

The energy security of Pakistan is at the mercy of imported fossil fuels. Pakistan relies mainly on oil and gas to meet its energy demand. The national energy system of Pakistan for various energy sources for the year 2018–2019 is shown in Figure 3.

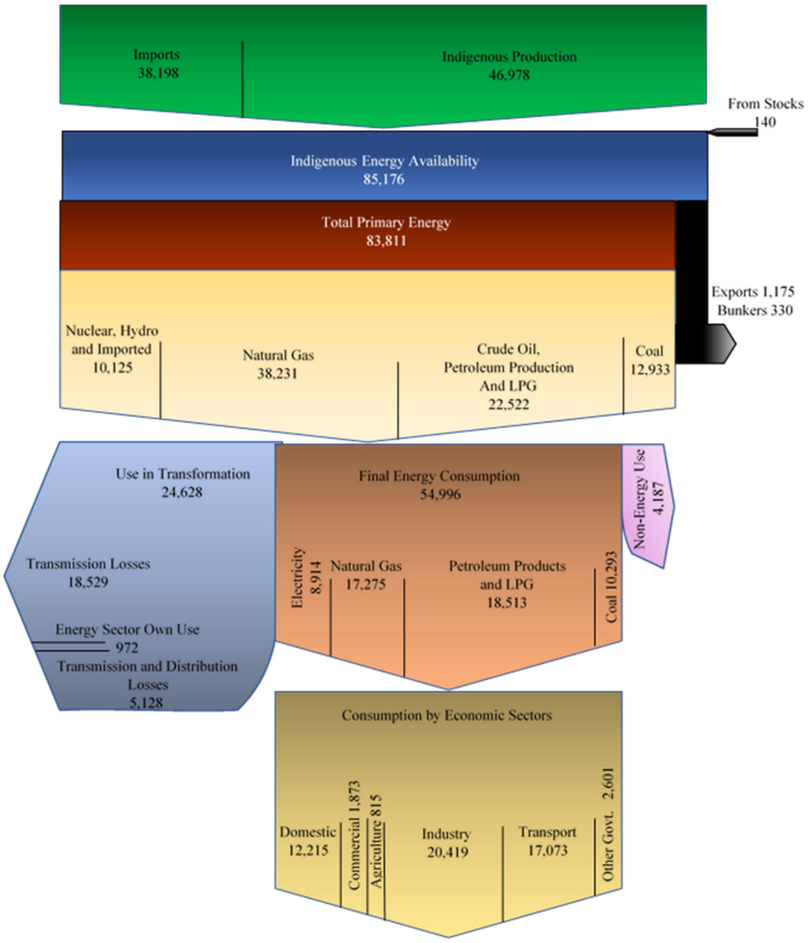


Figure 3. Flow chart of Pakistan's energy system [7].

It is evident from the above illustrations that indigenous energy availability is limited; therefore, the county must rely on imports. The share of different sources in primary commercial energy supply in the period from 2013–2014 to 2018–2019 has varied substantially. In 2013–2014, the oil share in the overall energy mix was 34.4%, which was reduced to 25.7% in 2018–2019. It is pertinent to note that the share of gas was also reduced from 46.3% in 2013–2014 to 35% in 2018–2019. However, the share of coal increased from 5.4% in 2013–2014 to 15.4% in 2018–2019. Another key variation in the overall share of the energy mix is related to hydro and nuclear resources, the share of which was reduced from 13.3% in 2013–2014 to 10.7% in 2018–2019. On the positive side, in 2018–2019, the overall energy mix included a renewable energy share of 1.3%, which minimal but expected to increase.

With respect to energy consumption, the major consumers of primary commercial energy are the industrial, transport, and domestic sectors, as shown in Figure 4.

Industrial energy consumption accounts 37.11% for the total, whereas the domestic sector consumes approximately 22% of primary energy. The commercial, agriculture, and other sectors consumed approximately 3%, 2%, and 5% of primary energy, respectively, in 2018–2019. The electricity generation mix according to source for 2018–2019 is shown in Figure 5; fossil fuels, hydropower, nuclear, and renewable energy represent 67%, 21%, 8%, and 4% shares, respectively.

Indigenous oil and gas resources are limited, and the country is heavily dependent on oil and gas imports. Given the present production rate, indigenous recoverable oil and gas reserves may be exhausted after 12 and 13 years, respectively. In the meantime, there is considerable potential of coal (185 billion tons) in the country; however, this resource has not been effectively employed due to somewhat inferior quality, economic restrictions, the site of the resources, and a lack of expertise and convenience in modern coal conversion technologies. Approximately 85% of Pakistan's oil demand is fulfilled by imports, with an expenditure of approximately USD 14.7 billion per annum [9]. The import of oil is a serious stress on the economy and has worsened economic conditions. The country's energy demand is predicted to grow rapidly with economic growth, and it has been forecasted that the demand for primary commercial energy could increase at a rate of 4.3, 7.3, or 10.4% per annum depending on the situation. Therefore, the government of Pakistan (GOP) has planned to bridge the energy demand–supply gap by considering various alternative options. The options for import of regional gas have been controlled by the delicate local security situation, technical matters, and complications related to profitability and working measures, which are challenging in typical large-scale projects demanding intercountry contracts.

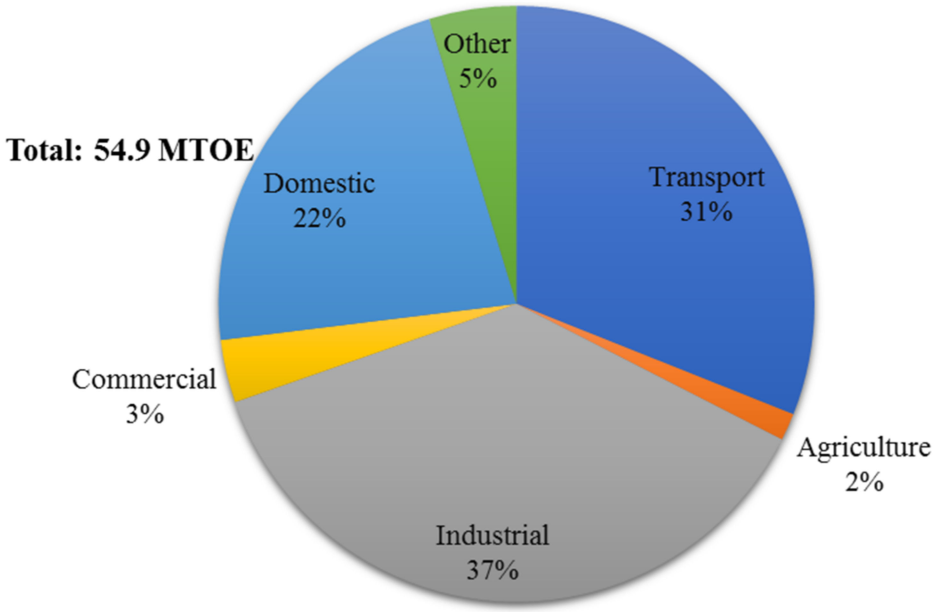


Figure 4. Primary energy consumption by sector [7].

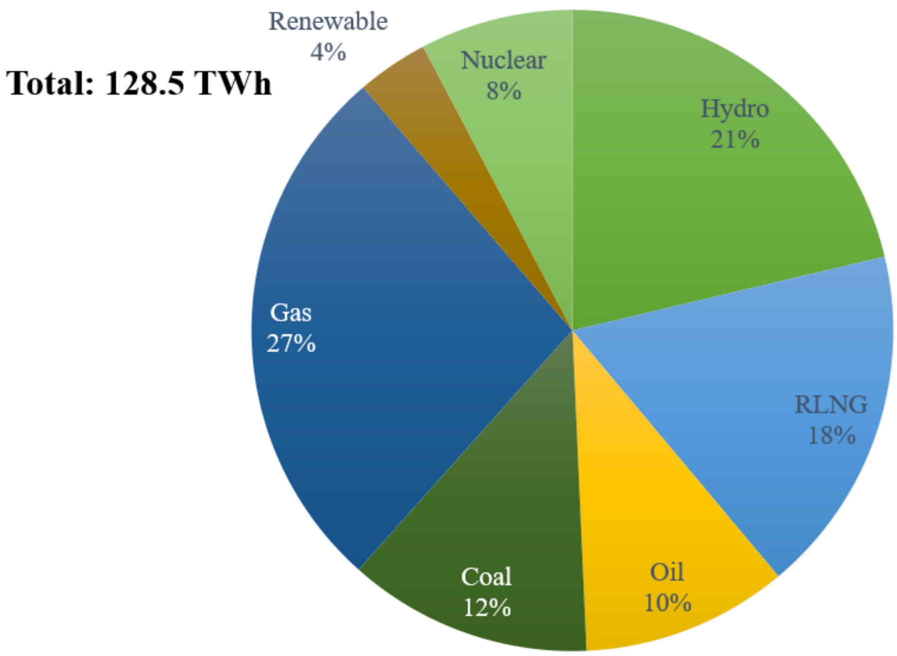


Figure 5. Electricity generation by source [8].

