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Research article

Demand side management through energy efficiency measures for the sustainable energy future of Pakistan

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ABSTRACT

Pakistan is facing energy crises due to localized shortages, market manipulation, infrastructure disruption, rising demand, governance issues, climate and geopolitical events. In this situation Demand Side Management (DSM) is a promising solution to overcome the problem of energy crises. DSM strategy helps to manage consumer demand through energy conservation rather than to addition of new power capacity. In this study, Low Emissions Analysis Platform (LEAP) develops an energy model for Pakistan for the period 2022–2050. Three scenarios has been to constructed namely Baseline (BAS), Green Energy Policy (GEP), and Energy Efficiency (ENE) to predict the future energy demand, production, carbon emissions and the investment cost which covers capital, operational and maintenance costs. The model results suggest that DSM targets should be achieved through the implementation of ENE scenario. Predicted energy production and consumption under the ENE scenario are substantially less than those under the BAS scenario. The country can meet its 635.83,000 GWh energy demand with its 747.15,000 GWh energy production. Non-renewable sources produce 171.27,000 GWh, whilst renewable sources produce 575.88,000 GWh. According to this scenario, by 2050, CO_2 emissions will be produced around 93.16 million metric tons, requiring an investment cost of $46.80 billion for building new power capacity. The study provides a roadmap with a suggestive optimal balance between energy saving with DSM approach and utilizing renewable energy production to meet energy demand for different sectors of the economy.

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1. Introduction

One of the greatest risks to the survival of the human species on planet is global warming [1]. Environmental economists argued that high carbon emissions are a result of rapid growth in fossil fuels based power generation [2]. The Paris Agreement on Climate Change (PACC) in 2015 have indicated that the climate change is raising sea levels, melting glacial ice, and causing extreme weather events that can obliterate 50 % of the population in coastal areas [3]. Moreover, it is expected that the economic costs of global warming would surpass those of World Wars I and II [4]. According to PACC report, CO_2 emissions have been rising quickly over the past 20 years. The average temperature of the world is increased beyond 20 °C as a consequence of CO_2 emissions, and they will continue to rise by 1.7 times until 2030 [3]. Researchers are focusing on the increasing danger posed by climate change and global warming in an effort to prevent serious damages. Similarly, it has been observed that the major cause of CO_2 emissions is the power sector [5]. Therefore, it is possible to suggest ways to reduce power use in order to deal with the issue of CO_2 emissions by incorporating the energy efficiency and conservation (EEC) measures in the demand side management.

Environmental economists claimed that economic expansion is the solution to environmental problems three decades ago [6]. Environmental Kuznets Curve (EKC) was formed when Kuznets noted that a curve can be found between income and environmental degradation. According to the EKC, there is an inverse U-shape relationship between economic rise and environmental deterioration [7]. Economic expansion will initially increase CO_2 emissions, but beyond a certain point (a turning point), this relationship will become inverse. Therefore, after a certain time period, a rise in economic growth will result in a reduction in CO_2 emissions [8]. The Environmental Kuznets curve suggests that economic development initially causes deterioration in the environment. Later due to economic growth, society begins to improve the relationship with the environment, and environmental degradation reduces. Thus, the economic growth is good for the environment. In this regard, economic expansion is the remedy in keeping a clean environment. Having economic growth is such a good solution, there has been an increase in literature testing EKC during the last two decades. As EKC results are extremely sensitive to one of the important country factor such as time range but the validity of EKC is still a controversial topic for developing countries therefore energy conservation through energy efficiency measure is the best possible solution to reduce CO_2 emissions [9].

Fossil fuels, such coal, oil, and natural gas, are used by many nations around the world to meet the energy demand, promote industrialization and urbanization, and handle population pressure, but these sources causes climate change and environmental damage [10]. Because of high rates of CO_2 emissions, mitigation techniques must be developed to balance greenhouse gas concentrations. However, no worldwide implementation plan has been reached on any such measures to minimize the environmental problems [11]. New developments in renewable energy give substitutes for the conventional use of fossil fuels. Most of renewable energy sources are sustainable and produce less CO_2 emissions in contrast to fossil fuels [12]. Lower prices of solar and wind, renewable energy has grown rapidly during the past few years. Whereas a 33 % rise in the cost of generating renewable energy is expected by the year 2025 [13].

Many countries are using efficient ways to improve environmental quality by limiting further environmental damage. Government regulatory interventions, both direct and indirect, help to form these methods. Different methods, including environmental education through energy efficiency, societal standards, behavior, and moral preaching, can be used to promote awareness for more environmentally conscious living among the general public [14]. Pakistan is a developing country with lack of financial resources, instability of political situation and governance issues, the energy planning efforts in Pakistan lacks to recognize demand side management (DSM) as key ingredient of policy instrument. It is identified from the literature that only partial and piecemeal DSM steps were considered in past but not as a policy on the whole [15]. Resultantly the country is in the grip of energy crises for over the years and currently the crises are worst in its history [16]. As such, the country's depleting energy system necessities the development of a sound DSM planning, policy and implementation framework to overcome the energy crises.

EEC measures aim to reduce energy demand by using energy-efficient appliances/tools/equipment or by changing the behavior patterns of individuals [17]. Ensuring security is a major factor in the wide acceptance of energy conservation and efficiency as a solution to energy shortage and climate change concerns [18]. Energy systems worldwide are shifting towards sustainability, driven by energy security, equity, and environmental sustainability goals [19]. Historically, Pakistan has been subjected to energy demand suppression due to limited supplies and a lack of adequate infrastructure development to provide energy to the industrial sector. Resultantly the country suffers from a large demand-supply energy gap in the power sector; which stood to be 5000 MW in 2022 [20].

The requirements for designing environmental policies and effectively implementing them to improve environmental quality using DSM have not been identified. The effectiveness of each country's environmental policy framework has been determined using a country-based environmental sustainability scale. This scale can be used to track a number of important parameters, including the efficiency of current institutions, the legal framework for the protection and smart use of natural resources, and environmental management for reducing greenhouse gas emissions. All of this information is used in this study to examine how environmental management policies in developing nation (Pakistan) affect greenhouse gas emissions using DSM technique. This study can be used by policymakers and practitioners in the developing economies to create effective policies and improve environmental management challenges.

The structure of the article as follows. Section 1 describes the study background and significance. Section 2 provides the overview on the national energy sector development plans and policies and demand side management strategies are given in section 3. Section 4 covers the research methodology which discussed the proposed model, model setup, data collection and scenario development for detailed examination. Section 5 and section 6 presented the results and discussion with study limitations and future work and finally, section 7 covers conclusion.

2. National energy sector development plans

The supply side has always been Pakistan's main investment focus, although some investments are also made in the transmission lines. Despite the excess capacity, the majority of upcoming legislation and international agreements are centered on boosting generation capacity. Along with that, a poor infrastructure for power distribution, it is difficult for the majority of Pakistan's rural areas people to access electricity [21]. Efforts to limit the usage of coal, oil and gas by increasing the amount of natural energy in energy supply systems have had little success. Imported fossil fuels are the main source to fulfill the energy requirements of Pakistan. The process to switch toward renewable energy sources has been started but its mechanism is still in developing phase [22]. Despite the fact that numerous energy policies have been in effect since 1985 that stressed the necessity of using renewable energy sources but none of them have offered a framework for the execution of such projects [23]. To enhance the proportion of renewable energy in Pakistan's total energy mix, a variety of programs and policy frameworks have been devised only. The following sub-sections presented the renewable energy-related initiatives and policies.

2.1. *Renewable power generation policy 2006*

Pakistan's first energy strategy was primarily designed to boost renewable energy production projects. This initiative aimed for renewable energy technologies (RETs) to account for 10 % of Pakistan's overall energy mix by 2015. The policy focuses on solar, wind and small-scale hydro power projects. This policy includes numerous key efforts that encourage the development of RETs in Pakistan, including: expand the use of renewable, encourage the development of renewable energy markets and the private sector's investment in RETs, develop measures to mobilize financing, support the growth of a domestic RET manufacturing industry by reducing prices, enhancing service and creating jobs. The established strategy resulted in the formulation of additional policies and programs that offered a significantly more diversified and evolving system for the implementation of renewable energy technologies throughout the first two years [24].

2.2. *Alternate and Renewable Energy policy 2019*

A recent policy, the Alternate and Renewable Energy (ARE) policy 2019, was developed to promote the growth of renewable energy in the power sector. The policy includes every form of sustainable energy, such as wind, biomass, solar, waste into electricity, hydrogen innovation, and combinations of sustainable energy technology, with the goal of obtaining 20 % of total generation capacity from renewable energy technologies by 2025 and 30 % by 2030. Furthermore, the program plans to expand the share of hydropower in the mix of energy generation to 30 % by 2030. According to the plans, Pakistan would be able to generate almost 60 % of its total energy from renewables. The program also aims to reduce the average price basket of tariffs by permitting competitive bidding for new projects and exempting imports of machinery required for renewable energy projects from all taxes and levies [25].

2.3. *Indicative generation capacity expansion plan (IGCEP) 2030 and 2047*

The National Transmission and Dispatch Company (NTDC) have released yet another thorough analysis, which forecasts future electricity consumption and sets a plan to increase capacity from 2018 till 2040. The demand forecast is presented under three growth rate scenarios. Future energy demand is projected to reach 457,939 GWh in 2040 under the normal scenario with a 5.5 % growth rate. By the end of the study period, the plan calls for the addition of 79,448 MW of capacity, by 2040 after taking power plant retirements into account with a goal of reaching 98,091 MW in total installed capacity. NTDC, on the other hand, altered the capacity expansion plan, and the new version was released in June 2021. However, this version drew major constructive criticism owing to the fact that committed projects accounted for a significant amount of the total and renewable energy was only 12 % until 2030 [26,27].

