



# Pakistan road towards Paris Agreement: Potential decarbonization pathways and future emissions reduction by A developing country

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## ABSTRACT

Pakistan is a signatory of the Paris Agreement and is ranked among the top 10 most highly vulnerable countries towards climate change. Being the 5th most populous country in the world, with ambitious economic growth goals, a countrywide emissions assessment of the GHGs following various economic scenarios and planning objectives is crucial; especially using dynamically integrated, technologically rich, bottom-up, and robust models. Hence, we used LEAP (low emissions analysis platform) for setting up long-term decarbonization and energy transitioning pathways following global commitments (e.g. Paris Agreement) thereby contributing towards climate change mitigation and adapting net-zero policies in the country. These pathways are based on various scenarios and sub-scenarios e.g. Business as Usual (BAU), the National Decarbonization (NDS), and Net-Zero Emissions Scenario (NZES) spanning over a time-window of 2020–2050. Extensive technological reforms and changes in energy fuel mixes across residential, transportation, agriculture, industrial, and power production sectors have been anticipated. The result shows that, following NDS-based policies, 26 % GHG emissions reduction i.e. 170 MtCO<sub>2</sub>eq is possible in the short-run (2030) followed by 67 % (773 MtCO<sub>2</sub>eq) reduction in the mid-term (2040) and a remarkable 90 % (1756 MtCO<sub>2</sub>eq) reduction in the long run (2050). On the other hand, fuel-switching and substitution, an adaption of maximum renewable energy resources and hydrogen fuel in the national fuel mix followed by the proposed installations of carbon-capture and storage technologies have led to the achievement of net-zero-emissions in the NZES scenario. However, considering Pakistan's technological capabilities and economic conditions, developing a low-carbon society by achieving net-zero emissions until 2050 seems a highly ambitious plan. Nevertheless, international financial and technological support can play a vital role in helping countries like Pakistan enhance their capacity to achieve long-term decarbonization and climate resilience goals. This support can bolster Pakistan's efforts to transition to a low-carbon economy and adapt to the challenges posed by climate change.

## 1. Introduction

Global CO<sub>2</sub> emissions grew by around 0.9 %, reaching 36.8 billion tons in 2022, emphasizing the discrepancy between current emissions trajectories and the targets needed to limit warming to 1.5 °C [1,2]. Efforts to reduce emissions include the Paris Agreement, which aims to limit global warming to below 2 °C and achieve carbon balance by the end of the century. Countries have submitted Intended Nationally Determined Contributions (INDCs) to decrease carbon emissions [3].

The global community aims to limit the rise in global average temperature to 2 °C by the end of the current century. To achieve this, Intended Nationally Determined Contributions (INDCs) submitted by various countries at the 21st Conference of the Parties (COP21) in December 2015 serve as crucial guidelines [4]. These contributions target the reduction of individual nations' CO<sub>2</sub> emissions to mitigate the impacts of climate change. Stabilizing CO<sub>2</sub> emissions reflects significant progress in enhancing the quality of life on Earth, with investments in energy efficiency leading to a 6 % global efficiency improvement in 2015 compared

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to the previous year [5]. Annual greenhouse gas (GHG) emissions have surpassed 53 Gt of CO<sub>2</sub>eq, with approximately 40 Gt representing CO<sub>2</sub> emissions [6]. The rate of global mean sea level rise has more than doubled since the early satellite records, with recent estimates indicating an increase of approximately 3.6 mm per year from 2006 to 2015, due to a combination of ice melt and thermal expansion of the oceans [7]. In the IPCC's Sixth Assessment Report (AR6), scientists projected global surface temperature could increase by 1.5 °C relative to pre-industrial levels as early as 2030 under high-emission scenarios, with a potential rise up to 4.4 °C by 2100 if emissions remain high [8]. The Global Climate Risk Index 2021, based on data from 2000 to 2019, serves as a crucial reference amidst escalating challenges. Countries such as Haiti, the Philippines, and Pakistan, consistently among the most affected by catastrophic events, highlight the urgency of addressing climate risks through sustained global initiatives [9]. In 2020, Pakistan ranked as the fifth most vulnerable country to climate change [10]. The country must take extensive adaptation and mitigation measures to reduce these impacts while transforming the energy sector towards less polluting and carbon-neutral options [11]. Pakistan's international commitments concerning climate change also find appearance in its nationwide policy contexts such as the Economic Growth Framework [12], Climate Change Policy of Pakistan [13], One UN Programmed on Environment, National Environmental Policy [14], and the National Energy Efficiency and Conservation Policy [15]. Present documents plainly define how the government aims to honor its global commitments. The nation also proclaimed and executed the CDM National Operational Strategy to signal its entrance into the international carbon market [16]. Pakistan contributes approximately 0.9 % of global greenhouse gas (GHG) emissions [17]. On a per capita basis, Pakistan's GHG emissions are 1.9 tons per capita, roughly one-third of the global average, one-fifth of Western Europe's average, and one-tenth of the U. S. emissions per capita [18]. However, its emissions are expected to increase significantly as the country addresses its growing energy needs [18,19].

According to the National Economic Empowerment and Development Strategy (NEEDS), concerns heighten over Pakistan's future energy reliance on coal. In a Business as Usual (BAU) scenario, total GHG emissions are projected to increase from 347 MtCO<sub>2</sub>eq in 2011–4621 MtCO<sub>2</sub>eq in 2050, closely linked to the expected sectoral GDP growth in agriculture. However, there is substantial potential for "Win-Win" mitigation actions, addressing rural public needs, cost savings, water resource conservation, and significant GHG reductions. Pakistan faces alarming rates of deforestation, particularly in the forestry sector, but tree shelter development presents a viable CO<sub>2</sub> sink for mitigation, supported by financial mechanisms like UN-REDD [20]. To effectively implement climate initiatives outlined in Pakistan's Nationally Determined Contributions (NDCs), financial assistance, technological support, and capacity building are crucial, as per guidelines from Article 4 of the UNFCCC and Articles 9, 10, and 11 of the Paris Agreement [20]. Paragraph 5 of Article 4 of the Paris Agreement stresses the importance of aiding developing country Parties, enabling them to pursue ambitious climate actions. Pakistan aims to contribute to global GHG mitigation efforts while meeting essential energy and food needs, aligned with its economic development, energy security, and technological capabilities [21].

Despite the availability of various modeling tools globally for shaping energy policies, emerging nations like Bangladesh, India, Greece, Turkey, and Nigeria, among others, are effectively utilizing these tools to address urgent energy issues and formulate informed policy measures [22]. Effective energy planning requires a thorough evaluation of resources and reliable long-term demand projections. However, Pakistan faces challenges due to a lack of dependable data on energy resources and reliable long-term demand projection, hindering the development of effective energy policies [23]. Recently, the Long-Range Energy Alternatives Planning System (LEAP) has been employed to model energy consumption and economic sector trends

from 2015 to 2050, albeit limited to certain sectors [24,25].

It is noteworthy that Pakistan has yet to fully utilize energy modeling tools for comprehensive energy planning and policy formulation. As a result, fragmented energy planning across various levels has contributed to the country's electricity crisis. Limited academic studies [26–36] have explored the use of these tools. Only one government-led effort for integrated energy planning occurred through Technical Assistance (TA) from the Asian Development Bank (ADB) in 2007. This initiative employed the International Energy Agency's (IEA) TIMES energy model, but the resulting PAK-IEM model did not significantly influence policy formulation. Consequently, none of the country's energy policies to date have directly incorporated findings from energy modeling exercises. Given this context, Pakistan must adopt these modeling tools for a more consistent planning approach and energy policy analysis e.g. energy demand projection, energy supply projection management, energy modeling using econometric approaches, energy modeling using accounting and simulation approaches, energy modeling using machine learning, etc.