The country also suffers from an economic impediment known as circular debt. This issue in the energy sector has largely remained uncontrolled, even with unrelenting efforts of different governments. The reported debt of PKR 450 billion in 2013 had increased to PKR 2.3 trillion as of 31 December 2020, which is equivalent to 5.6% of the country's total GDP. The key reasons for circular debt in Pakistan are (i) the high cost of power generation affecting collection efficiency; (ii) pitfalls and delays in tariff determinations; (iii) high transmission losses, power theft, corruption, and revenue collection problems; (iv) government subsidies; and (v) high financial costs of government borrowing and expensive late-payment penalties on payables. A summarized illustration of the energy crises of Pakistan is shown in Figure 6.

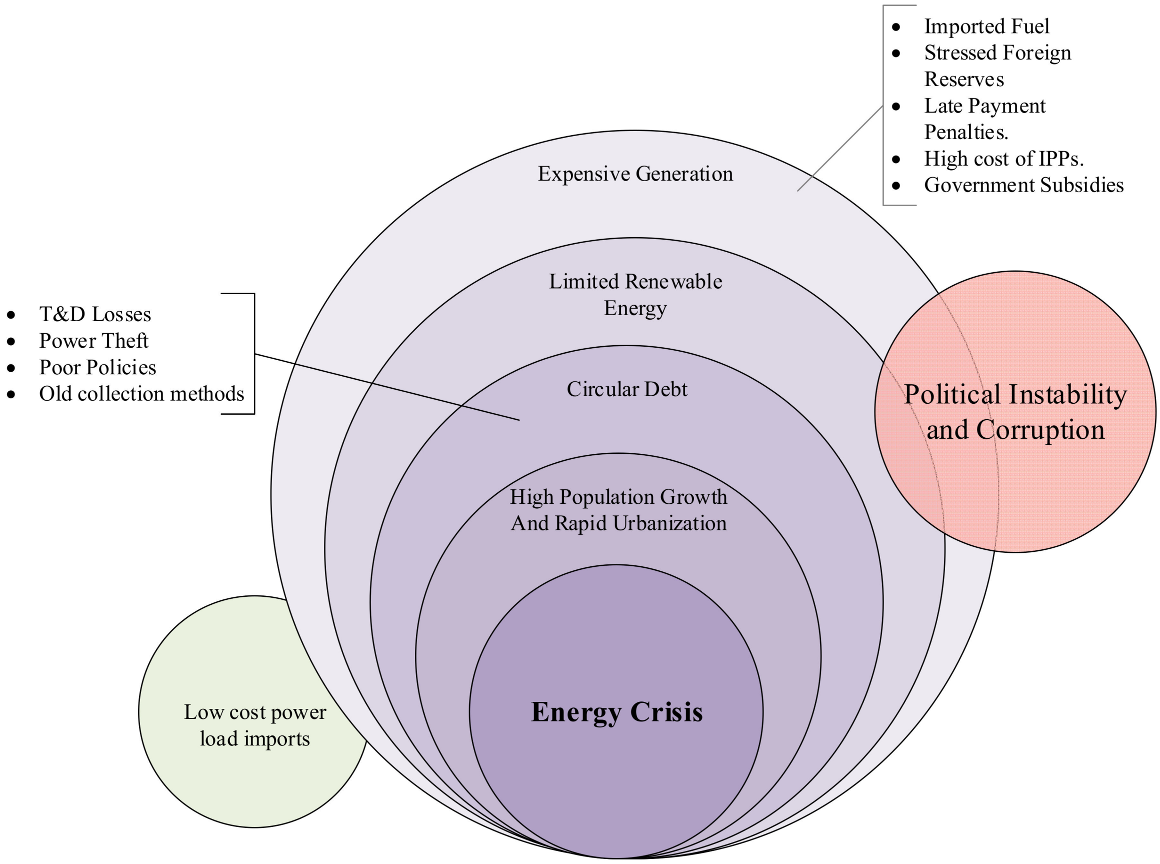


Figure 6. Energy crises in Pakistan.

The resolution of Pakistan's energy crises could be essentially achieved with effective energy planning by considering optimal diffusion of renewable energy resources and improving governance. This approach could help to overcome oil import expenses, contain climate change, and ensure energy security in the long run. If the country's energy crises are not tackled at both operating and strategic levels in the immediate future, Pakistan's energy crisis might become a national security threat.

3. Energy Sector of Pakistan

Energy plays a key role in the economic development of any nation and is one of the most important commodities for humans. However, Pakistan is confronting severe crises of energy in the form of electricity and fuel in all major sectors. Energy crises have resulted in the shutting down of a number of industries and factories, paralyzing production and worsening redundancy. The main causes the energy crises are increasing demand, planning, and governance.

Pakistan's indigenous fossil fuel reserves (oil and gas) are limited and rapidly depleting. The progress in identifying new reserves of oil and gas, harnessing indigenous coal reserves, and utilization of renewable energies is extremely slow. The institutional structure of the energy sector has been shaky over the years, and until the emergence of industry and transport, the energy sector was principally considered to be an electricity system. Following the establishment of the Water and Power Development Authority (WAPDA) in 1958, various large and small dams were developed. Under the WAPDA, various power projects were developed based on hydro and fossil fuel resources; as such, all primary energy sources were mainly dedicated to power generation.

The concept of an integrated energy system could not evolve and attain any importance until the growth in other economic sectors in 1980s. As such, no formal energy policy was announced by the government until 1994. The energy policies declared then lacked an integrated energy and planning approach, did not consider renewable energy resources, and remained contradictory, resulting in issues associated with their implementation.

3.1. Institutional Structure

The energy and power sector of Pakistan has had been subject to various reorganization and reforming phases from time to time. The restructuring of this sector commenced in 1990s with the ultimate aim of autonomy and privatization but still undergoing various trials. In its current form, Pakistan's energy sector under the Ministry of Energy (MoE) mainly comprises two divisions, namely the Petroleum and Power Divisions, with relevant roles and responsibilities. Key energy infrastructure organizations and their roles and responsibilities are summarized in Table 1.

Table 1. Key energy infrastructure organizations and their roles and responsibilities [10,11].

Governing Ministry	The Ministry of Energy Petroleum Division and Power Division
Coordination	Energy Wing Planning Commission(policy formulations, legislation, and implementation)
Payments	Ministry of Finance
Regulatory body	• Directorate General of Petroleum Concessions • OGRA, NEPRA, CPPA (market operator), and PPIB
Legitimate Framework	**Upstream (E&P)** • 1923 Act for mines of Pakistan • 1948 Act for regulation of oilfields, mineral and mines control, amended in 1976 • 1976 Act for water territories and naval zones **Oil and gas downstream** • OGRA Rule 2002 **Power** • NEPRA Act no. XL of 1997
Polices	**Upstream (E&P)** • 1994–2012 policies pertaining petroleum • 2011 policies pertaining cost of gas • 2011 policies for tight gas **Oil and gas Downstream** • 1997 Petroleum Policy • 2005 policy for allocation of natural gas • 2018 regime for the tariff of natural gas • 2016 production and distribution of natural gas **Power** • Power Policy of 2015 and Transmission Line Policy of 2015

Table 1. *Cont.*

Rules and Regulation	**Upstream (E&P)** • 2013 gas pricing criteria and guidelines • 2003 Offshore Petroleum Rules • 2011 regulations for third parties • 2013 Onshore Petroleum Rules **Oil and gas Downstream** • 2016 Refining, Blending, Transportation, Storage, and Marketing Rules • 2018 OGRA Rules **Power** • NEPRA Rules (1998), NEPRA Licensing Rules (2000), and Performance Standards Rules (T&D 2005 and generation 2009)
R&D	• NEECA and AEDB focused on electric power • PCRET and various academic institutes
Production and Distribution companies	**Oil and Gas** • OGDCL, PPL, PSO, SSGC Limited, and private multinationals **Power** • Public GENCOS, WAPDA (hydro only), Pakistan Atomic Energy Commission (nuclear only), IPPS (hydro, thermal, and renewable), KE, and 10 distribution companies

Other than the MoE, the Ministry of Finance; the Ministry of Science and Technology; the Ministry of Planning, Development and Reforms; the Pakistan Atomic Energy Commission (PAEC), power sector regulator NEPRA; and various multinationals, as well as IPPs, are key players in the energy sector. However, these organizations only undertake energy and power-planning-related activities, and electricity-related work undertaken by the NTDC. At the national level, only a few integrated energy and power planning efforts, without renewable energy as a focus, have been reported, which are briefly discussed in the following section.