2.4. *National electricity policy 2020*

The proposed national electricity policy will take precedence over the 2015 version of the power policy in cases of inconsistency, while the other directives stay the same. This policy seeks to eliminate power production from costly imported fuels while enabling the best possible growth of energy generation, transmission, and distribution. Efficiency, competitiveness, economic viability, transparency and most importantly environmental stability, are the six driving principles of this approach [28].

2.5. *Competitive trading bilateral contract market (CTBCM) model 2020*

To convert the electricity market from a single buyer to a multi-buyer model, submitted by Central Power Purchasing Agency (CPPA), has recently received approval from National Electric Power Regulatory Authority (NEPRA). The plan is expected to come in action by mid-2020. CPPA is a government-owned company and is only and single power purchasing unit of Pakistan. Now, even if doing so prevents the power producers from business hazards, it costs the government and the people who are using the electricity. A multi-buyer model will help the government move to a competitive market in order to improve operational effectiveness and reduce electricity cost for customers [29].

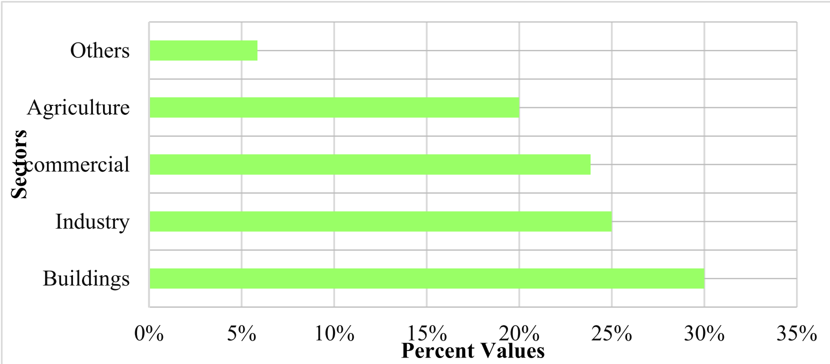


Fig. 1. Pakistan's energy saving potential.

2.6. Pakistan's electric vehicle policy 2020–2025

According to this policy, Pakistan's aim to have a strong electric vehicle market with a 30 % and 90 % share in heavy duty trucks and passenger vehicles by 2030 and 2040. The policy's main goals were to divert emissions from major cities and more importantly, to cut Pakistan's yearly oil imports which are currently estimated to cost $13 billion. If Pakistan can build upon its international agreements, the country's energy sector can have a sustainable outlook. Some of these aims seem overly ambitious and may have a higher cost of inaction when taking into account the financial constraints and extremely restricted fiscal space. Some of these goals are at contradiction with one another, which raises serious concerns about how multiple government departments' policies differ from one another [30,31].

2.7. Paris agreement and Pakistan

Pakistan is one of the 200 nations that have signed the 2015 PACC. The agreement's goals include lowering overall CO_2 emissions and minimizing the rise in the earth's temperature of 1.5–2.0 °C. As a part of the framework of international climate policy in 2016, Pakistan submitted its first Intended Nationally Determined Contribution (PAK-INDC) to show its commitment to addressing climate change-related challenges. According to the filed INDC, Pakistan's CO_2 emissions are considered to be 1603 million tone CO_2-equivalent in 2030. Pakistan's Vision 2025 [32], an important policy document that lays out a strategy for guiding national development through the year 2025. According to vision 2025, the target rate of economic growth is 7 % on average through 2025 and much higher in the years to follow. According to Pakistan's climate goal under this agreement, CO_2 emissions will be reduced by 20 % from expected levels of 2030 [33,34].

3. Demand side management in Pakistan

Pakistan has one of the world's lowest per capita electricity consumptions. The system losses are among the highest, yet there is no awareness of the importance of electricity conservation. On the other hand, the energy saving potential in Pakistan from energy conservation and efficiency measures is substantial at an estimated 17 % of total electricity use [35]. In the Vision 2025 document, it is reported Pakistan has great potential for energy savings through the use of more power-efficient equipment, with expected savings of 15–20 % of total energy consumption. The energy saving potential of Pakistan is estimated to be over 11 million tons of oil equivalents (MTOE) [36].

Conservation of energy has always been a vital part of managing demand and plays a significant role in reducing energy consumption. Any action or behavior which results in reducing the use of energy is known as energy conservation. Energy conservation programs limit the end–users to avoid excessive consumption, in return it reduces their energy bills [37]. Energy efficiency focuses on updated and modern systems. It uses less energy while receiving the same end service level, like replacing an old refrigerator with a more efficient model. From the utility's perspective, energy conservation reduces the overall electricity demand. Two primary policy instruments were introduced to institutionalize energy efficiency and conservation management in Pakistan: National Energy Efficiency Conservation (NEECA) Act of 2016 and NEECA policy of 2023 [38]. Across all sectors, the country has an accumulative margin of 20 % in energy savings. Energy saving is cheaper than energy generation and the most affordable solution to energy shortfall. The saving of energy potential in Pakistan is shown in Fig. 1 [38].

NEECA Act of 2016 provides the governance framework to facilitate national efforts and reinvigorate wide-scale adoption of sound energy-efficient practices. The Act declares the NEECA as the apex agency to coordinate and catalyze efforts to promote conservation in all sectors of the economy. NEECA has been entrusted with various regulatory responsibilities under this Act. NEECA policy of 2023 identifies interventions to ensure deep-rooted institutionalization, operationalization, and implementation of EEC in the country. The policy also informs, on the basis of techno-economic analysis, enforcement mechanisms required for the adoption and compliance of EEC regulatory measures along with precise guidelines for coordination with the provincial governments [39].

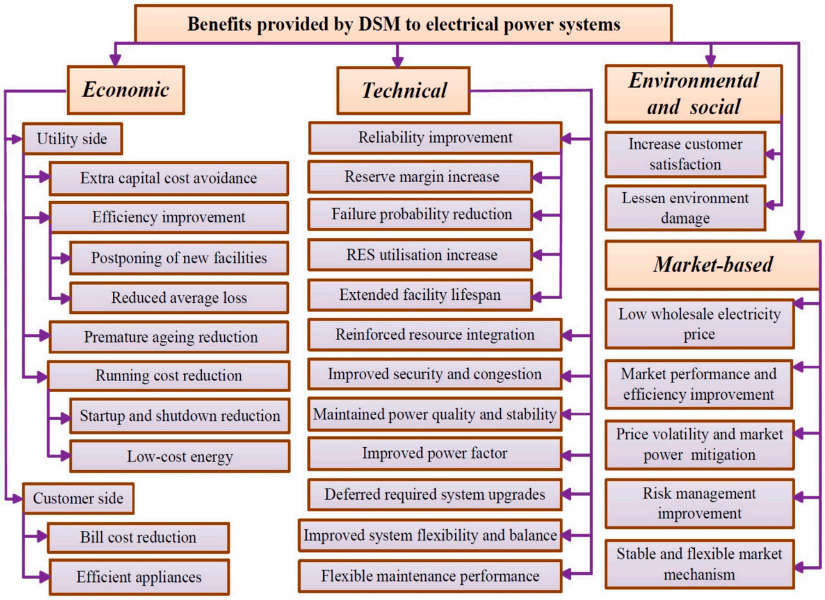


Fig. 2. Benefits provided by DSM to electrical power systems.

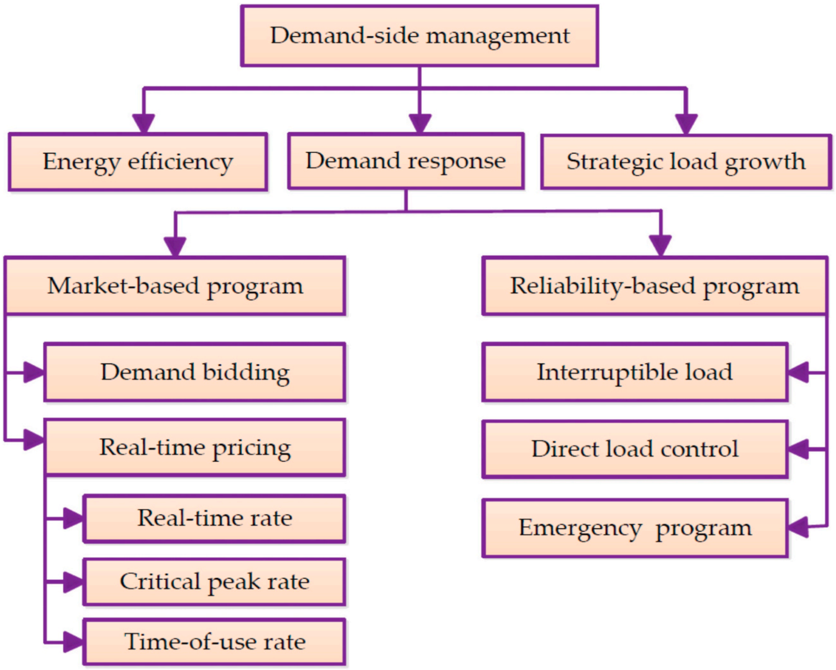


Fig. 3. Demand-side management techniques.