However, despite discussing various aspects of energy planning and management, the above studies failed to investigate the future of Pakistan concerning global climate change mitigation commitments and efforts. Similarly, net-zero emissions and Pakistan's potential for energy transition have never been reported in such detail as we are about to provide in this paper. This is the first-ever study from Pakistan whereby energy systems of various economic sectors e.g. residential, transportation, agriculture, industrial, and power production sectors have been planned by considering Pakistan's intentions of net-zero emissions, decarbonization, and energy transitioning towards renewables. Together these efforts resulted in the development of a national-scale GHG inventory and made it possible to assess sectoral actions required following global climate change mitigation commitments. Some of the policy options investigated across these sectors include but are not limited to fuel switching and substitution, technological integration such as carbon capture and storage (CCS) in the power generation sector, net-metering and solarization in the residential sector, electric and hydrogen-based transportation, industrial waste-to-energy generation, solar-based irrigation systems in agriculture. Looking towards the current economic situation it is been proposed that focusing on renewable energy with integration with local coal use for power production with installing CCS technologies can be a feasible option for a developing country like Pakistan.

We performed bottom-up energy modeling using a revised LEAP model following multiple scenarios. The LEAP model provides a flexible framework for assessing present and projected greenhouse gas emissions across economic sectors, which is essential for modeling the long-term energy and carbon emissions goal. The findings of this study are being presented by constructing three distinct scenarios, i.e. Business as Usual (BAU) scenario, the National Decarbonization Scenario (NDS), and Net-Zero Emissions Scenario (NZES) spanning over a time-window of 2015–2050. The upcoming parts of this paper consist of a detailed yet comprehensive literature review (section 2), Theoretical and Methodological Framework (section 3), Results (section 4), Discussion (section 5), and conclusion and policy recommendation (section 6).

## 2. Literature review

Research in the field of GHG emissions from the energy sector essentially comprises two facts: the projection of carbon emissions and energy, and the establishment of an energy utilization warning system. The first facet involves projection, evaluating, and examining the upcoming evaluation of energy systems and carbon emissions. When considering both aspects in conjunction with the first, the second facet is primarily carried out through the development of mathematical models that depict the inner workings and external linkages of the energy system. As shown in Table A1 in the appendix, multiple studies on energy modeling tools have been started for various nations in the

contemporary literature.

Recent energy security challenges involve economic issues related to energy consumption, systems, carbon emissions, and balance between supply and demand. Technical data extrapolation and structural models can predict usage and emissions [37,38]. In contrast, Uniform integrated structure models reveal complex relationships among variables, classified as hybrid, top-down, and bottom-up models for energy and carbon emissions projection [39,40].

In contemporary times, hybrid models are increasingly used for energy projection, combining bottom-up and top-down methods to represent energy production and consumption. These models, such as MARKAL-MACRO and ETA-MACRO, simulate dynamic energy system behavior across various sectors. They are commonly used in China to predict energy and carbon emissions by 2050 [41,42]. Chen [43] utilized MARKAL-MACRO to analyze future energy consumption and carbon emission trends in China, considering measures like industrial restriction, energy efficiency, and energy substitution. The MARKAL-MACRO-Italy model was created by Contaldi et al. [44] to estimate the holistic effect of renewable energy provision on the power industry in Italy. Top-down models dictate energy generation and consumption technology, considering carbon emissions and measuring supply and demand through different production methods. Bhattacharyya and Timilsina [45] argue that this model, as a partial equilibrium model, lacks macroeconomic modules, requiring external determination of structural and macroeconomic variables. Meng et al. [46] merged the Computable General Equilibrium model (CGE) and power supply models, Tavakoli and Motlagh [47] utilized the Ecology, Energy, and Environment (3Es) tools to analyze energy sources' availability and accessibility in Iran, aligning with the green economy concept. Bahn [48] and Pan [49] utilized the GEM-E3 global model to promote the Joint Implementation and Clean Development Mechanism (JI and CDM). Karkatsoulis et al. [50] utilized the GEM-E3 model to analyze the macroeconomics and sector-specific consequences of promoting a low-carbon transport system in Europe by 2050. Additionally, within the category of bottom-up model, you'll find models such as SAGE, AIM/Enduse, MARKAL, MessageIV, and LEAP. Lee et al. [51] conducted a parametric study using the SAGE model to rank the effects of modeling uncertainties on estimates of fuel burn and emissions. In Thailand research conducted by Selvakkumran and Limmeechokchai [52] employed the AIM/End use model to investigate the potential impact of emission taxes and Low-Carbon Society (LCS) policies and emission taxes on the land transportation system. Spearrin and Triolo [53] utilized the MARKAL framework to assess the US transport industry's economic situation and potential increase in demand-side natural gas consumption. Ozawa et al. [54] found that achieving an 80 % CO<sub>2</sub> reduction between 2013 and 2050 would significantly reduce emissions from Japan's power generation sector using the MARKAL model. Morales and Sauer [55] used the LEAP model to analyze the impact of expanding landfill gas cap on South Korean power market production costs and GHG emissions. Phdungsilp [56] employed the LEAP model to simulate the expansion and consequences of 16 climate and energy-related policies in Bangkok from 2000 to 2050, projecting the trends in energy usage and fossil fuel emissions. Sadri et al. [57] used the LEAP model to develop a comprehensive methodology for long-term energy and environmental planning in developing nations, focusing on regulating petrol usage for LDVs. Similarly, in separate studies, Kemasuor et al. [58] studied Ghana, exploring the implications of biofuel usage in similar sectors. These investigations had a distinct emphasis on the role of biofuels in environmental mitigation. Ates et al. [59] investigated the Turkey's iron and steel industry's energy sufficiency and its potential for mitigating CO<sub>2</sub> emissions by employing the LEAP tools. Nojedehe et al. [60] developed the LEAP framework in Tehran for 2012–2035, integrating the IPCC model to estimate methane emissions and assess energy and non-energy emissions. Hong et al. [61] developed LEAP modeling tools to assess the usefulness of implemented policies within South Korea's transport sectors and to analyze their

current and future consequences on energy and the environment. Cai and Guo [62] developed the LEAP-China-Power model to simulate power planning policy scenarios from 2012 to 2050, including reference, CCS, and N&N scenarios. The literature on GHG emissions and energy modeling highlights a collective commitment to versatility, integration, and innovation in modeling methodologies. Researchers are working collaboratively to push the boundaries of modeling, contributing unique insights to enhance understanding of energy systems and emissions projection. This diverse effort fosters a sophisticated and adaptable modeling landscape, characterized by collaboration, continuous improvement, and synthesis of varied perspectives. As these studies shape advanced modeling practices, they aim to offer accurate projections and nuanced insights into the complex energy landscape, positioning the research community to address energy sustainability and environmental challenges. To summarize, the broad collection of writing inspected above highlights the perplexing exchange between energy security, financial frameworks, and the major problems encompassing fossil fuel byproducts and energy frameworks. As featured by past exploration, the displaying scene for energy and fossil fuel byproducts expectation contains different techniques and arrangements, including data extrapolation, hybrid models, integrated structure models, and top-down and bottom-up models. These different displaying approaches act as important apparatuses to dissect and figure out the perplexing connections between energy, the economy, and the environment.