3.2. Energy Planning/Modeling Studies Undertaken by the Government of Pakistan

The development in the energy sector to meet demand with limited resources was gradual following independence in 1947. Pakistan inherited only 60 MW of installed capacity for electricity. At the outset, the energy sector made some progress, but this did not last long. The dilemma of ever-increasing energy demand and fuel crises has rendered Pakistan in a constant state of energy crises; most of the population has no or limited access to electricity, with only expensive transport fuel available [12].

The first-ever water- and power-focused organization, WAPDA, was established in 1958 and proposed a five-year planning paradigm conceived through the Ministry of Finance and formally endorsed by the Economic Coordination Committee (ECC). However, only limited studies have been carried out domestically by the government with respect to the water and power sectors over the decades.

These limited government-level energy planning/modeling efforts were often technically and financially supported by international organizations with their vested interests. A summary of such studies undertaken by the government of Pakistan at the national level are summarized in Table 2 [13].

The methodologies of these studies were generally based on statistical or survey tools, with limited attention on forecasting energy demand of other sectors, renewable energy assessment, technologies for different end uses, and modeling of optimal renewable energy penetration in the energy mix of Pakistan.

Table 2. Government-level studies analyzing the energy system.

Study	Initiator	Method/Tools	Key Focus	Limitations/Challenges
Lieftricnk Report (1967)	World Bank	• Statistics • Linear programming	• New fuel supply • Installations of gas power plants • Creation of a fuel depot	• Change in energy infrastructure
RESPAK Model (1988)	Planning Commission of GOP	• Optimization planning framework	• Optimized planning framework with technoeconomic and efficiency constraints	• Lack of expert team and capacity building
Energy and nuclear power planning study for Pakistan (1994)	PAEC	• MAED • BALANCE • WASP • IMPACTS • FINPLAN	• Optimal share of nuclear power	• Focused on power generation only
National Power Plan (1994–2018)	WAPDA	• System Expansion Plan	• Load forecasting • Power generation mix based on indigenous fuel	• GOP focused privatization of power sector
Energy Security Action Plan (2005–2030)	Planning Commission of GOP	• Statistical methods	• Energy consumption trend • Future load growth estimation • Additional installations	• Global economic recession, 2008
Pakistan Integrated Energy Model (2007)	International Resource Group	• TIMES	• Integrated resource utilization • Energy efficiency • Indigenous resource utilization	• Unwanted delays • Model complicity • Unavailability of trained manpower
Overcoming Pakistan's Energy Crisis (2014)	Wilson Centre	• Policy analysis	• Policy recommendations for: • Hydrocarbon exploration in Pakistan • Renewable power generation • Iran–Pakistan Pipeline Project • Energy theft control	• Mainly focused on power generation • Political interests • Law and order situations
Electricity demand forecasting (2014–2037)	NTDC	• Regression analysis	• Electricity demand forecasting	• Only electricity demand considered • Ineffective methods
Electricity demand forecasting (2014–2024)	DISCOsNTDC	• Power market survey	• Effects of load shedding • Demand-side management	• Only electricity demand considered
National Power System Expansion Plan (2011)	NTDC	• System planning and production costing (SYPCO)	• Hydropower feasibility • Extension of gas pipelines • Thar coal development	• Slow implementation

Table 2. *Cont.*

Study	Initiator	Method/Tools	Key Focus	Limitations/ Challenges
Least Cost Generation and Transmission Expansion plan (2015)	Japan International Cooperation Agency	• Plant capacity analysis	• Increased generation capacity	• Delayed commissioning of projects • Failure of development plans
Renewable Energy Mapping Project (2016)	World Bank and AEDB	• Survey • Weather stations	• Development of a solar and wind map • Agriculture resource assessment	• Improper, slow, and limited utilization of data • Mainly focused on power generation
Bankability of the Transport Sector	Karandaaz Pakistan	• Survey	• Insights into the road transport sector • Growth in transport sector with financial services	• Limited/no attention to alternative and sustainable transport fuels
Integrated Energy Planning (IEP) Modeling for Sustainable Development (ongoing)	Planning and Development GOP and USAID	• GCAM • Regression • ARIMA	• Energy demand forecasting • Optimal integrated resource utilization	• Delays • Inflation • Political instability • Limited resources • Inadequate academic participation

3.3. Power and Energy Policies of Pakistan

A strategic policy outline based on rational planning efforts lays the foundation for economic prosperity. Pakistan is a developing country with an extremely fragile economy; as such, effective energy policy endeavors could play a significantly important role in the overall development and well-being of its population. However, in the recent past, Pakistan has not had a single energy policy document, with policy instead spread across sub-policies. Many policy documents have been introduced concurrently, such as a petroleum exploration policy, natural gas allocation and management policy, a national energy conservation policy, power policy, the recently proposed alternative and renewable energy policy, and the national electric vehicle policy. Debate continued about merging relevant policies into a single energy policy document, but due to multidepartmental concerns and a lack of coordination, a single integrated energy policy document has not been realized to date. Various national-level organizations are involved in the formation of different energy-related policies; these organizations, along with their functions, are summarized in Table 3.

Table 3. Key energy sector organizations [5].

Organization	Ministry	Functions
Energy Wing	Planning Commission and Reforms	• Management of policy formulation
Power Division	Energy	• Power policy formation and implementation
Petroleum Division	Energy	• Formulation of petroleum and natural resources for energy and mineral policy
National Energy Conservation Centre	Climate Change	• Development and implementation of climate change policies
		• Development and implementation of energy conservation policy

The following are the key energy and power policies announced by the government of Pakistan. Key strategies proposed as part of these policies are summarized under each policy announced to date in Figure 7 [14,15].

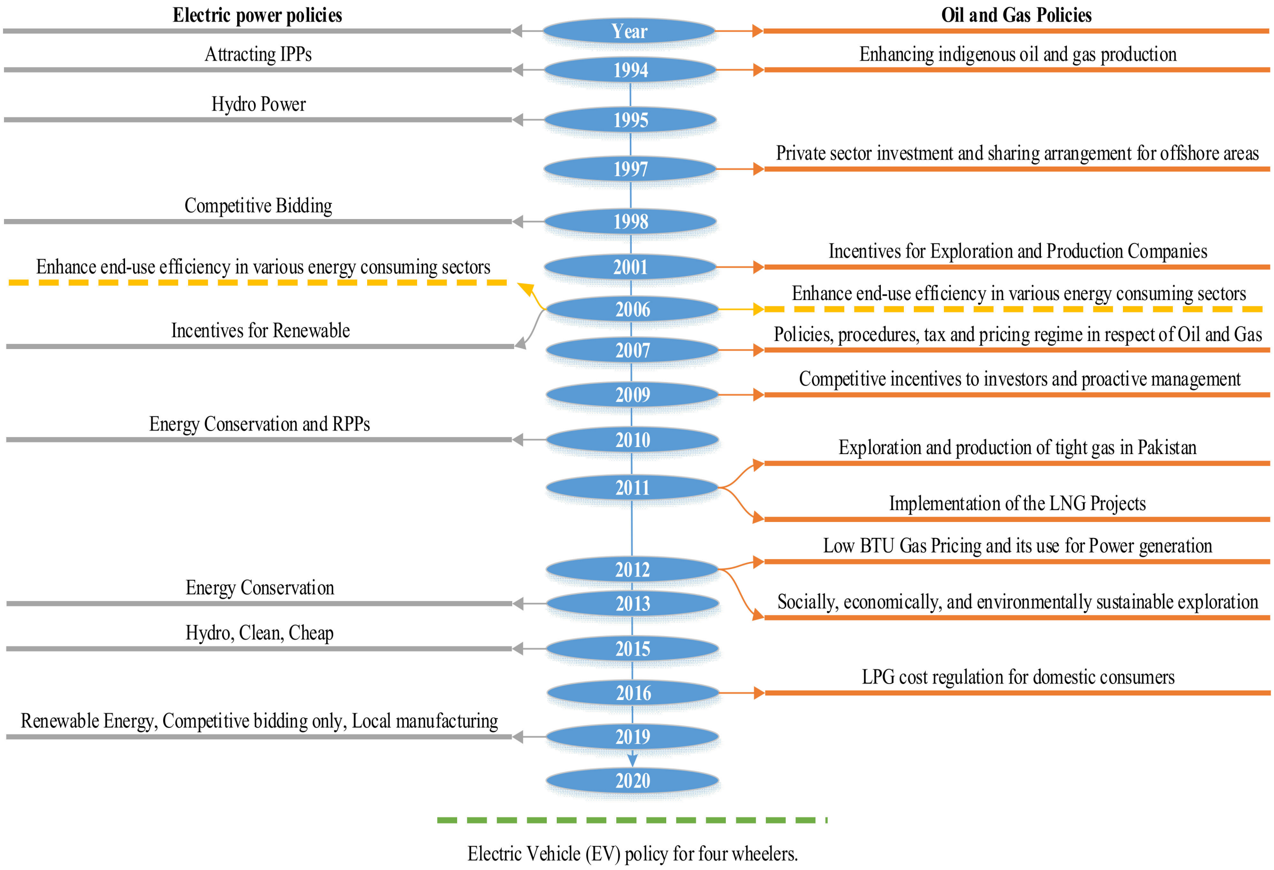


Figure 7. Energy and power policies and emphases.