There is significant potential for implementing DSM in Pakistan to improve the end-use efficiency of the electrical system and encourage efficient electricity consumption. The potential benefits of DSM are multi-dimensional, as presented in Fig. 2 [40]. The government utilities and customers can devise DSM programs to achieve these benefits. In Pakistan, the DSM strategies should incorporate the following measures.

- The priority in the development of a DSM plan and in creating an implementation strategy.
- The goal should be to educate consumers on the technical aspects of reducing energy demand, so they can make informed decisions when purchasing energy-efficient appliances. This involves offering comprehensive audit programs for industries and providing

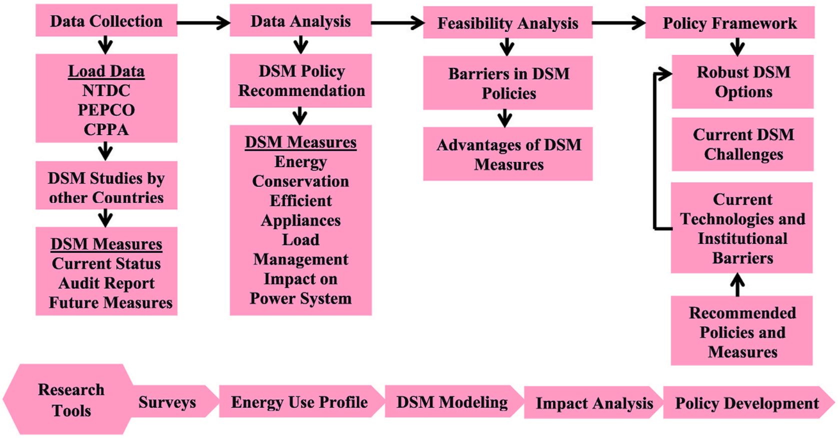


Fig. 4. Research flow diagram of demand side management.

advice on home energy conservation. Doing so makes it possible to influence consumers towards more sustainable and environmentally friendly practices.

- To begin DSM activities, it is crucial to prioritize the sectors that have the financial resources to do so. Industry and commercial sectors must be given priority for this purpose.
- To plan financial programs to cover the requirements of targeted groups like particular industries or other categories of the economy.
- To devise a structure that penalizes wasteful use and encourages efficiency.
- To frame incentive programs for manufacturers and equipment sellers to encourage them to produce and supply energy-efficient appliances, equipment, or services to the end-users.

To implement demand side management various DSM Techniques are adopted by utilities world over as shown in Fig. 3 [41]. Three major mechanisms of DSM include load management, energy loss reduction measures, and energy efficiency and conservation management.

If we talk about the prioritization and intensification of DSM measure in practice, some of the most feasible solutions on technology side include.

- Strict Monitoring on curbing the sale and use of poor/inferior quality materials like cables, wires, accessories, switches, sockets, chokes, lamps and fans, etc.
- LED lighting load conversion, beginning with public illumination and government buildings.
- Replacement of inefficient substandard agriculture tube well pumps and motors.
- Installation of capacitors for improvement of power factor. Application of smart meters/AMI meters.
- Promoting the use of inverter air conditioners.
- Implementation of energy efficiency and conservation act and building energy code of Pakistan.

To evaluate the impact of DSM on future Pakistan's electricity demand, a DSM model using of LEAP platform has been developed and salient features of the same are presented in section 4.

4. Data and methodology

There is limited work reported with respect to of DSM strategies in the context of Pakistan's power sector with focus on reducing the energy demand side. In the meantime, sustainable climate-change targets emphasis Pakistan to consider DSM strategy in a holistic manner. As a result, from 2022 to 2050, the LEAP DSM model is developed and utilized to optimize Pakistan's energy system. The research flow diagram of this study is shown in Fig. 4.

4.1. Proposed method

This perception of a DSM is becoming crucial in fostering low-carbon future pathways and communicating about cleaner transition and economic consequences. Lower global carbon emissions will help keep temperature change within 1.5 °C, requiring a rapid switch away from fossil fuels towards other forms of energy along with the implementation of DSM strategy. Earlier, the PACC proposed suggestions but investigations have seldom been undertaken only by developed and emerging economies across the world [42]. For this purpose, the LEAP software has been used to generate paths for the green energy system with the implementation of DSM strategy in Pakistan. LEAP model is used to predict future electricity generation, simulate energy usage, compute CO_2 emissions and forecast

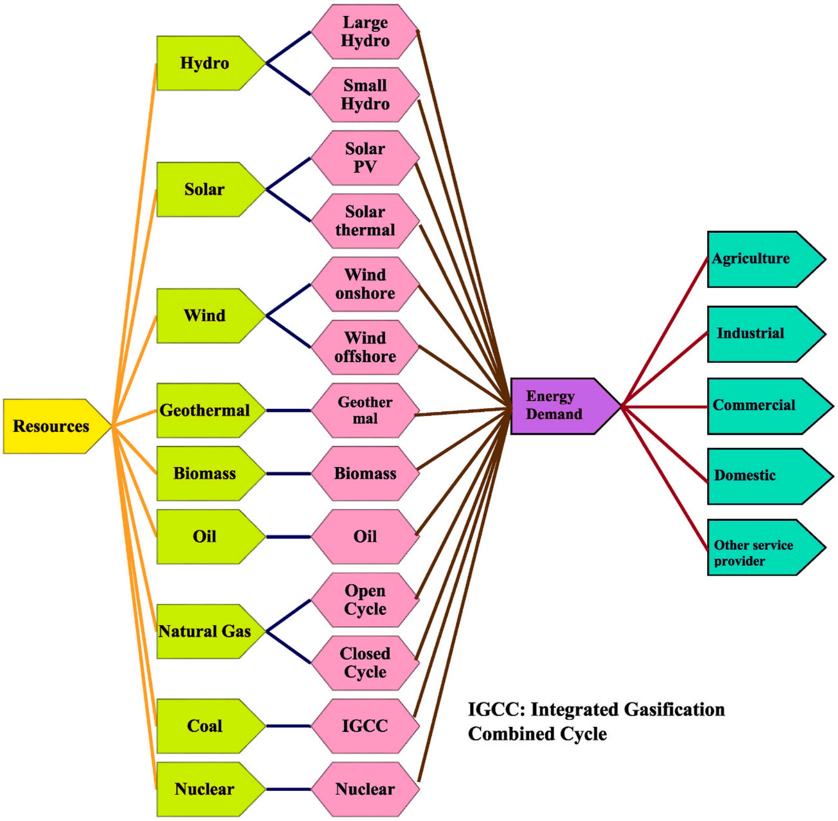


Fig. 5. LEAP DSM model for Pakistan [38].

the total cost (capital, operational, and maintenance cost) for energy systems. The main goal of the modeling and optimization approach was to decrease the utilization of fossil fuels, CO_2 emissions, and the overall annual system cost of the coupled power grid by implementing the DSM strategy. In this study, Pakistan's DSM strategy is modelled over 10-year increments, based on specified conditions. The model takes into account the main components of an energy system including energy demand areas like industry, commercial, residential, and agriculture. Energy generation areas based on renewables and non-renewables and simulate various scenarios of energy production and consumption. In developing the LEAP DSM model for Pakistan, techno-economic and socio-economic elements were taken into account. In a whole yearly resolution, all are integrated and optimized together. Fig. 5 illustrates the LEAP DSM energy design.

4.2. Main input parameters and data requirement

The primary input variables for predicting energy consumption, production, CO_2 emissions, and system costs are taken into account based on the socio-economic and techno-economic characteristics. Energy demand was calculated by the LEAP energy demand module using synthetic data that took into account important regional factors like population, gross domestic product, losses (transmission and distribution), and historical patterns of energy consuming sectors. The energy production module of LEAP featured eco-friendly methods for generating electricity from on-site energy resources. The approach described in Ref. [43] was used to calculate the region's generation profile for renewable and non-renewable sources. The direction of the energy transition depends heavily on the financial assumptions used to determine the least expensive solution.

This analysis takes into account cost estimation for transmission and distribution as well as the energy generation system and energy conversion technologies. The method presented in Ref. [44] is used to estimate electricity rates for the industrial, commercial, home, agricultural and other service provider sectors. Data required for modeling this study for the year 2022 include energy production of all energy sources includes wind, natural gas, solar, biomass, coal, hydro, oil and nuclear. Nuclear plant has greater maximum availability of 85 % followed by furnace oil (88 %), biomass (80 %), coal (75 %), natural gas and LPG (70 %), hydro (53 %), wind (35 %) and solar plant (18 %). Life time of fossil fuel-based power stations are in the range of 30 years–50 years, having greater system efficiency of power production and renewable based power plants having life time in between 20 years and 30 years, having smaller system efficiency of power production. In the year 2022, Hydro has greater exogenous capacity of 9874 MW (36,982 GWh) followed by LPG 7325 MW (31761.81 GWh), furnace oil 6274 MW (10596.06 GWh), coal 4770 MW (28000.78 GWh), natural gas 4529 MW (17917.02 GWh), wind 1235 MW (2899.94 GWh), solar 400 MW (711.63 GWh) and biomass 364 MW (710.14 GWh) [23,

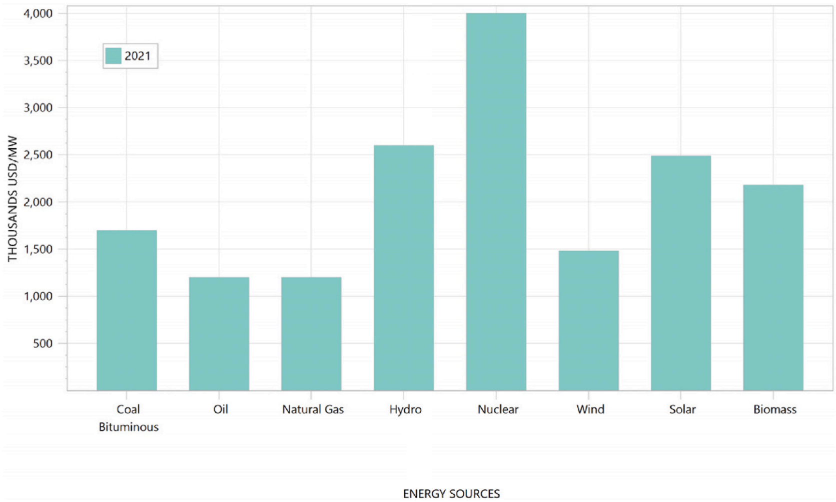


Fig. 6. Base year investment cost of energy sources [38].