Previous studies conducted in Pakistan have likewise assumed an essential part in addressing the energy and emissions challenges well-defined for the country. These findings have explored several aspects of Pakistan's energy sector, including energy generation, consumption methods, and the effect of policies and measures on the emission of carbon. Noteworthy among these efforts by Mirjat et al. [63], who established the framework for Pakistan's power sector by using LEAP modeling for the period 2015–2050. An Integrated Modeling Approach MARKAL/TIMES was used for the projection of Long-Term Energy Demand in Pakistan by Ref. [23]. A Further link of Energy-environment-economy in Pakistan was determined by Ref. [64] using the PAK-TIMES model. Shah et al. [65] implement an ARMA model projection procedure based on a component's estimation technique to project medium-term electricity consumption. Aslam et al. [66] provide the energy sector outlook (2020–2040) of Pakistan under different scenarios i.e., Pre-COVID-growth, Business-as-Usual, Slow Recovery, and Green Recovery from COVID using LEAP. Abbas et al. [67] utilized a grey model for the analysis and projection of transport sector demand for energy and carbon emission in Pakistan. Their findings give valuable intuitions into long-term potential scenarios and electricity demand to cope with the energy predicament in Pakistan. Our study's application of the LEAP model is particularly relevant in the Pakistani context, where energy security and emissions reduction are paramount concerns. The insights gleaned from this study will not only contribute to the global discourse on mitigating carbon emissions but will also provide policymakers in Pakistan with a robust foundation for crafting sustainable energy strategies tailored to the country's specific challenges and opportunities.

### 3. Methods

#### 3.1. LEAP-Pakistan model

Our study utilizes the LEAP model to project energy trends from the base year 2015 to the target year 2050. This comprehensive analysis encompasses a detailed examination of the existing energy demand and supply dynamics, a projection of GHG emissions associated with this demand, and the formulation of alternative scenarios aimed at meeting future energy requirements while following low-carbon emission pathways. Within this framework, two primary areas of focus emerge. Firstly, our research delves into the energy consumption trends within the

specific sector under consideration, providing critical insights into real carbon emissions associated with these trends. By doing so, we aim to understand the current carbon footprint and its implications for the environment and the economy. Secondly, we explore mitigation measures drawn from policies tailored to future energy consumption patterns, carbon emission reduction targets, and economic development objectives. LEAP's capabilities extend to various tasks, including the development of alternative energy scenarios, demand projection, GHG mitigation analysis, integrated resource planning, and the formulation of comprehensive energy master plans (see Fig. 1) (see Fig. 2).

### 3.2. Key assumptions

Key assumptions provide the key variables of the model, such as GDP, GDP Growth rate, total population, population growth rate, number of households, per-capita income, and sectorial GDP contribution. The basic assumptions used in the Pakistan LEAP model are the table's key social, economic, and demographic indicators. The population growth rate of 2.4 % from 'Statistics 2017' was used for this analysis [24]. The 300 billion USD total GDP refers to 2019–2020 yrs. Electricity demand and consumer growth rates are taken from the Pakistan Energy Yearbook 2019 [68]. Electricity demand and consumption, primary energy supply, and plant data are taken from the NEPRA State of Industry Report 2018–2019. Electricity transmission & distribution losses are assumed to be 22 % which are expected to be reduced to 15 % by the end of 2040 and these cover both technical and non-technical losses [69]. Similarly, natural gas losses are assumed to be 9.5 % and these are expected to reduce by 5 % by the end of 2050. For the long-term projection of Pakistan's electricity supply and demand, it is applied long-range energy alternatives planning. Load Duration Curve shows of energy demand variation of the consumer on a source of supply concerning time. The dispatch rule in a model is set to merit order to operate power plants to balance nominal and instantaneous demand within rated capacity limits. Capacity credit is the fraction of rated capacity considered to calculate the module reserve margin, and it is assumed to be 100 % for all the technologies used in the model except solar and wind, owing to their intermittent availability. The environmental parameters and Greenhouse emissions are assessed based on Tier 1 emission factors as stated by the Intergovernmental Panel on Climate Change (IPCC) [70].

### 3.2.1. Demand module

The demand module comprises five economic sectors: domestic, commercial, industrial, transport, agriculture, and other services. Demand analysis is applied to model the needs related to final energy consumption. To project electric demand and supply, the electricity consumption figures from the base year 2020 were utilized. Activity level, total energy, and demand cost are used for demand analysis. The final energy intensity is determined by using each sector's level of activity and total annual consumption. In this case, the activity level is for the number of electric consumers, and the final energy intensity is for electricity consumed per consumer. Energy sectors rely on the nature of energy usage patterns and the kind of consumed energy. In the context of LEAP modeling for demand projection, a comprehensive approach is employed to gather essential data and evidence for branch establishment. This involves a combination of fieldwork, enterprise investigations, expert consultations, and extensive literature research. To inform our analyses and prioritize sectors in Pakistan, various key resources and references are tapped into, including but not limited to "Pakistan Energy Yearbook 2020", the "Economic Survey of Pakistan", "State of Industry Reports", and "Bauru Statistics of Pakistan." These resources offer valuable insights and serve as foundational references for identifying sectors of significant importance within the country's energy landscape.

Inside these areas, various range of end-use energy types are considered. Primary energy sources incorporate both "non-renewable" resources like Coal and Natural gases, and "renewable alternatives" such as Solar Power, Wind Energy, Hydropower, and Geothermal Energy. Conversely, secondary energy sources encompass various essential fuels and energy forms, including diesel, fuel oil, gasoline, liquefied petroleum gas (LPG), electricity, and heat. In parallel, secondary energy sources encompass an array of vital fuels and forms of energy, such as diesel, fuel oil, gasoline, LPG, electricity, and heat. This comprehensive approach, backed by data from various sources and a thorough understanding of primary and secondary energy in different sectors, forms the foundation for robust modeling and projection within the LEAP framework.

### 3.2.2. Transformation module

The transformation module consists of the transmission, distribution, and generation sectors. In a transformation module, energy conversion

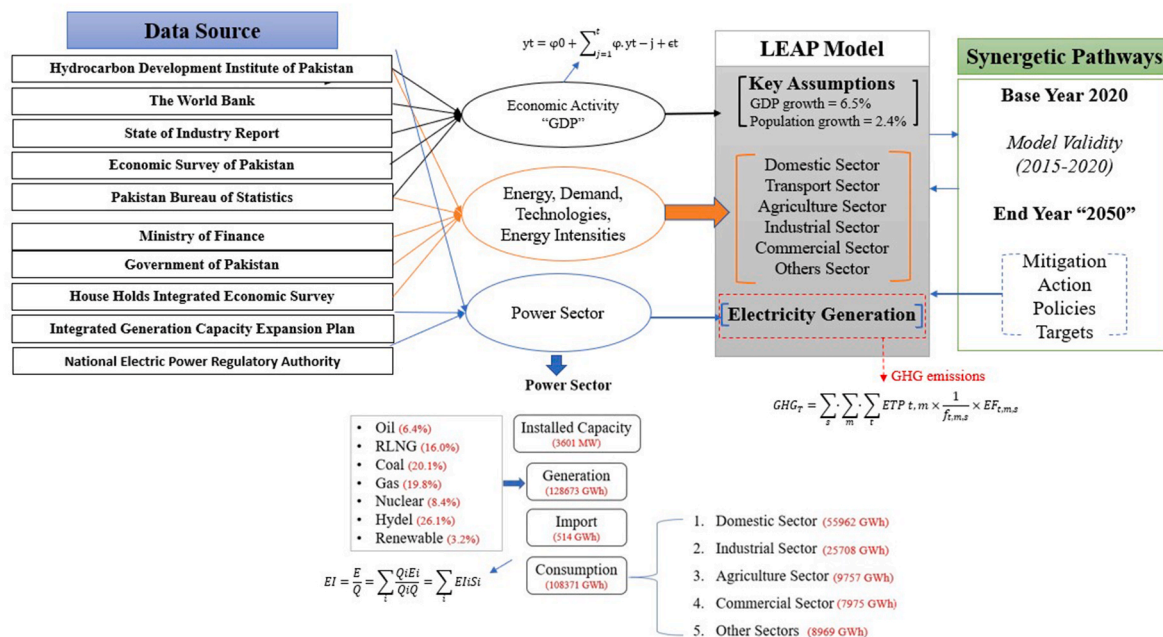


Fig. 1. LEAP- Pakistan modeling and data sources.