These energy policies were devised with specific goals and objectives for each regime, and some serious efforts were also undertaken for their implementation. However, the majority of these policies were undertaken without considering the conformist energy planning efforts based on energy modeling. In addition, some of these policies lacked an effective implementation framework. It is also pertinent to note that only two energy polices (RE Policy 2006 and ARE Policy 2019) emphasized the use of renewable energy resources, although they lacked a formidable energy modeling basis. Therefore, it is very important that new energy policies based on integrated energy modeling and planning efforts considering renewable energy resources be devised. These future policies should also consider past experience, focusing on the depletion of indigenous fossil fuel resources and addressing the environmental concerns and affordability.

4. Potential of Renewable Energy in Pakistan

The assessment of energy resources in a country or region requires an imperative approach including forecasting of energy demand and production. In this context, a limited number of relevant studies for Pakistan are reported in the literature, with certain details and limitations. A review of such studies with respect to Pakistan and other relevant studies follows below.

In its first attempt, in 2014, AEDB, in collaboration with the World Bank, implemented a renewable energy mapping project for Pakistan based on satellite and ground-based data. In this regard, wind masts with a height of 80 m were installed in 12 locations across the country to collect ground-based wind data. Similarly, nine weather stations, of which two were tier 1 and seven were tier 2 were also installed across the country to collect ground-based solar energy data. These highly accurate ground-based data were used to produce solar and wind atlases for Pakistan. Global horizontal irradiance and wind speed maps of Pakistan at a height of 50 m are shown in Figures 8 and 9, respectively.

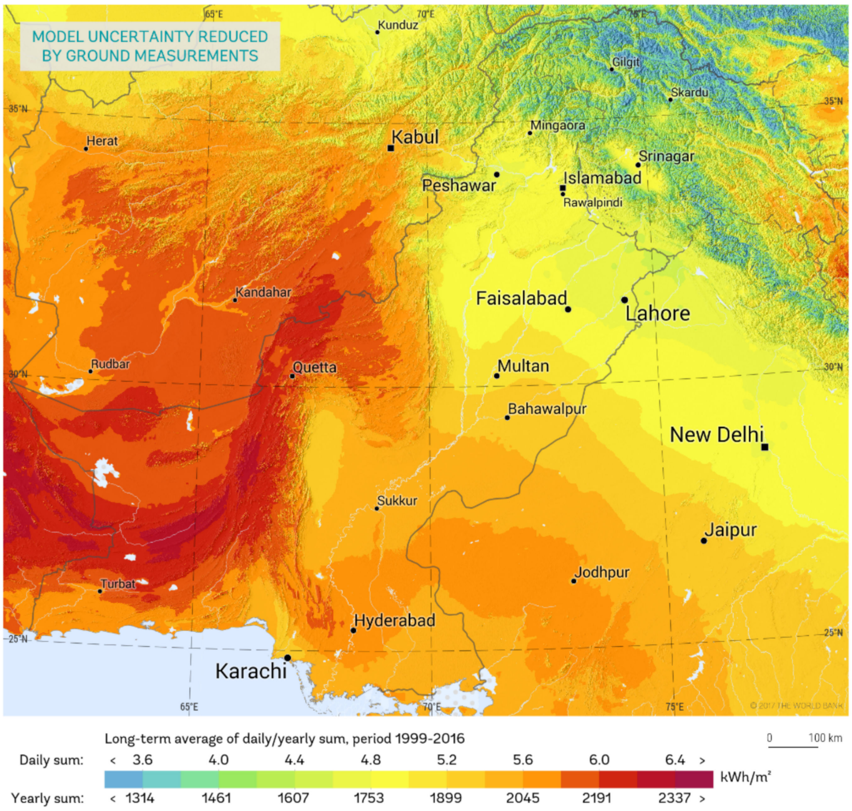


Figure 8. Global horizontal irradiance map [10,16,17].

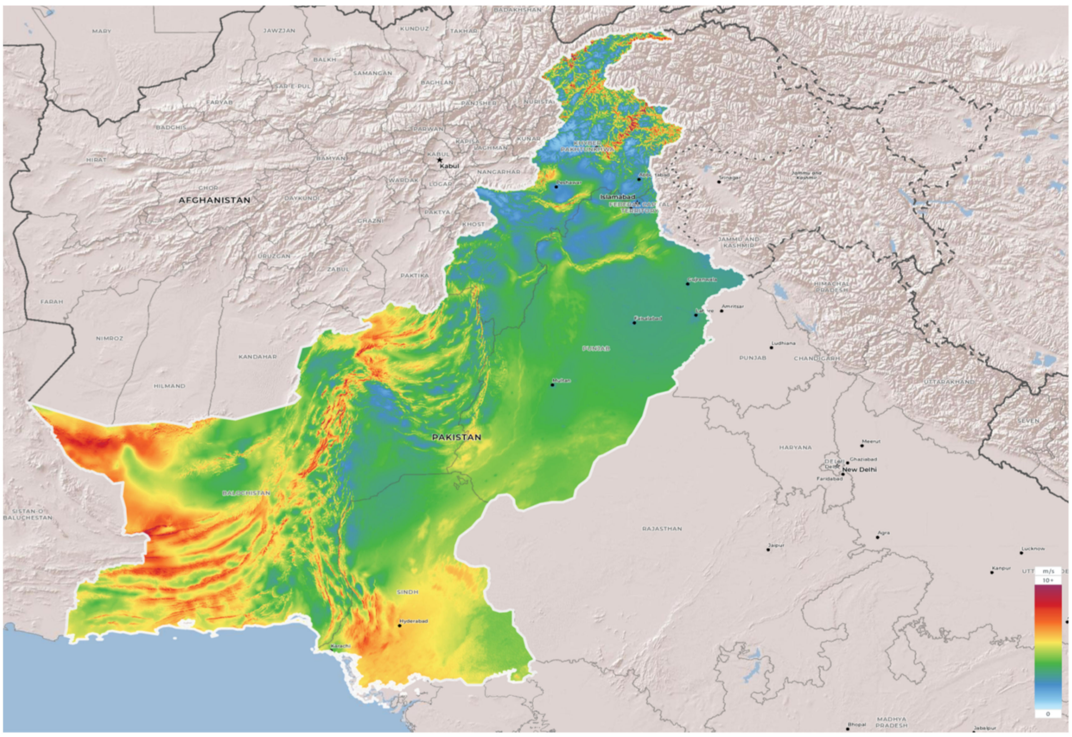


Figure 9. Wind speed map of Pakistan [11,16,17].

It can be seen from these figures that Pakistan has good potential for both solar and wind energy in various locations across the country.

The biomass component of the AEDB and World Bank project covered the four provinces of the country and helped to quantify the available biomass and agricultural waste for energy production. This survey suggested that in 44 districts of the country, the biomass potential is substantial for electricity generation, as shown in Figure 10.

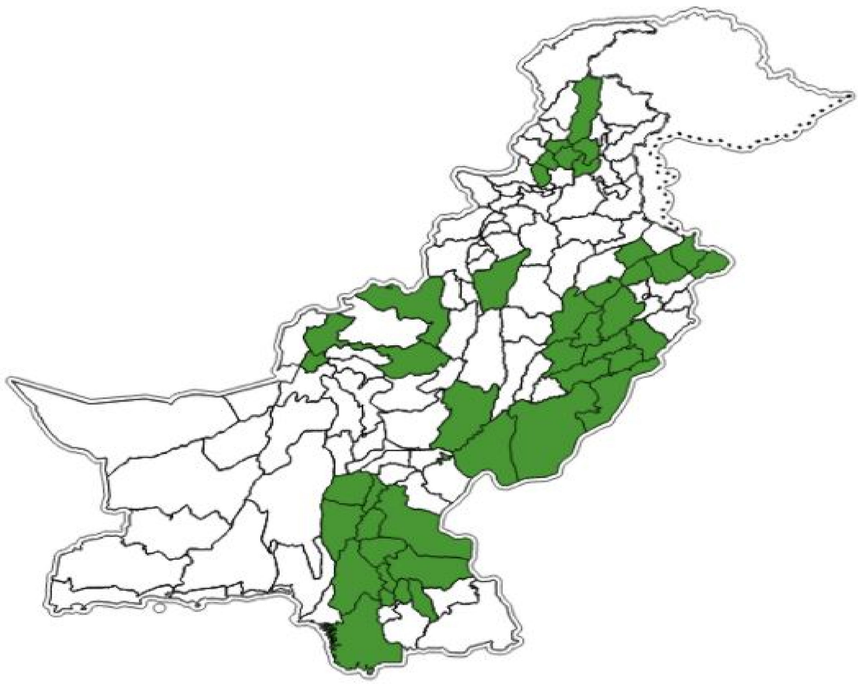


Figure 10. Distribution of Biomass for electricity generation [18].