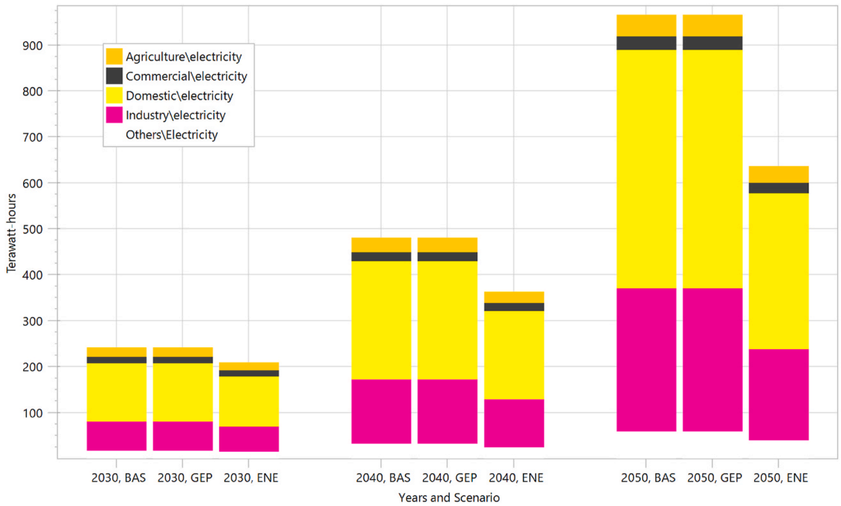


Fig. 7. Demand of energy consuming sectors in Pakistan.

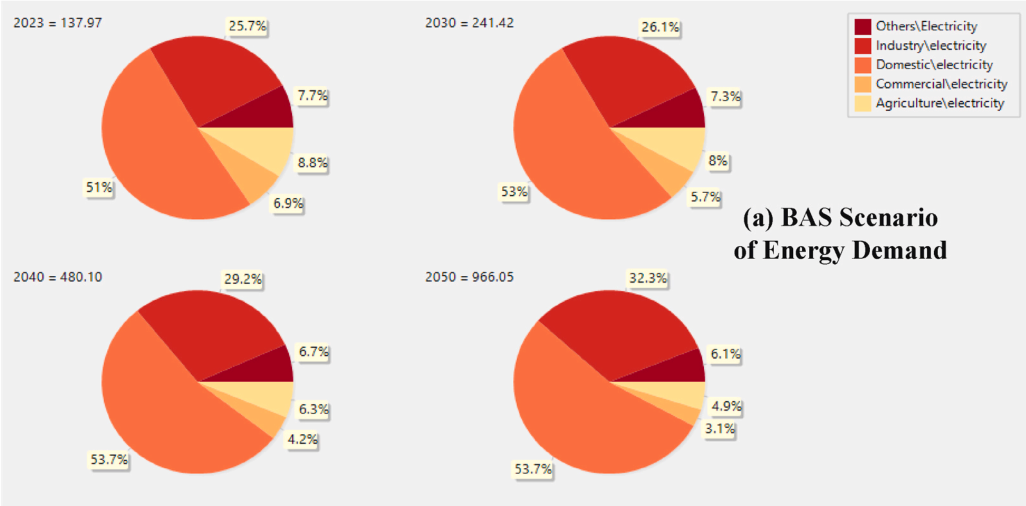
45–52]. Residential solar panels emit around 41 *g of CO2 per kilowatt-hour (g CO2/kWh)* of electricity generated. Wind energy produces *around 11 g CO2/kWh and* hydropower has a median emission intensity of 24 g CO_2/kWh**.** However, the source plants for biomass capture almost as much CO_2 through photosynthesis as biomass releases when burned. The natural gas, oil and coal have capability of producing 56.7 kg/Gj, 74 kg/Gj and 101.2 kg/Gj carbon emissions. The investment cost is calculated using rate of return which can be found by subtracting the initial cost of the investment from its final value, then dividing this new number by the cost of the investment, and finally, multiplying it by 100. Fig. 6 shows the base year prices all energy sources.

The devloped model is further analysed under a scenario insight approach as described in the following section.

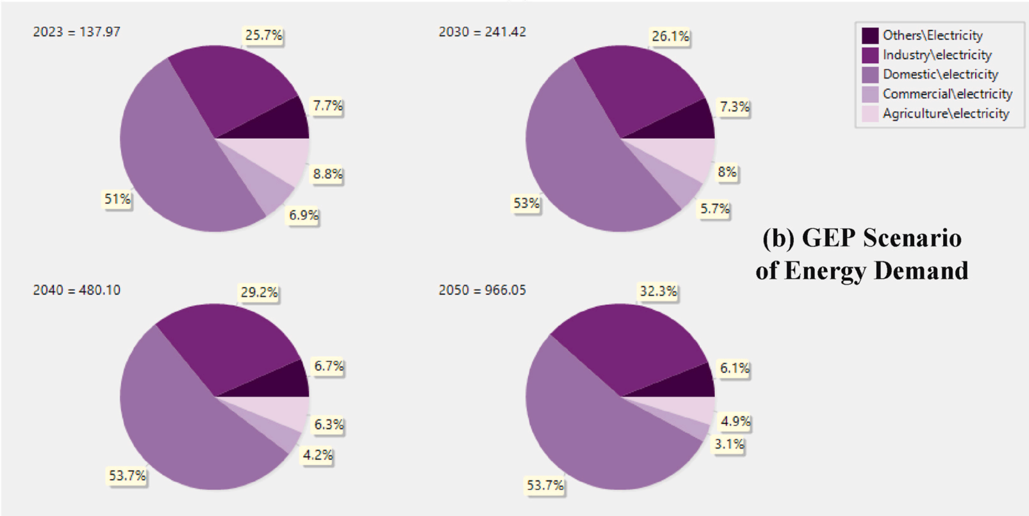
4.3. Scenario analysis

Three different scenarios were taken into consideration in order to thoroughly explore the potential transition pathways. A thorough description of these scenarios is given below.

1. Baseline (BAS) scenario: The ongoing scenario will be used to anticipate Pakistan's future energy consumption, generation, CO_2 emissions, and cost of the energy system. With the assumption that the same pattern will persist into the future as suggested by the Pakistani government in the Power Generation Capacity Expansion Indicator Plan (IGCEP) for 2021.
2. Green energy potential (GEP) scenario: The objective of this is to implement the ARE Policy 2019. The policy states that 20 % of energy must come from renewable sources by 2025 and 30 % by 2030. In this scenario, wind, biomass, and solar energy sources will



(a)



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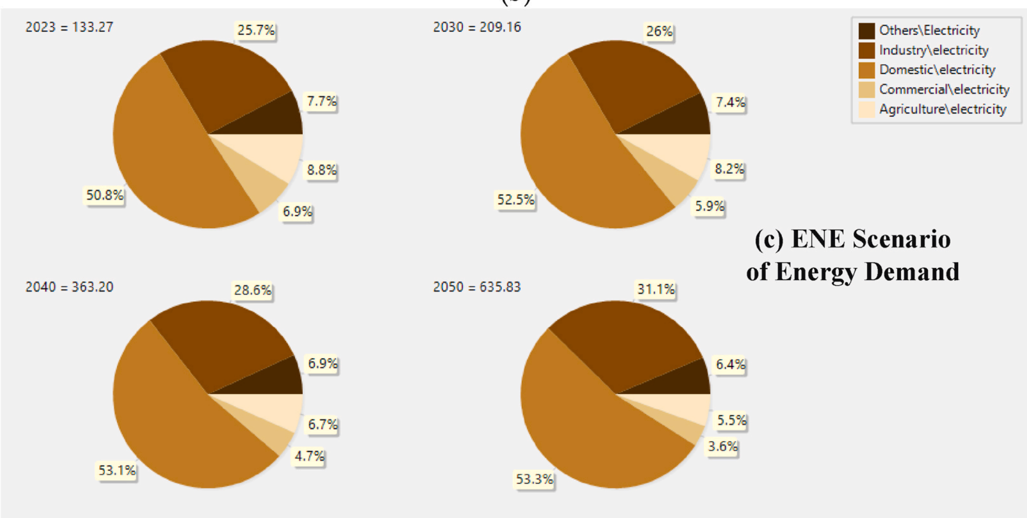

(c)

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Fig. 8. (a,b,c): Percent share statistics of each energy consumption sector under the BAS, GEP and ENE scenarios for the years 2023, 2030, 2040 and 2040.