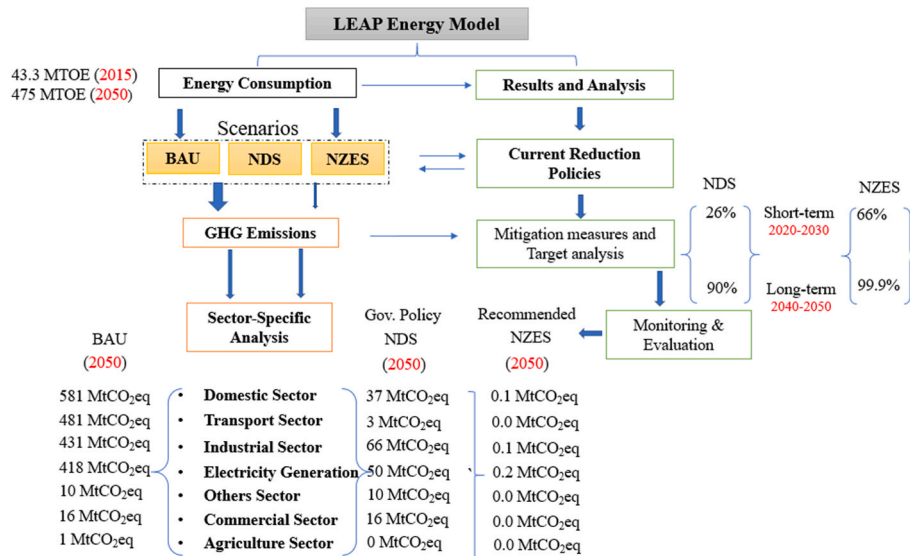


Fig. 2. Integrated policy framework for scenario building.

simulation and energy transportation from primary energy sources to final fuel consumption are done. Transmission and distribution sectors require planning reserve margin, system peak load shape, exports-imports priorities, short-fall surplus rules, and transmission losses. Power generation technologies include different types of combined cycle cogeneration, wind turbines, gas turbines, hydroelectric generation, oil combustion turbines, coal plants, bagasse/biomass power plants, and solar PV systems. For each of these technologies, parameters like dispatch rule, merit order, historical production, exogenous capacity, endogenous capacity, maximum availability, process efficiency, plant lifetime, capital costs, fixed OM costs, interest rate, capacity credit, addition size, etc. are required. Exogenous and endogenous capacities refer to the new and additional capacities based on the additional retirement of the power plants. The LEAP model also accounts for GHG emissions linked with each fuel type for power generation.

### 3.3. Scenarios setting

The proposed study has been designed to investigate the future of the energy environment of Pakistan following the use of LEAP so that policy and decision guidance can be obtained. The country’s future and energy-environment dynamics shall be revealed under two main and five sub-scenarios described as follows:

**BAU (Business as Usual Scenario):** This scenario projects Pakistan’s future energy and environmental trajectory based on a trend extrapolation using 2015 as the reference year. It assumes a continuation of existing patterns in energy consumption and emissions without the implementation of new energy-saving policies, mitigation measures, or improvements in energy intensity. The BAU scenario serves as a baseline to compare the impact of alternative policy scenarios, reflecting a future where no additional interventions or strategic planning are undertaken to curb emissions or enhance energy efficiency.

**NDS (National Decarbonization Scenario):** This scenario aligns with Pakistan’s updated Nationally Determined Contributions (NDCs) and the National Energy Efficiency and Conservation Authority (NEECA) plan for 2020–2030. It reflects the government’s strategic policies for reducing carbon emissions through energy conservation, greenhouse gas mitigation, and emissions control measures to meet the country’s NDC targets. The NDS explores decarbonization pathways by adjusting key parameters to reflect Pakistan’s commitments under its NDCs, ensuring consistency with the country’s emission reduction goals. It categorizes 21 sub-sectors across five primary energy-consuming sectors—domestic, transportation, agriculture, industrial, and electricity generation. While

the first four sectors represent the demand module, the electricity generation sector represents the transformation module. Sub-sectors are designed to support the main sectors by incorporating specific mitigation measures and reforms as detailed in Table A2 of the Appendix.

**NZES (Net-Zero Emissions Scenario):** This scenario is designed to align with Pakistan’s commitments under the Paris Agreement, focusing on achieving net-zero carbon emissions by 2050. It emphasizes energy efficiency improvements across key sectors, targeting a 50 % reduction in emissions by 2030 as per the government plan under the Paris Agreement. The NZES integrates technical analyses and policy insights from the NEEC-Action Plan 2023–2030, as well as guidelines from national publications such as Cleaner Production in Pakistan by the National Productivity Organization (NPO) and Cleaner Production Institute (CPI). Key measures include the adoption of hydrogen energy and electric vehicle (EV) policies to facilitate a transition towards low-emission fuel sources, reflecting growing global trends. The scenario also incorporates Carbon Capture and Storage (CCS) technology within the electricity generation sector, based on recommendations from the Asian Development Bank, to effectively mitigate emissions from power production. For specific parameter adjustments and detailed mitigation measures, refer to Table A2 in the Appendix.

## 4. Results and discussions

### 4.1. Demand and final energy consumption by the sectors

The initial step in assessing the energy mix demand involves analyzing the final energy consumption across various sectors. Fig. 3 provides an overview of the energy consumption trends in different sectors over a 35-year period, highlighting the increasing demand for energy across various sectors, particularly in the domestic and transportation sectors. Without new governmental policies, the final energy demand will be 72 % higher with reference to 2015, while it will be 68 % higher regarding the base year 2020 energy consumption value. Meanwhile, the trend of energy demand shows that the dominant trend of future energy consumption is shown by the transportation sector, followed by the domestic sector.

The energy consumption in various sectors is outlined, with distinct trends observed. In the agriculture sector, energy usage increased from 0.7 MTOE in 2015 to 6.5 MTOE in 2050. The "Other Sectors" encompass energy consumption outside agriculture, with values rising from 0.9 MTOE in 2015 to 8.2 MTOE in 2050. Commercial establishments, including offices and retail stores, contribute to the commercial sector’s

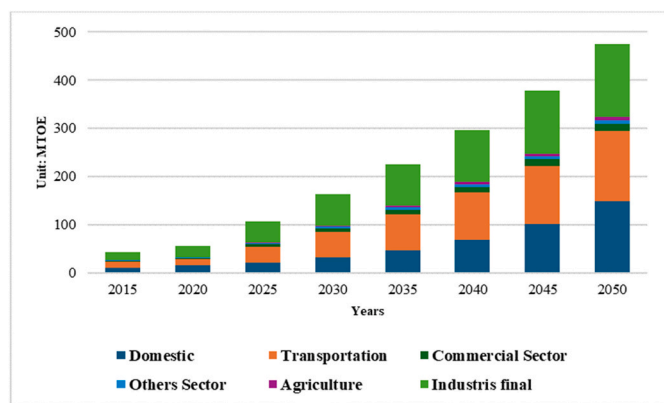


Fig. 3. Different types of energy consumption projection in various sectors under BAU scenario.

energy consumption, escalating from 1.7 MTOE in 2015 to 15.1 MTOE in 2050. In the domestic sector, household energy usage surged from 10 MTOE in 2015 to 148.1 MTOE in 2050. The transportation sector, covering vehicles, witnessed a notable increase from 13.4 MTOE in 2015 to 146 MTOE in 2050. Lastly, the industries sector displayed a moderate rise, reaching from 16.7 MTOE in 2015 to 151.1 MTOE in 2050. Overall, each sector reflects distinct patterns in energy consumption over the specified timeframe.