It is estimated that that Pakistan has the technical potential for approximately 101 Twh/year of electricity generation from biomass and waste.

Pakistan is home to one of the world's largest river and canal systems. In this regard, the Aqua Media International annual publication suggests that Pakistan has a gross theoretical hydro potential of approximately 475 Twh/year, of which 204 Twh/year is regarded as technically feasible. A map of hydropower and dams in Pakistan is shown in Figure 11.

In its first 50 years of independence, Pakistan somewhat effectively utilized its hydropower potential by developing major dams and erecting power stations. However, in subsequent years, the growth of hydropower has been marred by sociopolitical controversies, a lack of consensus among federating units, and the lack of availability of investors to finance such projects.

Assessment of Renewable Energy: Related Studies

In addition to the above estimates of renewable energy published by reputed local and international organizations for various regions and countries, the contemporary literature also provides some insight into these estimates, and renewable energy potential assessment has been undertaken. In this context, some prominent studies are reviewed in Table 4.

The diffusion of renewable energy resources is progressing as active research and governmental policy on renewable energy attempts to adapt and develop these resources in the country. However, the literature suggests that there is considerable potential for renewable energy sources in Pakistan, which has yet to be systematically investigated. Proper utilization of these indigenous resources may replace expensive fossil fuels for power generation, transport, and energy requirements for cooking and heating.

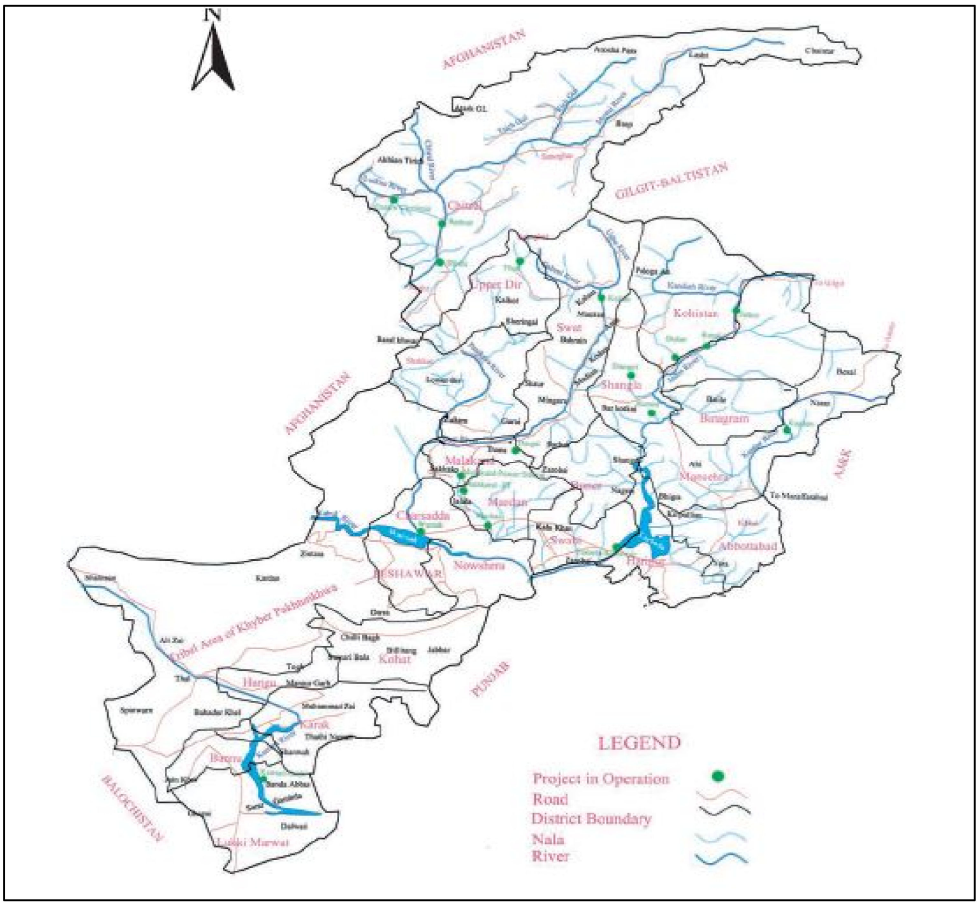


Figure 11. Hydropower map of Pakistan [19].

Table 4. Summary of the assessment of renewable-energy-related literature.

Author (Year)	Summary	Study Area
Ghaffar et al. (1995) [20]	Estimated potential of biogas from dung for cooking and lighting in rural areas of Pakistan. Using a flat plate collector and solar PV, they also estimated the potential of solar energy in different locations in Pakistan.	Pakistan
Siemek, Nagy, and Rychlicki (2003) [21]	Estimated long-term natural gas demand employing logistic modeling for Poland. Used the Gauss-Newton algorithm for estimation of logistic model parameters.	Poland
Evrendilek and Ertekin (2003) [22]	Assessed the potential of hydro, wind, solar, and geothermal power, along with biogas and biofuels, in Turkey using secondary data.	Turkey
Uemura et al. (2004) [23]	Used data on wind speed, solar irradiance, biomass, waste, etc., to estimate the potential of wind power; solar, thermal, and PV electricity; and biomass energy.	Yakushima Island
Lund (2006) [24]	Estimated renewable energy diffusion in India using logistic modeling and estimated the model parameters according to the ordinary least square (OLS) principle.	India
Harijan (2008) [19]	Used a logistic modeling approach to estimate the long-term diffusion of wind energy for power and water pumping; solar energy for power and heating; biomass energy for power, transport, and cooking; and hydropower in Pakistan. The study estimated the parameters according to the OLS principle using analogous data.	Pakistan