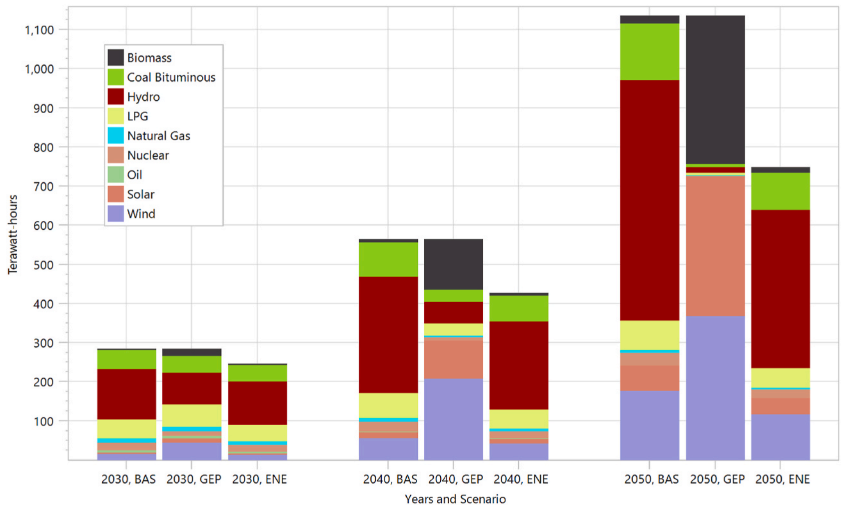


Fig. 9. Generation of energy through domestic energy assets in Pakistan.

be used frequently than hydropower plants because many hydropower plants will be decommissioned in the future and there will be less pressure to develop new hydroelectric power plants due to higher capital costs.

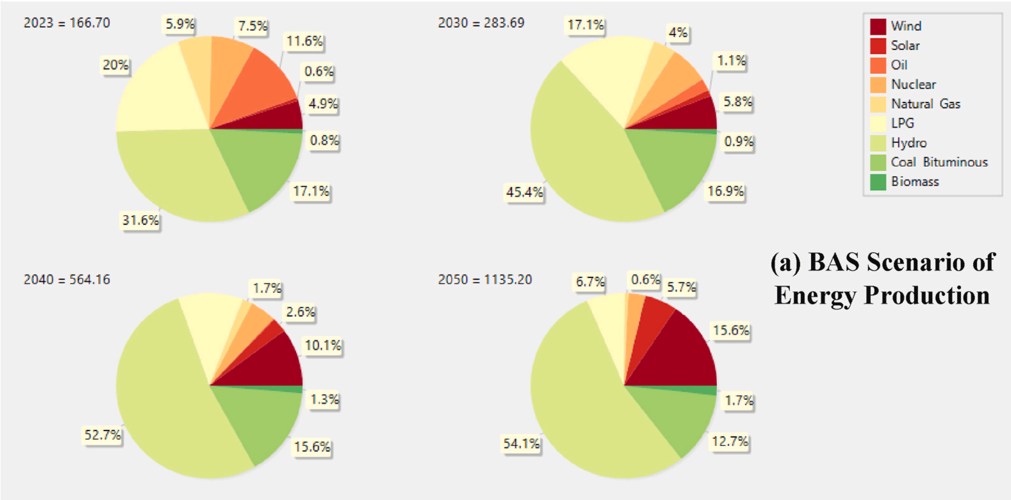
3. Energy efficiency scenario (ENE): The energy shortfall has been filled by the cost-effective and ecologically friendly practice of conservation of energy. This scenario is based on the NEECA policy, this policy focuses on the energy saving potential in energy consumption sectors of around 20–25 %. In LEAP, a growth function is employed to execute a 20 % decrease in the entire demand sector.

5. Results and analysis

The model results are analyses for the study period of 2022–2050. The increased renewable penetration along with DSM is illustrated by the results of GEP and ENE scenario in energy demand, production, CO_2 emissions and investment cost that are presented for comparison. Total energy demand in each sector is estimated in Fig. 7. The energy demand was highly increased over this entire period of analysis and the domestic sector is accountable for the increase in end use energy utilization due to significant changes in people's lifestyles. Similarly, the industrial sector is also consuming more energy as the government has encouraged industries to consume more energy to increase economic growth of the country. In this aspect, the numbers of all types of industries are increasing faster. The energy demand is constant from 2022 to 2050 for BAS and GEP scenarios that is 966.05,000 GWh, however the energy demand is significantly low in the ENE scenario by considering sector-wise saving potentials. BAS and GEP cases predict domestic sector energy demand of 518.94,000 GWh in 2050, industrial 311.70,000 GWh, agriculture 46.95,000 GWh, commercial 29.62,000 GWh, and others 58.85,000 GWh respectively in the year of 2050. The ENE scenario has a significantly lower energy demand that is 635.85,000 GWh. The consumption pattern showed that, energy consumed by domestic 339.09,000 GWh, industrial 197.95,000 GWh, agriculture 34.85,000 GWh, commercial 23.07,000 GWh and other loads were registered at 40.87,000 GWh respectively. The complete statistics of percent share of each energy consuming sector under the BAS, GEP and ENE scenarios are presented in Fig. 8(a,b,c) for the years 2023, 2030, 2040 and 2050.

Energy generation is likewise forecasted with BAS, GEP and ENE scenarios for the period 2022–2050 as shown in Fig. 9. In BAS 614.14,000 GWh of hydro source is contributed in the total energy mix until 2050 followed by 177.07,000 GWh wind, 144.48,000 GWh coal, 75.57,000 GWh LPG, 64.61,000 GWh solar, 32.74,000 GWh nuclear, 19.15,000 GWh biomass, 7.25,000 GWh natural gas and then lastly 0.19,000 GWh oil up to 2050 electricity generation. The GEP scenario will deliver 30 % from biomass, wind, and solar in the final energy mix by 2030. At this rate until 2050, biomass will contribute 378.80,000 GWh followed by wind 368.56,000 GWh, solar 356.70,000 GWh, hydro 13.82,000 GWh, coal 8.83,000 GWh, LPG 6.455,000 GWh, nuclear 1.932,000 GWh, gas 0.88,000 GWh and oil 0.02,000 GWh etc. Finally, ENE scenario addressed the energy savings potentials, which in term reduces the power generation capacity. In the ENE scenario, hydro share has major contribution of 404.21,000 GWh in total energy mix followed by wind 116.54,000 GWh, coal 95.09,000 GWh, LPG 49.74,000 GWh, solar 42.53,000 GWh, nuclear 21.55,000 GWh, biomass 12.60,000 GWh, natural gas 4.77,000 GWh and oil 0.12,000 GWh until 2050. The complete energy mix statistics of percent share of each energy source under the BAS, GEP and ENE scenarios are presented in Fig. 10 (a,b,c) for the years 2023, 2030, 2040 and 2050.

Fossil fuel-based CO_2 emissions are also provided for the 2022–2050 as seen in Fig. 11. Coal produced 138.27MtCO_2 under the BAS, with natural gas at 3.17MtCO_2 and oil produces 0.10MtCO_2 by 2050. Under ENE, energy efficiency measures reduce demand and



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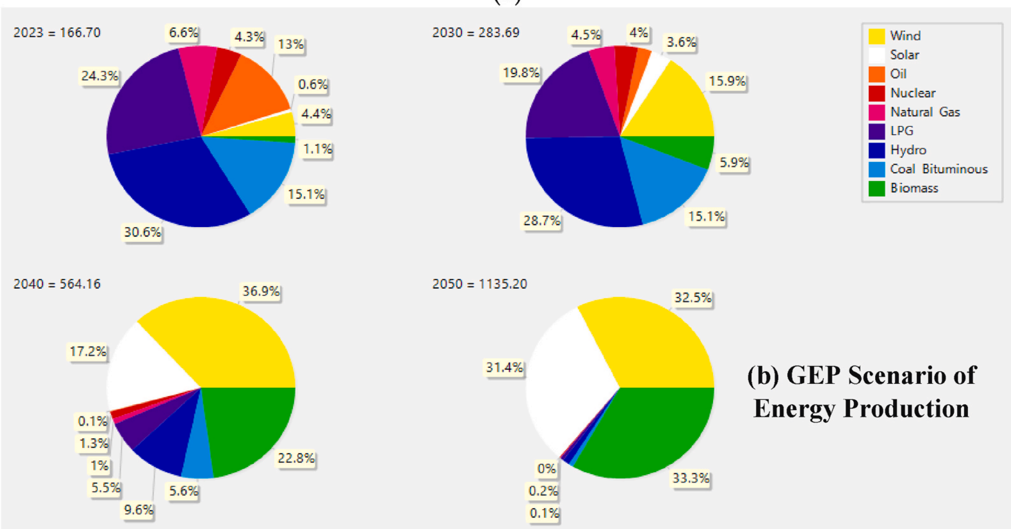