#### 4.2. GHG emissions projection and mitigation

The study’s examination of mitigation potential within considered scenarios reveals intriguing insights into the future emissions reduction trajectory. We gain a nuanced understanding of the strategies’ efficacy by dissecting each scenario’s impact on emissions compared to the baseline BAU. Through discussing the mitigation potential of current policies discussed in the NDS scenario on each sector to know the future reduction impact contribution after following the amendment made by the government. Leading towards the recommended scenario NZES scenario focusing on mitigation measures and carbon reduction efficiency after the failure of the current emission reduction approaches to achieve the desired targets i.e. Paris Agreement by 2030 and Net-Zero carbon emission by 2050.

Fig. 4 reveals that under the BAU scenario, the carbon emissions steadily increase over time, reflecting the continuation of current trends and policies without additional mitigation measures. Carbon emissions are projected to rise from 211 MtCO<sub>2</sub>eq in 2015 to 1940 MtCO<sub>2</sub>eq in 2050, indicating significant growth over the decades. In the NDS scenario, carbon emissions follow a different trajectory compared to BAU,

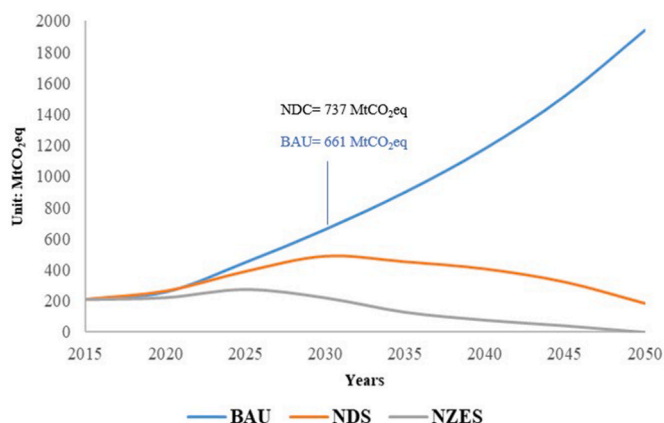


Fig. 4. Emissions reduction potential of GHG reduction of each scenario.

reflecting the implementation of new development strategies and policies aimed at reducing emissions. While emissions initially track closely with BAU in the early years, they start to diverge later on. By 2050, carbon emissions under NDS will be substantially lower than BAU, reaching only 184 MtCO<sub>2</sub>eq. The NZES scenario represents a more aggressive approach to decarbonization, incorporating enhanced energy efficiency measures and the adoption of low-carbon technologies. Carbon emissions under NZES show a significant reduction compared to both BAU and NDS. By 2030, emissions drop to 222 MtCO<sub>2</sub>eq, and by 2050, they nearly reach zero, with only 0.2 MtCO<sub>2</sub>eq emitted.

Both NDS and NZES demonstrate considerable emissions reductions compared to BAU throughout the projection period. In 2030, NDS achieved a reduction of approximately 170 megatons (or 26 %) compared to BAU, while NZES achieved a reduction of 439 megatons (or 66 %). By 2050, NDS will achieve a reduction of around 1756.1 MtCO<sub>2</sub>eq (or 90 %) compared to BAU, while NZES will achieve a reduction of 1940 MtCO<sub>2</sub>eq (or 99.9 %). Overall, both NDS and NZES demonstrate significant reductions in carbon emissions compared to BAU, with NZES achieving more substantial reductions due to its more aggressive decarbonization measures. These scenarios highlight the importance of implementing proactive policies and strategies to mitigate climate change and achieve long-term sustainability goals.

These results unveil diverse reduction potentials across various scenarios and sectors. They underscore the importance of tailor-made strategies, technological innovations, and interdisciplinary cooperation to reduce emissions substantially. Specific scenarios exhibit unparalleled potential, indicating the urgency of their implementation within Pakistan’s broader emission reduction framework. Furthermore, these findings resonate beyond Pakistan’s borders, contributing to global emission reduction goals. They demonstrate that targeted policies, innovation within sectors, and ongoing endeavors can clear the path toward a future that is more sustainable and environmentally conscientious. In essence, this analysis provides a roadmap for policymakers, stakeholders, and researchers to navigate the complex landscape of emissions reduction strategically. It emphasizes the need to capitalize on high-potential scenarios, driving forward comprehensive decarbonization strategies that align with Pakistan’s commitment to a greener future on both national and global levels. In conclusion, this comprehensive analysis underscores the critical role of sectoral mitigation strategies in achieving substantial GHG emissions reduction. The percentage differences among scenarios highlight the tailored nature of each sector’s challenges and opportunities. Pakistan’s progress in emissions reduction relies on these insights to forge a path towards a low-carbon future.

#### 4.3. BAU scenario: short-term, mid-term and long-term projection

Pakistan established 2015 as the reference year for quantifying GHG emissions in its inventory and projecting future total emissions from all sectors for 2030, estimated to reach 1603 MtCO<sub>2</sub>eq as stated in the 2016 INDCs submission. These projections considered factors such as GDP growth exceeding 9 %, the economic effects of the China-Pakistan Economic Corridor (CPEC), and sector-specific growth rates. The calculations were based on carefully considering economic and industrial parameters, alignment with government growth targets, and the country’s social, economic, and infrastructural development goals. Particular emphasis was placed on estimating energy demand and ensuring the fulfillment of energy requirements. Fossil fuels account for approximately 60 % of Pakistan’s energy composition, encompassing power generation, heat production, transportation fuel, and more. The proportions of fossil fuels and zero-carbon technologies in the nation’s energy makeup remained relatively unchanged throughout the decade leading up to 2019. The results in Fig. 4 above show for the short-term 2020 to 2030, mid-term 2020 to 2040, and long-term 2020 to 2050 in the BAU scenario with no mitigation measures taken, GHG emissions projection from the energy sectors and the increasing trend of GHG in

each sector along with the period. The short-term, mid-term, and long-term projection data show that the intensity of GHG will be 661, 1178, and 1940 MtCO<sub>2</sub>eq. Another study by Abas et al. [71] estimated the emissions in 2030 will be 560 MtCO<sub>2</sub>eq. Updated-NDCs [17] give the projected about 737 MtCO<sub>2</sub>eq in 2030 from the energy sector. These calculations demonstrate the growth in total emissions over time. From 2015 to 2030, there is an approximate 214 % increase in GHG emissions from the energy-related sectors. This trend continues with a more significant increase from 2015 to 2040, which reflects a growth of approximately 460 %. Finally, from 2015 to 2050, there is a substantial increase of about 821 %.

4.3.1. Analyzing GHG Emission projections across sectors

Following a decade of relative stability in Pakistan, there has been a rise in energy-related total GHG emissions since 2015. The primary contributor is the industrial sector, accounting for 32 %, followed by the transport sector at 28 %, and the electricity sector at 27 % [72]. The major shares of GHG emissions in Pakistan are attributed to the energy and transport sector, together accounting for a significant portion of the country's total GHG emissions. However, it's worth noting that the agricultural sector, according to a 2008 national GHG inventory, contributes 39 % of these emissions [71,73]. A recent study of Pakistan's energy monitoring authorities suggests that there is room for improvement in managing the fluctuations in energy consumption and prices caused by the COVID-19 pandemic. To enhance the operational efficiency of the country's energy infrastructure, the study recommends a greater reliance on renewable energy sources to meet future demand. This shift is particularly important because the volatility in oil prices during the pandemic played a significant role in reducing GHG emissions [74].