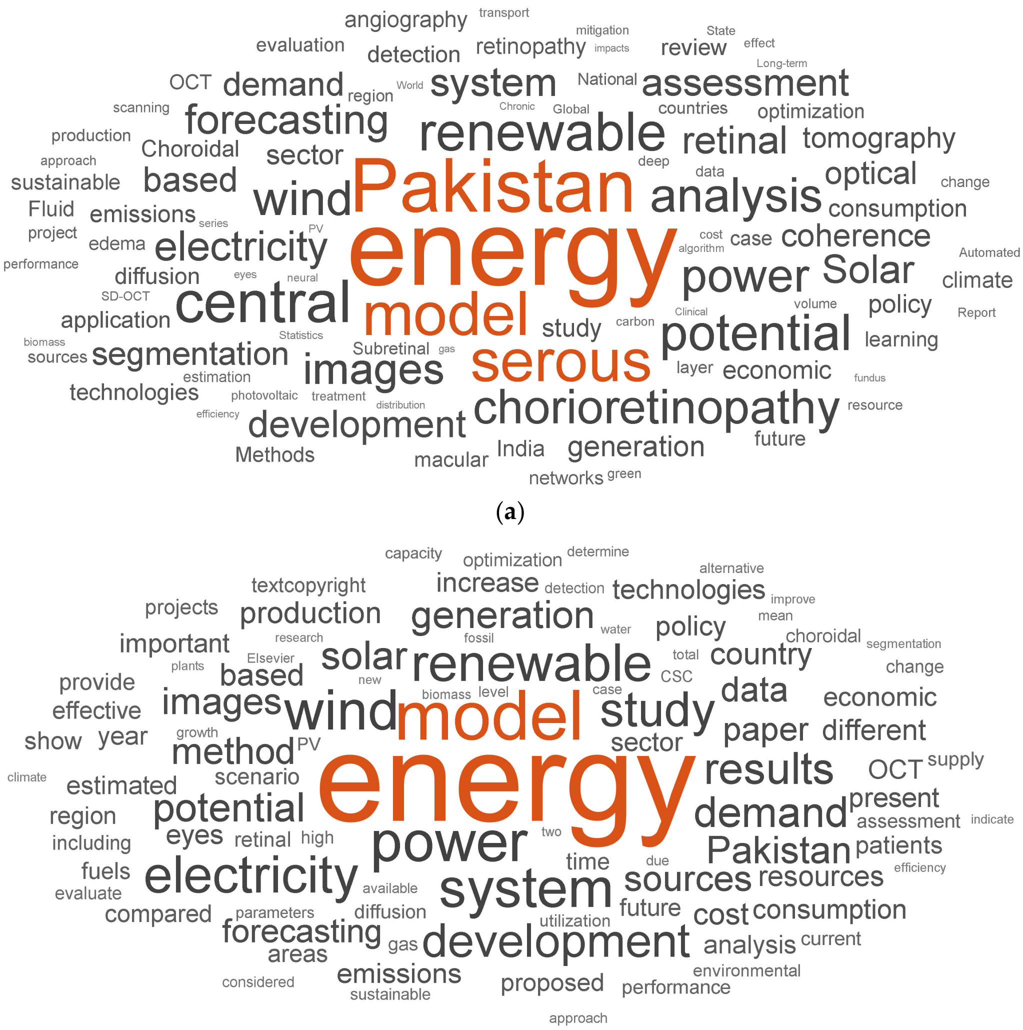
Table 4. *Cont.*

Author (Year)	Summary	Study Area
Harijan et al. (2009) and Bhutto et al. (2015, 2016) [25,26]	Analyzed perspectives on biofuel production and its utilization for clean transportation.	Pakistan
Forouzanfar et al. (2010) [27]	Employed logistic modeling to forecast demand for natural gas of residential and commercial consumers of Iran. The genetic algorithm (GA) and nonlinear programming (NLP) were used to estimate model parameters.	Iran
Xu, Li, and Zheng (2016) [28]	Forecasted wind energy diffusion using wind energy generation technological paradigm diffusion.	China
Dalla Valle and Furlan (2011) [29]	Predicted the accuracy of wind power technology diffusion models across countries.	
Harijan et al. (2011) [30]	Used logistic modeling to forecast the diffusion of wind energy in Pakistan. The model parameters were estimated according to the OLS principle with analogous data.	Pakistan
Melikoglu (2013) [31]	Estimated long-term natural gas demand of Turkey with a logistic model. This study estimated parameters of the logistic model using the SigmaPlot 11 optimization tool and reported enhanced performance of a logistic model relative to a linear model.	Turkey
Farooq and Kumar (2013) [32]	Considered solar PV, parabolic trough, run of river, and biomass gasification technologies for assessment of solar, wind, hydro, and biomass (field residue, animal waste, and MSW) potential for electricity generation in Pakistan. They estimated production of field residue based on the residue-to-production ratio of crops in a year. Animal waste and MSW were estimated based on animal and waste growth.	Pakistan
Shami et al. (2016) [33]	Evaluated the wind energy potential of three provinces of Pakistan based on wind data and evaluated suitable geographical locations for the installation of grid-connected wind farms.	
Ali, Khan, and Masood (2017) [34]	Analyzed wind energy potential with an optimal wind blade design for the Jamshoro wind corridor.	
Kamran (2018) [35]	Reviewed the status of renewable energy in Pakistan. The results indicate that a changes in the energy mix with increasing share of renewable sources reduce the demand and supply gap and stimulate local and foreign investment in the energy sector of Pakistan.	Pakistan
Farooqui (2014) [36]	Surveyed the availability of hydro, solar, wind, and biomass, as well as their current and future penetration prospects in the energy mix of Pakistan. This study estimated 30 GW and 50 GW as the feasible potential of installed power capacity from hydro and wind, respectively, by 2030.	Pakistan
Udhayakumar et al. (2020) [37]	Employed moth flame optimization to assess both onshore and offshore wind energy potential.	India
Teimourian et al. (2020) [38]	Employed the Weibull probability density function and assessed wind energy potential of the southern provinces of Iran.	Iran
Nazari et al. (2020) [39]	Used the TOPSIS method for the selection of wind sites in Iran.	Iran
Shoaib et al. (2019) [40]	Assessed the wind energy potential of Jhampir using wind energy conversion systems.	Pakistan

Table 4. *Cont.*

Author (Year)	Summary	Study Area
Glasson (2021) [41]	Highlighted the evolution of UK offshore wind farms and their community benefits in a macro study on the adoption of community benefits.	UK
Cai et al. (2022) [42]	Investigated the integration of hydrogen storage systems and wind generation in a power system under a demand response program.	
Khatri et al. (2022) [43,44]	Used the System Advisor Model (SAM) to assess the technical potential of solar PV and wind power in Pakistan. Technology diffusion was forecasted using logistic modeling. LMA was used to estimate the parameters. This investigation concluded that 600 × 103 GWh/year of electricity would be generated through solar PV and 150 × 103 GWh/year of electricity would be generated from grid-connected wind power.	Pakistan

The bibliometric analysis network is shown in Figure 12a,b. Figure 12a shows a bibliometric analysis network diagram with respect to titles, and Figure 12b shows the titles of various research studies.



(**a**)

(**b**)

Figure 12. Bibliometric analysis network according to (**a**) title and (**b**) abstract.

Limited work has been done on the assessment of the renewable energy potential of Pakistan. Only resource potential has been identified/assessed to date. However, it is important for a developing country such as Pakistan that such potential should be estimated according to possible applications (i.e., power generation, cooking, heating, energy processing, pumping, transport fuel, etc.) to effectively model renewable energy resources for optimal utilization. As such, in this study, the potential of renewable energy was estimated according to possible applications. The results of this study can be used to develop an optimal renewable energy penetration model for Pakistan.

5. Energy Planning Policies and Summary

Energy planning is a data-driven systematic process of providing insight into current accounts and elaborating future energy scenarios to secure modern-day commodities in the short term and the long run. It ultimately helps in devising energy policies to strategically plan, undertake, and implement assessed projects to achieve the aims and national objectives of socioeconomic development. The key starting point of energy planning is energy demand forecasting, which lays the foundation of this very important exercise. Energy demand forecasting using various statistical and mathematical approaches has been undertaken and reported in the contemporary literature. However, in recent years, these established methodologies have been more effectively used in a model-based approach. Therefore, in the following section, we provide a detailed review of energy demand forecasting models and approaches reported in the literature.

Management of energy demand at present and for the future is an important challenge; its outcome depends on present-day decisions. In order to address this challenge, energy demand models are developed and used worldwide to analyze and estimate future energy requirements. Energy demand models are primarily used to map future energy needs in various sectors in order to meet increasing demand due to industrialization, the use of modern domestic appliances, and rapid urbanization. The development of energy demand models for a developing economy such as Pakistan remains a challenge, mainly due to the lack of precise data, economic fluctuations, the informal nature of the economy, governance issues in the energy sector, political instabilities, etc.

Various energy demand models and approaches have been reported in the contemporary literature and widely used across the globe. These modeling approaches are broadly categorized as long-term and short-term demand models, as shown in Figure 13.

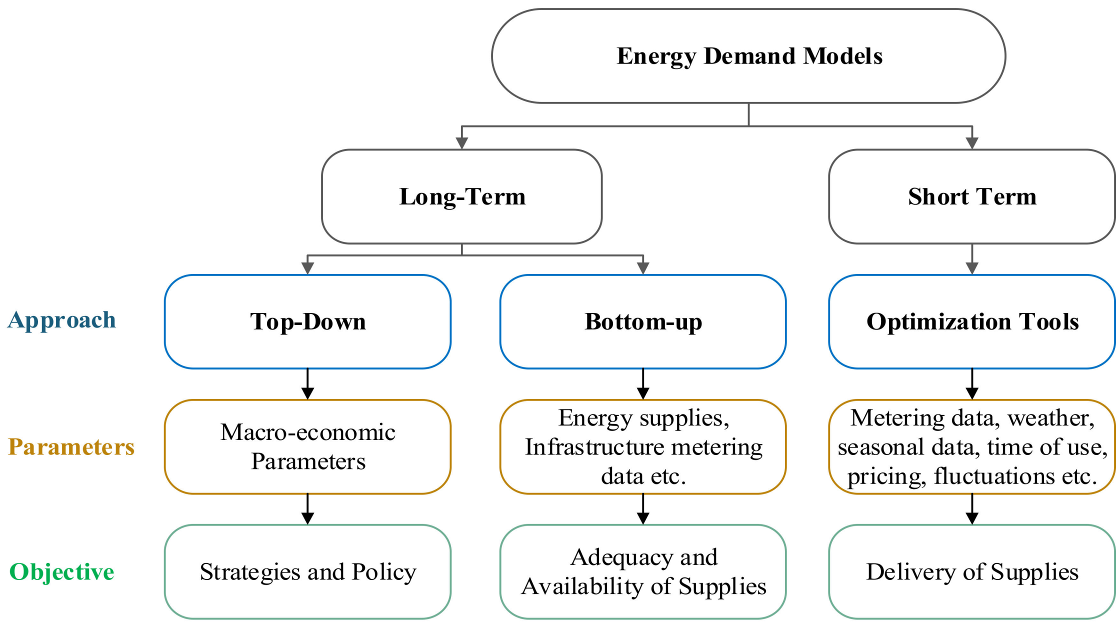


Figure 13. Energy demand modeling approaches.