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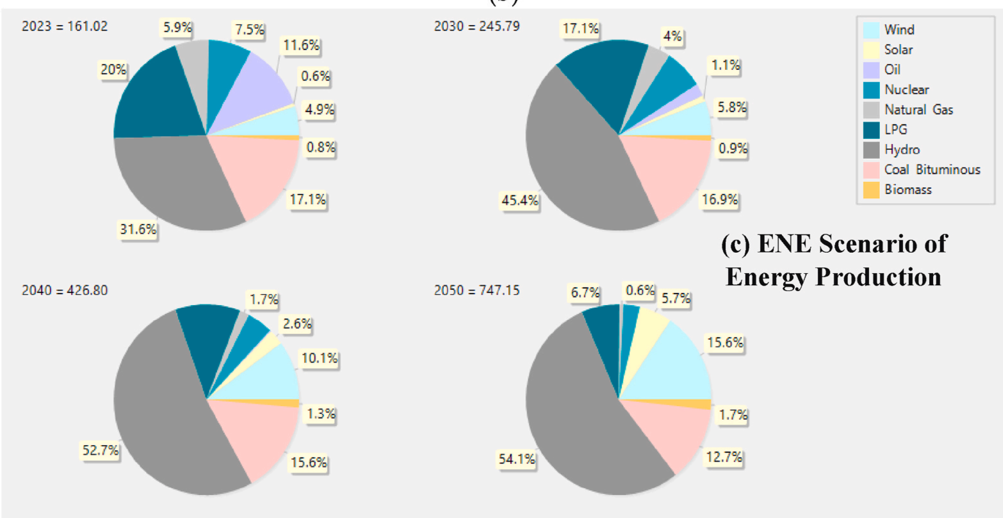

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Fig. 10. (a,b,c): Energy mix statistics of each energy source under the BAS, GEP and ENE scenarios for the years 2023, 2030, 2040 and 2040.

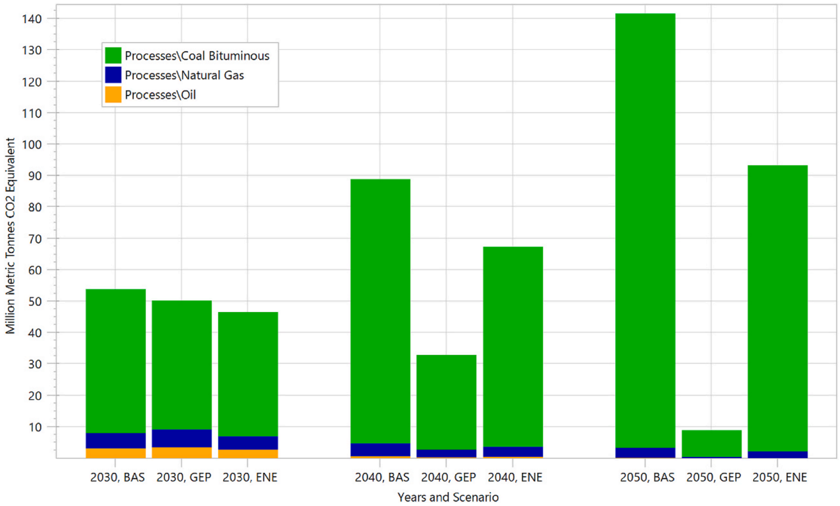


Fig. 11. Carbon emissions from domestic energy assets in Pakistan.

production causing CO_2 emissions to decrease as well, but coal still takes the lead at 91.01MtCO_2, followed by natural gas at 2.09MtCO_2 and oil at 0.06MtCO_2 by 2050. In GEP's case, coal produces 8.45MtCO_2 in 2050, followed by natural gas at 0.38MtCO_2 and then oil at 0.01MtCO_2. The percent contribution of CO_2 emissions of each fossil fuel is given in Fig. 12 (a,b,c) under the BAS, GEP and ENE scenarios for the years 2023, 2030, 2040 and 2050.

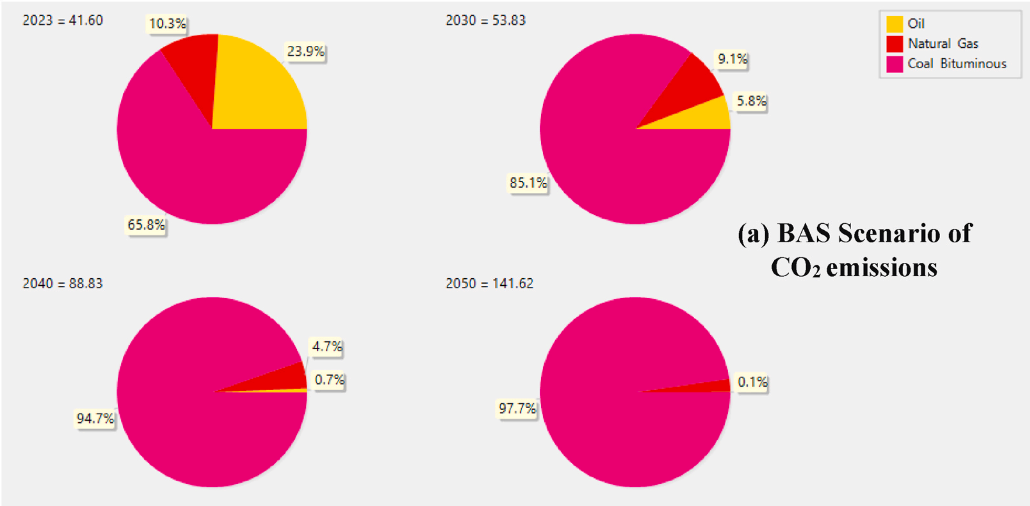
As shown in Fig. 13, the projected investment cost for putting the energy systems into place is also provided. In the BAS and ENE cases, investment costs are lower because the existing capacity will provide power plus additional plants to meet the country's energy need until 2050. The higher investment cost required for hydro development by 2050 is $23.96 billion; solar, $9.47 billion; wind, $7.85 billion; coal, $3.14 billion; biomass, $1.27 billion, and nuclear $1.10 till 2050 billion. Solar power plants under the GEP scenario requires acquiring investment costs of $417.07 billion; biomass, $286.31 billion; wind, $147.11 billion; hydro energy, $1.41 billion, coal only about $0.94 billion and nuclear just around $0.4 until 2050 respectively. The resource wise percent contribution of cost is presented in Fig. 14 (a,b,c) under the BAS, GEP and ENE scenarios for the years 2023, 2030, 2040 and 2050.

Renewable energy sources have significant economic benefits. Doubling the share of renewables is projected to increase the country GDP, compared to baseline scenario. This increase in GDP is driven by the increased investment in renewable energy deployment, which triggers ripple effects throughout the economy. Renewable energy deployment can create significant employment opportunities. Doubling the share of renewables by 2030 is expected to increase direct and indirect employment in the sector to 24.4 million by 2030. The renewable energy sector is expected to be a major driver of job creation in 2023, with millions of new employment opportunities emerging in diverse segments such as solar, wind, hydropower, and geothermal. The societal acceptance of renewable energy is crucial for its widespread adoption. While there are some concerns about the environmental and social impacts of renewable energy, the benefits of renewable energy in terms of reducing greenhouse gas emissions and improving energy security are widely recognized. The transition to renewable energy can also promote sustainable development and alleviate poverty by providing decentralized and scalable energy sources to remote regions.

6. Discussion

According to the GEP scenario, a higher share of renewable energy sources might be reached. The alternative and renewable energy strategy of Pakistan must be given top priority by the Pakistani government, with a 30 % share being implemented by 2030 and increasing to roughly 100 % by the year 2050. Under the ENE scenario, however, demand-side efforts are focused on reducing energy demands at the point of consumption in order to lower the requirement for electric power through implementing energy effective methods. This scenario is very beneficial for Pakistan in terms of energy unit savings, cost savings, and carbon emissions reduction, however the BAS scenario is not appropriate for Pakistan due to a higher proportion of imported fossil fuels. The comparison of our study with the published are given in Table 1. The complete detail of energy balance is given in **Annexure A** for the year 2023 and also energy balance comparison is presented for the years 2040 and 2050 in **Annexure B and Annexure C**. A snaky diagram is a graphic illustration of flows - like energy, material or money - where they can be combined, split and traced through a series of events or stages. The width of the lines and arrows represent amounts or volumes of resources. The study's findings imply that by achieving the optimal balance among power-saving and renewable power output initiatives.