Based on the results shown in Fig. 5, we observed the following trends in sector emissions over the years. In 2030, the sector with the highest emissions is the Industrial sector, which emits 187 MtCO<sub>2</sub>eq and the percent shares 28 % of the total emissions followed by the Transport sector, which contributes 178 MtCO<sub>2</sub>eq and percent shares are 27 %, meanwhile the Electricity Generation sector contributes 159 MtCO<sub>2</sub>eq and the Domestic sector emit 125 MtCO<sub>2</sub>eq of GHG and the percent shares in total emissions are 24 % and 19 % and the remaining 1 % emissions are from the Other and Commercial sectors. Moving to 2040, the Transportation sector takes the lead with emissions totaling 324 MtCO<sub>2</sub>eq. This signifies a significant increase compared to 2030, and the percent share in total emissions is 27 %. Emissions from the considered

sectors are 309, 268, 258, 11, and 7 MtCO<sub>2</sub>eq for the Industrial, Domestic, Electricity Generation sector, Others sector, and Commercial sector, while the percent shares are 26 %, 23 %, and 22 % with high emissions sectors and the Others sector and Commercial sector are the less emitters contribute 1 % to total emissions. Looking ahead to 2050, the Domestic sector emerges as the highest emitter with 581 MtCO<sub>2</sub>eq, and the percent share is 30 %, indicating a substantial increase compared to previous years. This suggests that emissions from domestic sources, such as households and residential activities, surpassed those from the remaining sectors with contributions of 481, 1, 431, 418, 10, and 16 MtCO<sub>2</sub>eq Transport, Industries, Electricity Generation, and Commercial for which the percent shares are 25 %, 22 %, 22 %, and 1 %. Therefore, the results highlight the changing emissions dynamics across sectors over time.

4.3.2. CO<sub>2</sub> intensity projection along the BAU scenario

Following a decade of relative stability in Pakistan, energy-related CO<sub>2</sub> emissions have increased since 2015 [72]. Pakistan's GHG emissions include CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO, and VOC [71]. Pakistan's accumulative CO<sub>2</sub> emissions are likely to reach 250 MtCO<sub>2</sub>eq by 2020, which may grow to 650 MtCO<sub>2</sub>eq if subsidies continue on fossil fuels [75]. Our study shows that the total intensity of CO<sub>2</sub> in 2030 and 2040 will be 651 MtCO<sub>2</sub>eq and 1164 MtCO<sub>2</sub>eq, while in 2050, it will be 1916 MtCO<sub>2</sub>eq as shown in Table 1.

Fig. 6 presents a comprehensive overview of emissions data spanning from 2015 to 2050 for various fuel types. Emissions from natural gas display a consistent upward trajectory, reaching 881 MtCO<sub>2</sub>eq in 2050. This increase is driven by the growing reliance on natural gas, often seen as a transitional fuel due to its lower carbon emissions coal and oil. However, the increasing emissions underscore the importance of transitioning to even cleaner energy sources and improving natural gas extraction and utilization technologies. Gasoline emissions have grown notably, particularly after 2020, culminating in 265 MtCO<sub>2</sub>eq in 2050. These emissions are primarily associated with the transportation sector, emphasizing the need for more sustainable transportation solutions, such as electric vehicles and alternative fuels. Emissions from aviation fuel, including jet fuel and kerosene oil, remain relatively low, with a combined total of 0.1 MtCO<sub>2</sub>eq and 2.0 MtCO<sub>2</sub>eq in 2050. Diesel emissions exhibit a continuous rise, reaching 199 MtCO<sub>2</sub>eq in 2050. Diesel is prevalent in transportation, industry, and as a backup power source. This trend underscores the need for emission reduction strategies in diesel-dependent sectors. LPG emissions increase gradually, totaling 63

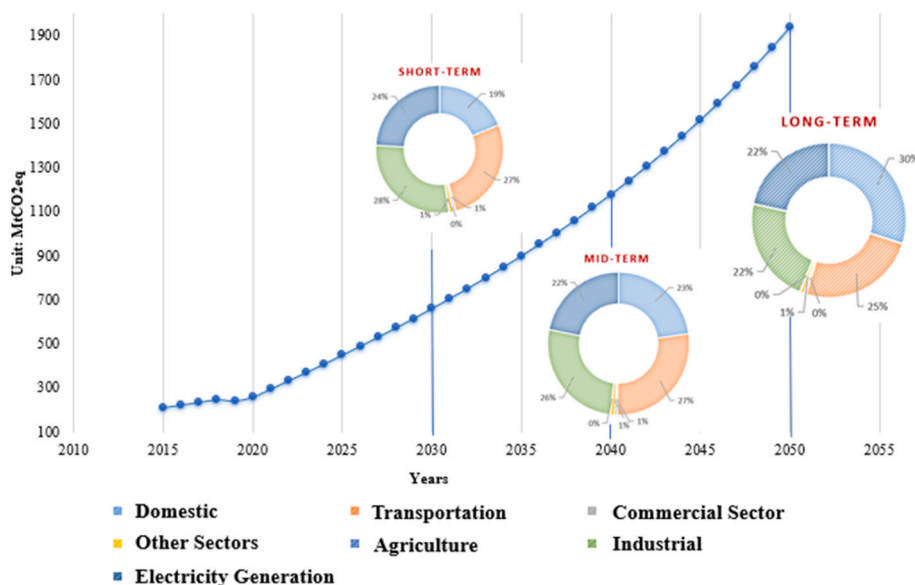
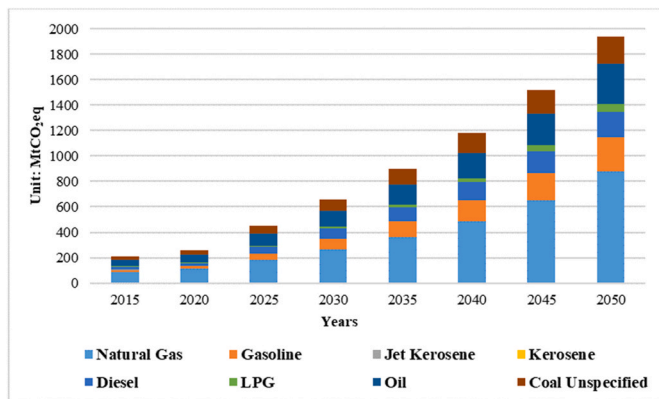


Fig. 5. Short-term, mid-term, and long-term GHG emission projection trend in the BAU scenario.

**Table 1**  
BAU CO<sub>2</sub> emission and sectoral projection (MtCO<sub>2</sub>eq) for Pakistan.

Sectors	2015	2020	2025	2030	2035	2040	2045	2050
Domestic	38.5	56.6	83.2	122.2	179.6	263.9	387.8	569.7
Transportation	43.3	41.8	105.6	172.6	242.7	315.8	392.1	471.4
Commercial Sector	1	1.4	2.8	4.1	5.5	6.8	8.2	9.5
Others Sector	1.7	2.4	4.6	6.8	9	11.2	13.4	15.7
Agriculture	0.1	0.2	0.4	0.5	0.7	0.9	1.1	1.2
Industrial	47.5	64.9	125.8	186.8	247.7	308.7	369.6	430.6
Electricity Generation	75.3	87.2	120.7	158.4	202.7	257.1	326.4	417.8
Total	207.4	254.5	443.1	651.4	887.9	1164.4	1498.6	1915.9



**Fig. 6.** GHG emissions future projection from all fuels.

MtCO<sub>2</sub>eq in 2050, while emissions from oil show an upward trend, reaching 315 MtCO<sub>2</sub>eq. Both fuel types are used in diverse applications, including heating, cooking, and industry. Reducing emissions from these sources will require a combination of efficiency improvements and alternative energy solutions. Coal emissions are a significant concern, with emissions from unspecified coal sources rising consistently to 215 MtCO<sub>2</sub>eq in 2050. This underscores the challenges in phasing out coal, a major contributor to greenhouse gas emissions, and highlights the importance of transitioning to cleaner energy alternatives.