The short-term energy demand models are used to analyze short-term energy demands (daily to weekly). These models use optimization tools for development and parameters such as weather forecasts, energy pricing, supervisory control and dada acquisition (SCADA), and demand fluctuations in the system. In contrast, long-term demand models estimate energy demand on the scale of years to decades.

These approaches are also often known as top-down and bottom-up modeling, respectively. Top-down energy demand modeling requires data from the top-down level in a demography i.e., data on population, GDP, annual progress, energy cost, and other suitable macroeconomic parameters. Sectoral or cross-sectoral effects of energy demand can be analyzed though this approach.

The bottom-up approach of energy demand modeling is used for energy system and network expansion, energization of more of the population, and upgrading of transmission and distribution networks from a demand perspective. This type of modeling aids in ensuring the availability of energy supply.

In this research, a top-down approach was used to develop an energy demand forecasting model for various sectors of Pakistan on a long-term basis. The simplest approach for such modeling is time series trend analysis [45]. In this context, Gonzales Chavez, Xiberta Bernat, and Llaneza Coalla (1999) predicted Spain's energy production and consumption using time series trend analysis [46]. Filippini and Hunt (2012) also used a time series approach to forecast sectoral energy consumption in the UK [47].

Regression models are also often used to forecast electricity, coal, and transport fuel demands [48–50]. Regression is one of the most widely used statistical techniques for forecasting, including energy demand forecasting [51]. The Energy Information Administration (EIA) of the United States of America (USA) employed a regression model with GDP and energy intensity as independent variables to analyze the accuracy in projection of USA energy consumption [52]. Lee and Chang (2007) examined linear and nonlinear considerations with respect to economic growth and found that threshold regression provides a better empirical model [53].

These models are also used for short- and long-term electricity forecasting [54–56]. De Martino Jannuzzi and Schipper (1991) studied the residential electricity consumption of Brazil and found that growth in electricity consumption was faster than that of GDP [57]. Harris and Liu (1993) observed a dynamic relationship between energy consumption and price, weather, and income [58]. Tunç, Çamdali, and Parmaksizoglu (2006) used regression to forecast Turkey's electricity consumption based on per capita use and population [59]. Al-Ghandoor et al. (2008) developed a multivariate regression model to estimate Jordan's electricity demand in the industrial sector [60].

Econometric models correlate energy demand with other macroeconomic variables [61]. Suganthi and Williams (2000) and Iniyan, Suganthi, and Samuel (2006) developed econometric models as a function of GDP, unit price, technology, and population to forecast energy consumption for India [62,63]. These models are effective in energy pattern forecasting [31,64]. Arsenault et al. (1995) forecasted sectoral energy demand for the province of Quebec as a function of the previous year's energy demand, energy cost, and income. This study used OLS principle to estimate the equation parameters. Similarly, Harijan (2008) analyzed, a tangential autonomous model, energy economic model, and dynamic energy economic model and developed a modified dynamic energy economic model (MDEEM) to forecast sectoral energy consumption in Pakistan. Based on model coefficients, R^2 values, and predicted values, they found that MDEEM was a better econometric model for Pakistan to undertake energy demand forecasting. This study further used data from previous years, GDP/Cap, and time trend variables to forecast Pakistan's sectoral energy demand. The OLS principle was used to estimate elasticities [65].

Valasai (2016) developed an index model according to the previous year's electricity demand, GDP, and the number of consumers as key parameters to forecast electricity consumption in Pakistan. This study considered three different scenarios: high economic growth (HEG), low economic growth (LEG), business as usual (BAU), and medium economic growth (MEG) [66].

Artificial neural networks (ANNs) and expert systems are also used for long-term energy demand forecasting. Many studies, such as [67], have forecasted energy consumption of residential appliances, [68] examined energy consumption in Turkey [69], and predicted world primary energy consumption.

Grey prediction models are also used for energy demand forecasting, owing to their simplicity and ability to characterize unknown systems with only a few data points. Many researchers have used this technique to forecast energy consumption; for example, Lu, Lin, and Lewis (2008) forecasted the energy consumption of vehicles in Taiwan [70]. Lee and Tong (2011) included GA in a grey model to forecast energy consumption in China [71], and Pao and Tsai (2011) explored dynamic relationships between emissions, energy consumption, and output in Brazil [72].

Modern computational techniques such as the genetic algorithm, fuzzy logic, and neuro fuzzy logic are also used to forecast energy demand. For example, Haldenbilen and Ceylan (2005) used GA to forecast transport energy demand in Turkey [73], and Ying and Pan (2008) forecasted regional electricity loads using a fuzzy interface system [74]. Many of these methods require complex computational efforts, and accuracy is seriously restricted. These methods are also prone to overfitting.

The Stockholm Environment Institute (SEI) developed a bottom-up energy accounting framework as a LEAP model, which is used to forecast national-, state-, and regional-level energy demands [13]. Shahid et al. (2021) evaluated sustainable scenarios to fulfill the regional electricity demand of Pakistan using LEAP [75]. Ahmad et al. (2010) predicted future energy requirements of the agriculture sector of Punjab province using LEAP [76]. This study developed scenarios for BAU, moderate improvement, and accelerated growth. Mirjat et al. (2018) developed a LEAP model to forecast long-term electricity demand and supply. This study used population growth, GDP, and households to forecast demand [13].

Autoregressive integrated moving average (ARIMA) models are also extensively reported for energy demand forecasting. This method is a combination of autoregression (AR) coefficients and moving average (MA) coefficients [77]. To implement an ARIMA model, time series are essentially linear and follow known statistical distribution. In this method, historical data of univariate time series are employed to analyze trends and estimate succession. ARIMA is a well-established method that has been abundantly reported in the literature on statistical methods [78]. This method is very adaptable and requires very few hypotheses.

The objective of the ARIMA technique is often to extrapolate a dynamic pattern from data to forecast future observations, to estimate the effects of known exogenous interventions, and to detect unsuspected interventions [79]. Box, Jenkins, and Bacon (1967) proposed seasonal ARIMA (SARIMA) for seasonal time series forecasting, which has been used in many studies [80–82]. ARIMA models are frequently used, owing to their flexibility to simply represent multiple time series variables, along with associated Box–Jenkins methodology, for optimal model development [81,83,84]. Due to preassumed linear time series, this model is subject to severe limitations, as it may not be suitable for many practical applications. Several other nonlinear stochastic models have been proposed in the literature to overcome this problem [84,85]. However, these methods are not as simple and popular as ARIMA models. The existing energy demand models of Pakistan reported in the literature are mainly based on multiple regression and econometric models with time series. However, only linear relationships are handled with OLS, which may not be suitable for time series data. As such, extended work and study on energy demand forecasting considering various aspects and limitations are inevitable.

In the 1980s, the annual average GDP growth was 6.5%; this value subsequently declined to 4.3% and 4.5% throughout the 1990s and 2000s, respectively [86]. The GDP growth rate was only 1.6% during the 2010 global economic recession, which caused a severe domestic energy crises. Numerous theories explaining this unstable economic posture reveal the inadequacy of the energy supply, which has caused further damage to economic productivity, prosperity, and growth [87], as growth and progress activities nominally stimulate demand for energy and its increased consumption [88]. Therefore, the industrial growth that the country witnessed during the 1980s and 1990s was stunted by the challenge of insufficient energy supply, causing a jolting economy for the first decade of the 21st century. The cause of this crisis was reliance on fossil fuel power generation as a result of 1994 power policy decisions [89,90]. The implications of this policy were reflected in changes in the energy mix landscape; for example, in 1990, hydropower generation accounted for 54% of the total energy mix, which was reduced to 34% in 2014, whereas thermal generation increased from 46% to 61% during the same period [91,92]. The effects of power generation capacity policy, along with fuel sources for electricity generation, are summarized in Table 5 [93,94].

Table 5. Statistics on various energy policies of Pakistan.