Governance and policy dialogue are critical in determining the green energy transition in Pakistan. Effective governance ensures the establishment of comprehensive policies and regulatory frameworks that foster the development of renewable energy. This includes creating favorable market conditions, developing supportive regulatory frameworks, and implementing financial incentives to encourage investments in clean energy technology. Policy dialogue enables collaboration, knowledge exchange, and consensus-building among stakeholders involved in the green energy transition. It allows for the exchange of knowledge, experiences, and



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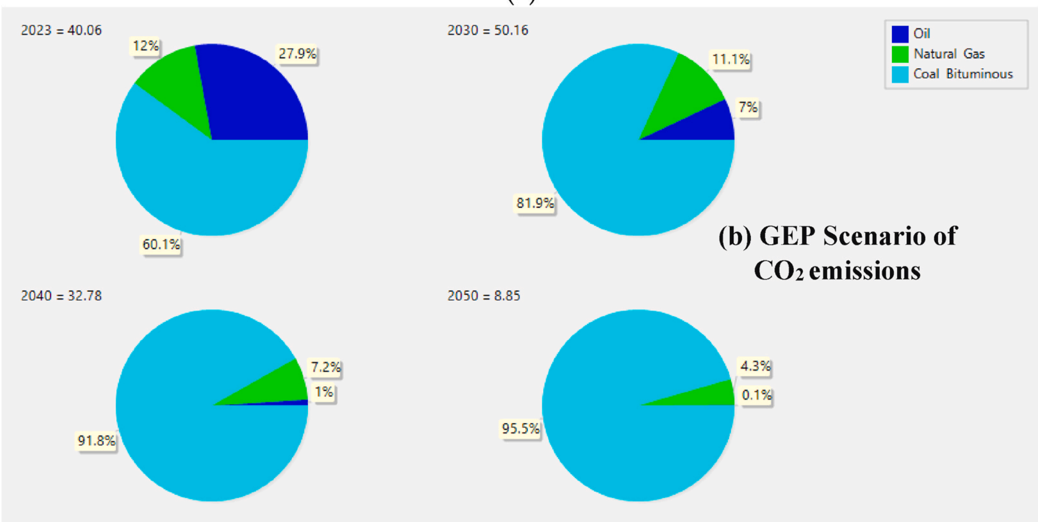

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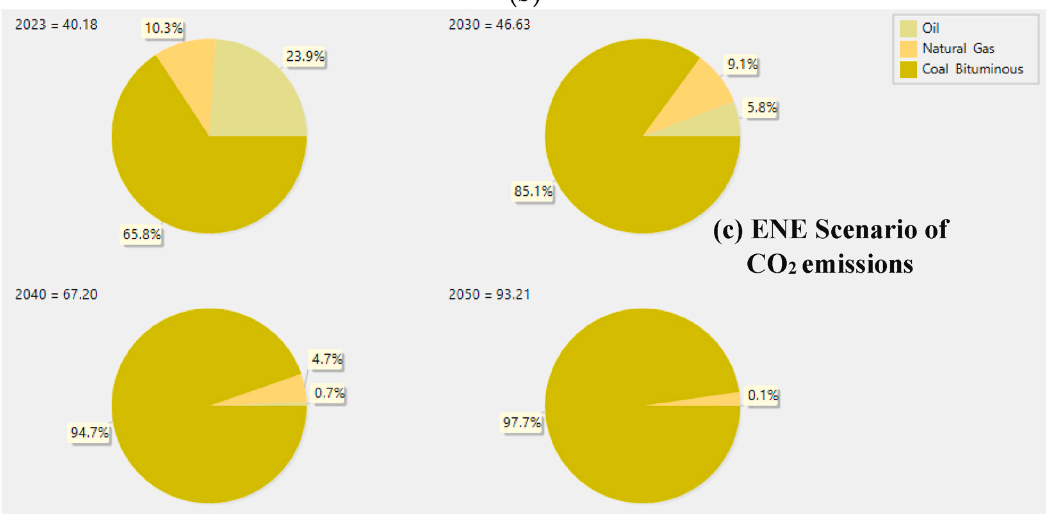

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Fig. 12. (a,b,c): The percent contribution of CO_2 emissions of each fossil fuel under the BAS, GEP and ENE scenarios for the years 2023, 2030, 2040 and 2050.

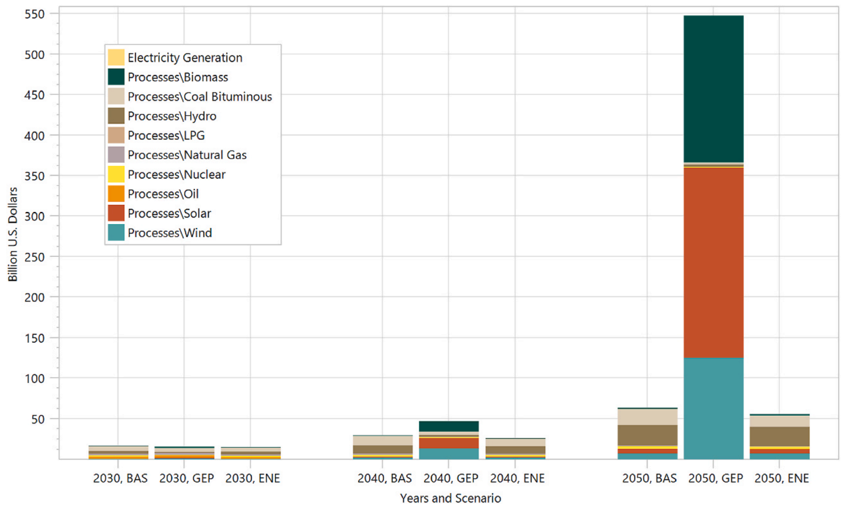
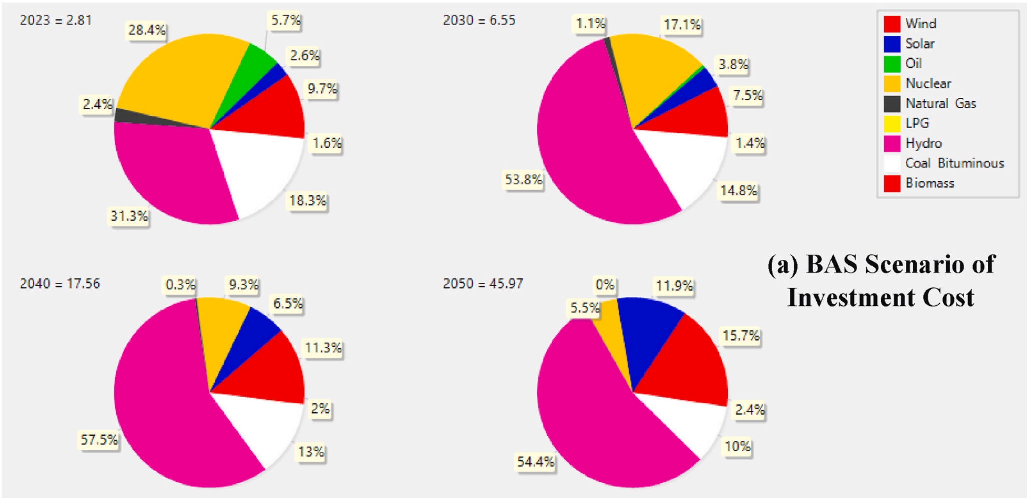


Fig. 13. Cost of energy production from domestic energy assets in Pakistan.

best practices, which aids in the development of effective policies and initiatives. Policy dialogue fosters an enabling climate for effective governance and implementation of green energy policies by promoting a shared feeling of ownership and responsibility. Major inter-governmental organizations are playing a key role in promoting the adoption of renewable energy worldwide. They have been providing policy advice and helping formulate economic incentives and energy control in an effective and flexible manner. Consistent policies are needed for renewable energy sources to flourish on a national level. The renewable energy law comprises of a policy framework which helps establish key policy ingredients like national RE targets, compulsory purchase obligations, feed-in tariffs, renewable energy certificates, and net metering. These policies directly or indirectly affect renewable energy development by addressing various barriers such as high costs, unfavorable power pricing rules, perceived risks, lack of access to credit, and interconnection requirements. Renewable energy policies can be broadly categorized into six types: renewable energy promotion policies, transport biofuels policies, emissions reduction policies, power sector restructuring policies, distributed generation policies, and rural electrification policies. Each policy reduces one or more key barriers that impede development of renewable energy.

For implementing the energy saving and green energy policy, several challenges such as political instability, financial constraints, and inadequate infrastructure can be resolved through the best practices as described below.

- Effective governance requires the establishment of comprehensive policies and regulatory frameworks that foster the development of renewable energy. This includes creating favorable market conditions, developing supportive regulatory frameworks, and implementing financial incentives to encourage investments in clean energy technology.
- Policy dialogue enables collaboration, knowledge exchange, and consensus-building among stakeholders involved in the green energy transition. It allows for the exchange of knowledge, experiences, and best practices, which aids in the development of effective policies and initiatives.
- Renewable energy policies can include targets, purchase obligations, feed-in tariffs, renewable energy certificates, and net metering. These policies directly or indirectly address barriers to renewable energy development such as high costs, unfavorable power pricing rules, perceived risks, lack of access to credit, and interconnection requirements.
- Policies should be designed to ensure an equitable clean energy transition, such as creating a clean energy equity office, developing a clean energy career advancement program, and implementing minimum resource investment requirements for clean energy projects benefiting disadvantaged communities.
- Best practices for integrating renewable energy into the grid include conducting grid integration studies, building capacity through training and knowledge sharing, promoting multilateral collaboration, fostering innovation, and establishing a robust legal and regulatory framework.
- Energy efficiency is a key component of green energy policy, as it can contribute to significant energy demand reduction and deliver multiple social and economic benefits