This data highlights the pressing need for comprehensive strategies to reduce emissions, transition to renewable and low-carbon energy sources, and implement energy efficiency measures. Achieving sustainability goals and combatting climate change will require concerted efforts across sectors and global cooperation. In conclusion, the emissions data presented, provide a clear picture of the environmental impact of energy consumption trends. It emphasizes the urgent need for innovative solutions, policy interventions, and sustainable practices to curb emissions and mitigate the effects of climate change in the coming decades.

#### 4.4. NDS (National Decarbonization Scenario): current policies and long-term GHG reduction potential

Pakistan submitted its INDCs to UNFCCC in November 2016 to recognize its accountability to the nation's community. Pakistan's initial INDCs envisioned up to a 20 % decrease in its 2030 predictable GHG emissions, focusing on the obtainability of grants from international members to encounter the total mitigation cost of about US\$40 billion and for adaptation US\$7–14 billion per annum at current prices [76]. Intended for the updated NDCs, Pakistan aims to climax the national initiatives since 2016, institutional preparations, and governance slants are adopted for boosted contributions. The reviewed INDCs follow a whole-of-government approach to changing, reviewing, and reporting on climate action. Hence, Pakistan anticipates setting a cumulative determined aim of uncertain and voluntary contributions of a total 50 % reduction of its expected emissions by 2030, with a 15 % drop below

from business as usual (BAU) with the country's resources and a further 35 % drop below BAU subject to international financial support [17]. However, although decreasing the GHG emissions under the Paris Agreement to border the temperatures among 1.5–2 °C, the Pakistan government remains dedicated to reducing the emissions to the extreme possible range.

The four identified sectors (Industrial, Transport, Domestic, and Electricity) will have the highest emissions, as shown in Fig. 5. The government of Pakistan is trying to mitigate the high-impact sectors, and different mitigation measures are forwarded for future sustainable development and to achieve the intended goals. After carefully analyzing each sector embedment's INDCs, results show that the total GHG emissions were 211 MtCO<sub>2</sub>eq in 2015, increasing steadily over the following years. Between 2015 and 2030, there is a significant increase in total emissions, with a notable jump from 264 MtCO<sub>2</sub>eq in 2020 to 490 MtCO<sub>2</sub>eq, and the percentage growth from 2015 value is 133 % in 2030. After reaching its peak in 2030, the emissions value gradually declines. In 2040, the GHG emissions will be 391.8 MtCO<sub>2</sub>eq, while by 2050, it will decrease to 184 MtCO<sub>2</sub>eq, which will show a 68 % and 42 % reduction trend. The comparison between the BAU scenario and the NDS reveals significant differences in greenhouse gas (GHG) emissions for 2020, 2030, 2040, and 2050. The NDS scenario represents the emission trajectory when the policies and measures to mitigate emissions are implemented, while the BAU scenario assumes no additional efforts beyond existing trends.

Between 2020 and 2025, emissions in the NDS scenario slightly exceeded those in the BAU scenario by approximately 2 %, primarily due to electricity and gas expansion projects targeting the domestic sector. However, from 2025 onwards, the NDS has remarkably reduced emissions. By 2030, the NDS will substantially reduce about 26 % compared to the BAU scenario. This trend continues to be even more promising in 2040, when emissions in the NDS scenario drop significantly, leading to a remarkable reduction of approximately 67 % compared to the BAU projections. Finally, in 2050, the NDS scenario achieves an exceptional emission reduction of about 90 % compared to the BAU trajectory, as shown in Fig. 4.

These results underscore the importance and effectiveness of the implemented policies and measures outlined in the NDS. The significant emission reductions achieved in 2030, 2040, and 2050 highlight the potential impact of climate-focused initiatives in steering the country towards a sustainable and low-carbon future.

From Fig. 7, it can be seen the contribution of each sector to the total GHG emissions short-term trend from 2020 to 2030. The sector with the highest contribution is Electricity Generation, with approximately a value of 156 MtCO<sub>2</sub>eq (32 %) of the total emissions. The Industries sector follows it with around 129 million tons (26 %) of the total emissions. The Transportation and Domestic sectors also significantly contribute approximately 99 MtCO<sub>2</sub>eq (20 %) and 95 million tons (19 %), respectively. The remaining Other sectors, the Commercial and Agriculture sectors, contribute to 2 % of emissions. Furthermore, the contribution of each sector to the mid-term GHG emissions from 2020 to 2040 shows that the sector with the highest contribution will be Electricity Generation, with approximately 127 MtCO<sub>2</sub>eq (35 %) of the total emissions. It is followed by the Industries sector with around 110

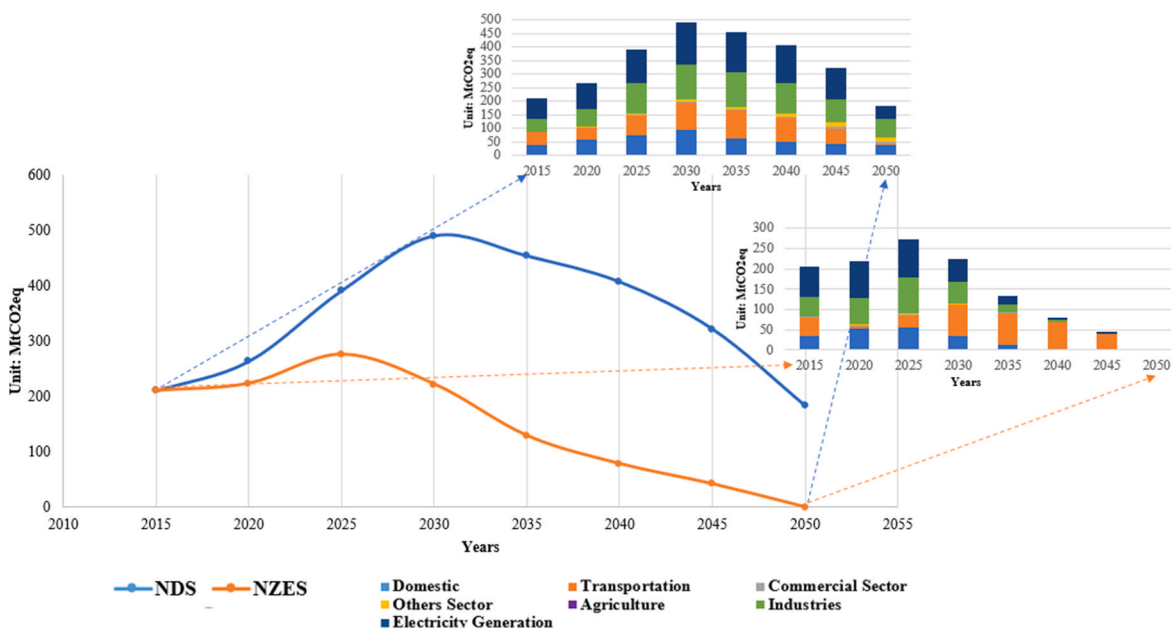


Fig. 7. Short-term, mid-term, and long-term sectoral GHG emission in (NDS) and (NZES) scenarios.