Power Policy	Capacity Addition (MW)	Fuel Sources				Remarks
		Oil	Gas	Hydro	Other Renewables	
1994	2898	63%	27%	-	-	High cost of generation resulting from imported fuel
1995	94	-	-	100%	-	Insufficient capacity added to the system
1998	-	-	-	-	-	Political interference prevented the addition of power generation to the system
2002	2782	42%	58%	-	-	Costlier power generation as a result of foreign direct investment
2006	355.4	-	-	-	100%	Wind- and solar-based electricity generation focused mostly in the southern part of the country
2008	145.1	-	-	-	100%	Mostly captive power plants with a focus on the sugar industry
2013	2019	58%	19%	17%	-	Limited share of RE resources dominated by thermal generation
2015	-	-	-	-	-	Under implementation

The proposed policies seem to be focused on attracting foreign direct investment (FDI) and private sector involvement to add to and enhance power generation capacity, mostly on the basis of oil and natural gas fuels. This has led to severely insufficient and incompetent power generation capacity, owing to high cost, poor recovery, and enhanced subsidies, resulting in circular debt and energy crises. Furthermore, the lack of a major expansion plan for power generation has caused a severe shortfall in energy demand and supply in first decade of the 21st century. As a result, electricity prices were high for stakeholders in power generation, so consumers were unable to afford this expensive commodity, resulting in a circular debt of approximately USD 7.6 billion [95]. The gap between demand and supply for electricity ranged from 4800 to 7000 MW in 2015, resulting in an adverse situation [96,97].

The major reason for failure of energy policies is ineffective planning and frameworks with inconsistent approaches and inefficient institutional structures. This has led to the establishment of numerous federal ministries and departments following partial and inconclusive institutional reforms. Furthermore, a regulator was established in 1997, namely the National Electric Power Regulatory Authority (NEPRA). All of these factors combined, resulting in a failure of the country to meet its stated goals for sustainable polices and plans [98]. Therefore, the challenge of achieving a suitable energy mix for Pakistan's power sector is multifaceted and remains unresolved, with the added to perturbation of economic conditions making it difficult to meet the energy demands of the country.

6. Research Issues and Knowledge Gap

A detailed literature review of Pakistan's demography, economy, energy trends, institutional structure of the energy and power sector, energy planning and policies, demand forecast, and relevant model potential of renewable energy resources of the country, as well as global energy planning practices, was undertaken in the present study. This systemic review can contribute to understanding of the energy dynamics and key issues that are attracting increasing attention. The essential outcome of this review can be summarized as follows:

- Pakistan has been facing energy crises for more than a decade, owing to poor energy planning and governance issues;
- Energy crises in the country have forced thousands of industries to shut down operations, affecting industrial production and the livelihoods of thousands of families;
- The energy crisis has been a major drag on the economy and a serious impediment to growth, with an estimated cost of 10% of the GDP over the past 5 years;
- Pakistan's energy crisis, if not tackled at both the operating and strategic levels in the immediate future, might become a national security threat;
- Therefore, in addition to planning and developing a conventional source of energy, Pakistan should harness the potential of its abundant renewable energy resources, i.e., solar, wind, hydro, and biomass, as attractive alternative sources of energy to constitute a substantial share of its overall energy supply;
- These renewable energy sources remain untapped to their full potential, and only account for 2–4% of the total energy mix.

Given the enormous potential of RE resources, their diffusion inevitable to meet increased demand, reduce upfront tariffs, contain climate change, and save foreign exchange reserves.

The literature also shows that limited work on RE potential assessment and consideration of these resources in the overall energy planning paradigm has been reported to date in Pakistan.

The energy models reported in the literature for energy planning range from simple econometric to mathematical, simulation based, top-down or bottom-up models, which require explicit details to achieve planning objectives. However, a simplex RE penetration approach requires a comprehensive strategy to offer optimal RE technology sizing and its diffusion in the overall energy mix. This may require a significant parametric approach considering efficiency, reliability, cost, and—most importantly—a climate action plan. Thus, a holistic approach is urgently needed to plan a sustainable energy mix of energy resources. Accordingly, a triple-helix model of research issues and knowledge gap analysis based on this literature review for Pakistan was developed, as shown in Figure 14.

It is evident from the triple-helix model presented above that the indigenous conventional energy resources of Pakistan are limited, and country has long relied on imported fossil fuel to meet ever-increasing energy demand. This reliance on imported energy resources has resulted in a considerable burden on the national exchequer.

On the other hand, Pakistan has been coping with energy crises for more than a decade, which has plunged country into economic crisis. These economic crises range from circular debt in the power sector to debt servicing to international lenders, often with very difficult terms and conditions. This situation has put Pakistan in a situation often termed an energy security challenge.

The above challenges are further intensified over time as population growth and rapid urbanization has resulted in increased power and energy demands. Emerging industry has also experienced a sharp decrease in production due to the unending energy crisis, which has directly and indirectly impacted the economy and the masses.

The challenges highlighted above required extraordinary efforts before the advent of the energy crises. However, only a few feeble government-level efforts have been reported in the literature, which failed to achieve effective implementation. Academics have also attempted to aid these efforts but have been limited by a focus on either energy resources planning on the supply side or by considering RE potential assessment without taking into account applications (i.e., power generation, cooking, heating, energy processing, pumping, transport fuel, etc.).

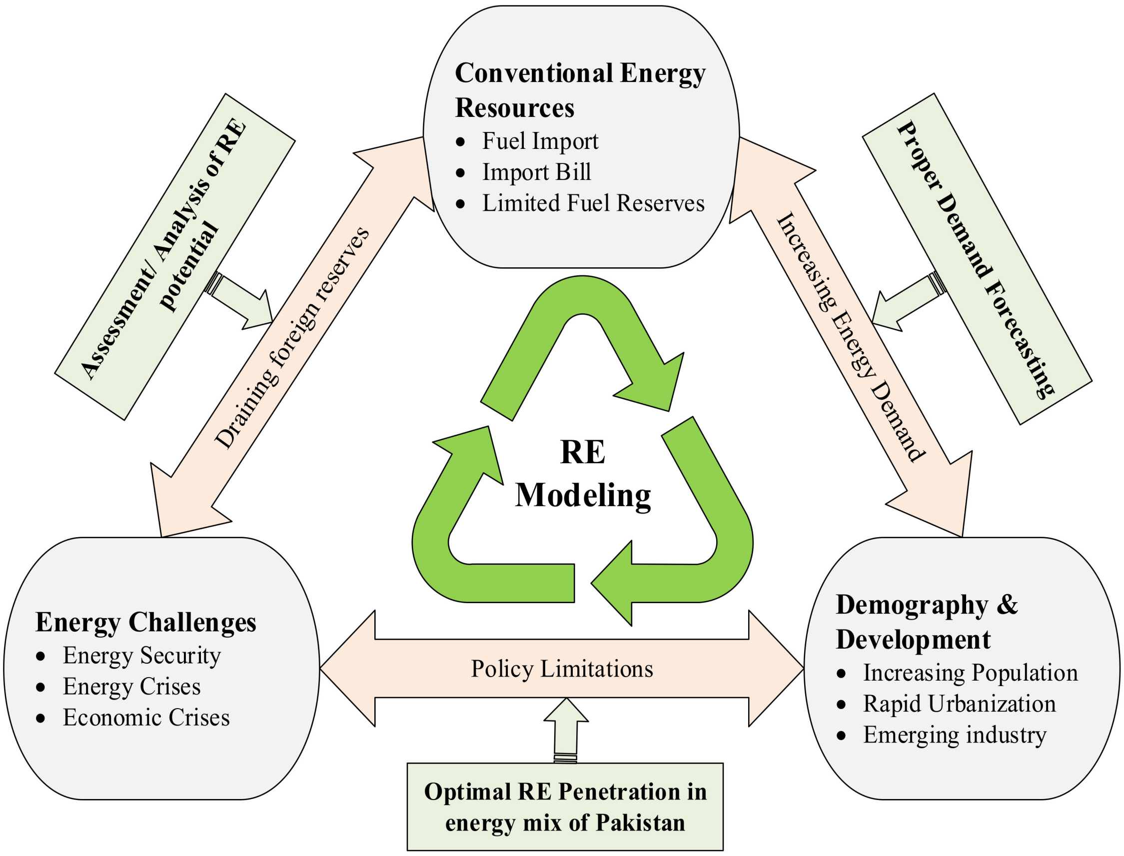


Figure 14. Analysis of research issues and knowledge gap.

At this juncture, it is pertinent to note that the globally energy transition has become an essential element of energy planning. As such, renewable energy resources are part and parcel of the energy planning paradigm. However, owing to various shortcomings apprised in this literature renew, limited work has been done in this context in developing countries such as Pakistan.

Therefore, it is important that energy assessment, demand forecasting, and modeling tools be effectively used to analyze future energy scenarios and optimally integrate RE in the energy mix of Pakistan. If the country fails to plan and effort are not made to support RE penetration, the ongoing energy crisis will only worsen. RE penetration, along with a high rate of return on investment, would encourage local and foreign investors and produce job opportunities. Given the lack of an existing body of knowledge, in this study, we undertook the assessment of RE potential, energy demand forecasting, and optimal penetration of RE in the energy mix of Pakistan. The results of this study can be used to develop an optimal renewable energy penetration model for Pakistan.

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