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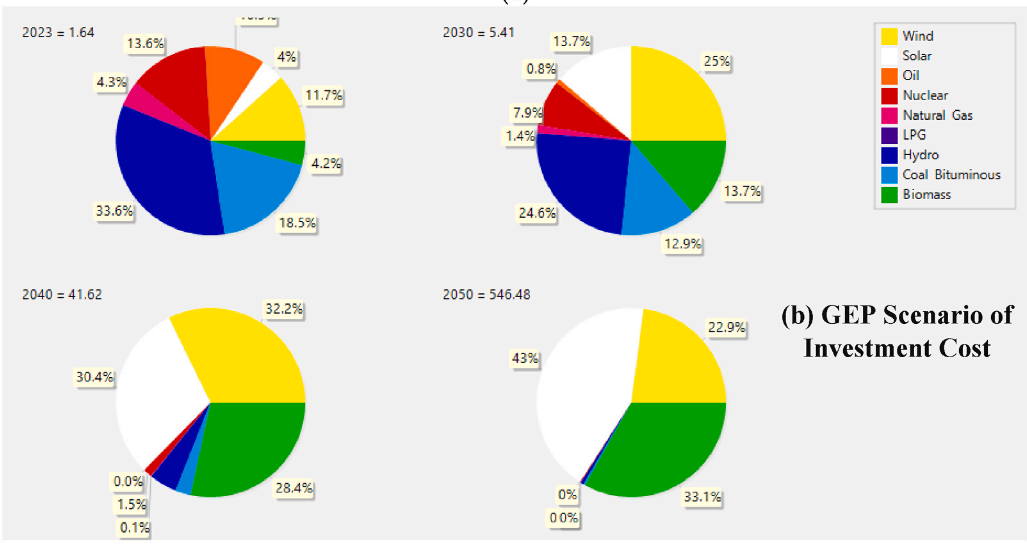

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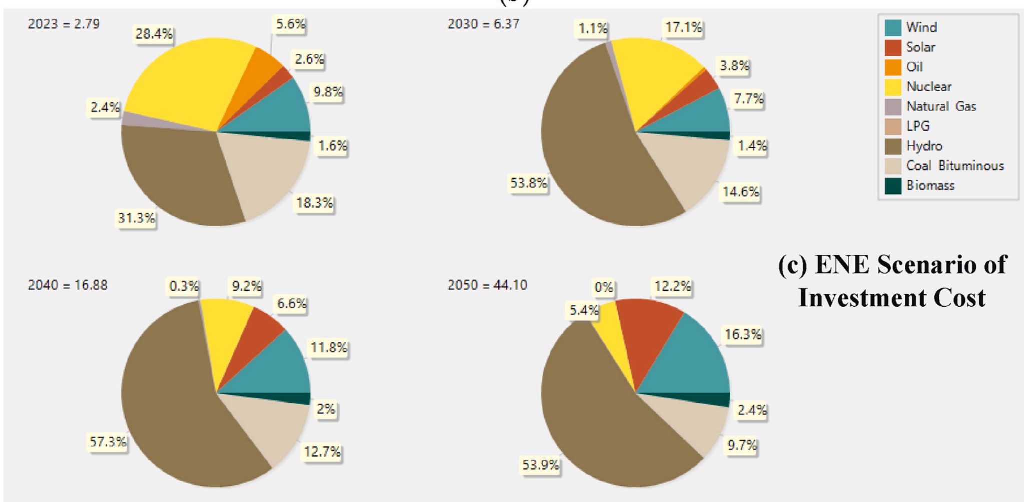

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Fig. 14. (a,b,c): The resource wise percent contribution of cost under the BAS, GEP and ENE scenarios for the years 2023, 2030, 2040 and 2050.

Table 1
Comparative analysis of past studies.

Study	Study aim
[53]	This study investigates the role of environmental-related technologies on energy demand and energy efficiency in a sample of 28 OECD economies.
[54]	The reduction of energy demand in buildings through the adoption of energy efficiency policy is a key pillar of the European Union (EU) climate and energy strategy.
[55]	This paper explores one possible explanation for the historical close relationship between energy consumption and GDP, namely that the economy-wide rebound effects from improved energy efficiency are larger than is commonly assumed.
[56]	We investigated the impact of energy efficiency on economic growth and environmental sustainability in the ten most energy-efficient countries from 1990 to 2019, using energy access, energy security, and energy depletion as moderator variables.
[17]	This study attempts to connect Sustainable Development Goals (SDGs) with energy efficiency for 20 Asian and Pacific (AP) countries using Data Envelopment Analysis (DEA) from 2000 to 2018.
[57]	The aim is to identify problems and knowledge gaps in the field for future projection related with energy efficiency measures.
[18]	This paper addresses the empirical relationship between energy poverty and energy efficiency in developed and developing countries through various domains.
[58]	This study investigated, therefore, the effects of technological innovation within certain countries on the energy efficiency performance of neighboring countries.
[59]	The results also show that urbanization curbs carbon emissions from the transportation sector, but the effect of urbanization is lower than the effect of energy efficiency.
[60]	To explore the impacts of energy efficiency on income inequality and energy poverty in China, this study constructs a dynamic panel model using a balanced panel dataset covering 30 provinces for the period 2004–2017.
[61]	New societal trends are unfolding, such as digitalization, sharing economy and consumer awareness. They will highly influence future energy demand and, depending on their realization, enhance or counteract projected energy efficiency gains.
[62]	In recent years, increasing interest has been shown in targeting energy efficiency as a roadmap for carbon mitigation, limiting energy use, improving buildings' energy performance, and reducing energy consumption for achieving sustainable buildings.
[63]	This study investigates the effect of green-bond financing on energy efficiency investment for green economic recovery.
[64]	Using Chinese provincial panel data for the period 2006–2017, this study investigates whether the internet has improved China's green total factor energy efficiency.
[65]	Energy saving and industrial pollution have become increasingly important issues, therefore the identification and adoption of more energy efficient machines and industrial processes are now industrial priorities, and worthy topics for further development through academic research.
[66]	This paper estimates the per capita capital stock of economic infrastructure and the green total factor energy efficiency of China's manufacturing industry.
[67]	This paper attempts to quantitatively summarize the existing empirical evidence on the effects of energy efficiency policies on energy demand and on the price of associated durable goods, as well as to identify the main factors that systematically affect the estimated impacts.
[68]	Despite the ongoing research on energy efficiency and innovation in the context of Industry 4.0, little is known on how degree of leakages in economy can impact the energy efficiency-innovation association.
[69]	This study aims to examine the effects of energy efficiency (EE), renewable energy (RE), and other factors on the carbon emissions of Mexico, Indonesia, Nigeria, and Turkey (MINT). The study covers the time from 1990 to 2014.
[70]	This paper presents a new, multi-objective method of analyzing and optimizing the energy processes associated with window system design in office buildings.

7. Future work

- Use public policy to innovate electric utility investment and regulation. The state energy policy role is distinct from the state regulatory role, yet both are critical to advancing a more modern and resilient transmission, distribution, and end-use electricity system.
- Realizing the grid of the future will require greater penetration of energy efficiency and distributed energy resources, as well as continued technological innovation. While the national laboratories have been the centerpiece of federal energy technology innovation efforts, there is a greater need to connect the broader energy innovation system, which incorporates not only the labs, but also large corporations, small and start-up business, research institutions, incubators, and innovative market deployment programs and channels.
- At the same time, electrification is itself a form of energy efficiency – after all, it has been estimated that transitioning from a fossil energy system to a fully electrified one could cut up to 40 % of final energy consumption. Given the increasing press on emissions reductions and resurgence of oil and gas, we need to build on existing potential and invest in next level energy efficiency.

8. Study limitations

The energy efficiency directive established new legally binding targets for.

- Energy saving potential exists for final energy consumption until 2030, across sectors such as buildings, transport, and industry.
- Determination of calculation rules that enable the evaluation of all energy use of buildings and classification in terms of carbon dioxide emissions and primary energy.
- Determining the minimum energy performance required for new buildings and existing buildings planned for significant renovation
- Control of cooling and heating systems, determination of application principles and performance criteria in buildings

9. Conclusion

The purpose of this research was to develop efficient roadmap which would provide optimal balance between energy saving ratios and renewable energy production metrics for the different economic groups in Pakistan. We suggested guidelines here, and went ahead with using those same recommendations for Pakistan. Modeling for 2022–2050 was done using the Low Emissions Analysis Platform (LEAP) software. Three scenarios: Baseline (BAS), Energy Efficiency (ENE), and Green Energy Potential (GEP) were developed to define the Demand Side Management (DSM). BAS case is aligned with the present policies of Government of Pakistan. The ENE case considers the 20 % saving potential and GEP case presents 30 % green energy share of biomass, solar and wind by 2030. In the BAS scenario, the total energy production reaches 1135.20,000 GWh, more than the required energy demand of 966.05,000 GWh of the nation until 2050. In the ENE scenario, predicted energy demand and energy production are significantly lower than the BAS scenario. The nation's energy demand is 635.83,000 GWh which can be met by the 747.15,000 GWh of energy production until 2050. However, in GEP scenario, the whole energy mix is made up of 1117.08,000 GWh of renewable sources and 18.12,000 GWh of non-renewable sources until 2050. The lower carbon emissions are produced in GEP scenario that is 8.85MtCO_2 whereas lower investment cost is required in BAS and ENE scenarios that are $46.80 billion. This study results can greatly help planning and policy makers to undertake strategic decision making to attain sustainability in the energy sector and sustainable development in general.

Data availability statement

The data sources employed for analysis are presented in the text.

CRediT authorship contribution statement

Arshad Chughtai: Writing – original draft, Methodology, Conceptualization. **Mohammad Aslam Uqaili:** Writing – original draft, Methodology, Data curation. **Nayyar Hussain Mirjat:** Visualization, Validation, Formal analysis. **Faheem Ullah Sheikh:** Methodology, Investigation, Data curation. **Muhammad Majid Gulzar:** Validation, Formal analysis, Data curation. **Salman Habib:** Visualization, Project administration, Investigation. **Kareem M. AboRas:** Supervision, Project administration, Methodology. **Wulfran Fendzi Mbasso:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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