MtCO<sub>2</sub>eq (27 %) of the total emissions. The Transportation sector also has a significant contribution of approximately 88 MtCO<sub>2</sub>eq (21 %), while the domestic sector accounts for 48 MtCO<sub>2</sub>eq (12 %) shares, the Agriculture sector, Others sectors, and the Commercial sector has a contribution of 5 %. Moreover, the total emissions in 2050 will be 184 MtCO<sub>2</sub>eq. Industries are the sector with the highest contribution, with approximately 66 MtCO<sub>2</sub>eq (36 %) of the total emissions. It is followed by the Electricity Generation sector with around 50 MtCO<sub>2</sub>eq (28 %) of the total emissions, while the Domestic and Transportation sector will be 37 MtCO<sub>2</sub>eq (20 %) and 3 MtCO<sub>2</sub>eq (2 %) contribution. The Other sectors and the Commercial sector also have a significant contribution of approximately (14 %), and the Agriculture sector has a contribution of 0 %.

In 2030, the NDS scenario shows a significant reduction in domestic sector emissions (125–96 MtCO<sub>2</sub>eq), driven by energy-efficient technologies, improved building standards, and behavioral changes. By 2040, domestic emissions in the NDS scenario are only (48 MtCO<sub>2</sub>eq), indicating substantial progress in sustainable living practices and energy conservation. In 2050, the domestic sector emissions continue to decrease significantly in the NDS scenario, reaching (37 MtCO<sub>2</sub>eq). This highlights the effectiveness of green living initiatives and the adoption of renewable energy sources. In 2030, the NDS scenario will achieve notable emission reductions in the transportation sector (178–99 MtCO<sub>2</sub>eq). This is attributed to the increased use of electric vehicles, public transport improvements, and efficient logistics. By 2040, transportation emissions in the NDS scenario will be (88 MtCO<sub>2</sub>eq), highlighting the impact of sustainable mobility solutions and reduced dependence on fossil fuels. In 2050, the transportation sector emissions will continue to decline in the NDS scenario (4 MtCO<sub>2</sub>eq), reflecting a transition to cleaner transport modes and infrastructures. Furthermore, for Industrial, the NDS scenario demonstrates significant emission reductions from 2030 to 2050, indicating the successful implementation of clean production technologies and improved energy efficiency. In 2030, emissions stand at (129 MtCO<sub>2</sub>eq), marking the baseline. By 2040, emissions decrease to (110 MtCO<sub>2</sub>eq), this reduction trend will continue in 2050, with emissions reaching (66 MtCO<sub>2</sub>eq), signifying a substantial decrease. This trend reflects a consistent commitment to emission reduction, showcasing a significant 38 % reduction from 2030 to 2050. This progress underscores Pakistan’s dedication to sustainable industrial practices and contributes to global climate efforts. While in the

Electricity Generation sector in 2030, the NDS scenario maintains similar emissions in the electricity generation sector (156 MtCO<sub>2</sub>eq), indicating a shift towards cleaner energy sources and better utilization. By 2040, the NDS scenario significantly reduce emissions in the electricity generation sector (143 MtCO<sub>2</sub>eq) through increased renewable energy integration. In 2050, this will lead to substantial emission reductions (50 MtCO<sub>2</sub>eq), highlighting the dominance of clean energy in the power generation mix. Globally, coal utilization in electricity generation must reach its highest point by 2020, and every region across the world should transition away from coal-fired power generation between 2030 and 2040. To achieve carbon neutrality in electricity generation before 2050, renewable energy emerges as the most favorable and promising alternative [77,78,79]. Renewable energy sources such as wind, solar, and hydroelectric power generate electricity without burning fossil fuels, thereby reducing the emission of greenhouse gases like carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) that contribute to climate change. Renewable energy technologies produce electricity with minimal or zero emissions during operation. For example, solar photovoltaic panels and wind turbines generate electricity without emitting any greenhouse gases, while hydropower plants emit relatively low levels of CO<sub>2</sub> compared to fossil fuel-based power plants.

According to the International Energy Agency (IEA), to address the energy crisis and carbon emissions, Pakistan aims to increase its renewable energy share to 30 % by 2030 through a new renewable energy policy. However, Pakistan’s Alternate Energy Development Board (AEDB) faces challenges in exploring and implementing renewable energy projects. The development of an energy structure with high saturation of renewables is becoming progressively important to face energy security and environmental issues [80]. Planning for electricity generation pursues to attain a reliable power generation system, environmental sustainability, economic efficiency, and social adequacy. Different substitutions of energy mixes that imitate emphasis on various strategic fundamentals of energy policy are proposed [81].

Pakistan has significant potential for renewable energy generation. According to the IGCEP plan (2018–2040), the transition to 30 % renewable energy could raise costs from an estimated (31 billion US\$) to (49–61 billion US\$) [82]. Under the NDS scenario, increasing the share of renewable energy to 50 % would raise costs further, reaching around (90 billion US\$). These investments are projected to significantly reduce

greenhouse gas (GHG) emissions, achieving a near 90 % reduction by 2050. By 2040, a shift to renewable energy could cut emissions from power generation by up to 50 %, increasing to a 70 % reduction by 2050.

#### 4.5. NZES (Net-Zero Emissions Scenario): Pakistan decarbonization potential to achieve net-zero emissions

There exists a compelling argument for Pakistan to prioritize investment in and attainment of energy efficiency to boost the nation's economy. According to studies conducted by the Asian Development Bank (ADB) in 2009, there is a significant potential for saving between 10 and 15 percent within the energy sector. Notably, substantial gains in energy efficiency have been correlated with heightened economic growth, as demonstrated by China's experience. The Government of Pakistan stands to conserve more than 10 (MTOE) through enhancements in energy intensity, all the while sustaining GDP growth. The assessment of energy efficiency hinges on metrics such as primary energy-based indicators and utilizes Purchasing Power Parity (PPP) for GDP calculations. In line with Sustainable Development Goal 7 (SDG-7), the target for energy efficiency is set to double the rate of improvement, necessitating a reduction in primary energy intensity by 3.4 % annually or approximately 50 % within the next 14 years [83]. While substitution of natural gas with hydrogen gas, adaptation of waste-to-energy technologies, promotion of retrofitting technologies, and carbon capturing saving and using technologies will lead to net-zero emissions from the industrial sector.

Looking towards the sectorial results after a detailed analysis of each sector and its energy efficiency and the estimation of carbon emission synergy along the sector's energy reduction trend. As shown in (Fig. 7) the emissions from the domestic sector exhibit a consistent decreasing trend from 2020 to 2050. Emissions reduced gradually from (53 MtCO<sub>2</sub>eq) in 2020 to (0.1 MtCO<sub>2</sub>eq) megatons in 2050, reflecting significant decarbonization efforts in residential activities by increasing the promotion of energy-efficient appliances in the domestic sector. The sectoral analysis of emission reductions highlights the domestic sector as a key area for achieving energy savings through targeted interventions such as net-metering and solarization. These measures are projected to grow at an annual rate of 3 %, based on market sales trends. According to the National Energy Efficiency and Conservation Action Plan (NEEC 2023–2030), by 2030, significant reductions in energy consumption can be achieved by promoting the adoption of efficient appliances and technologies. For instance, energy use could be cut by 60 % through efficient lighting solutions like LED bulbs, by 23 % through energy-efficient refrigerators, by 50 % through efficient fans, and by 40 % through the use of inverter technologies in air conditioners. Moreover, in terms of gas consumption, the NEEC Action Plan outlines reductions of up to 40 % for stoves, 30 % for geysers, and 36 % for heaters, which would contribute significantly to emission reductions in the residential sector. This emission can be reduced by public awareness changing of behaviors, according to IEA [5] Japan achieved a reduction of 7 %, New Zealand 4 %, and Korea 2 % in the previous year's household energy consumption.

From 2020 to 2030, emissions in the transportation sector follow a fluctuating trend, with a slight decrease from (7 MtCO<sub>2</sub>eq) to (28 MtCO<sub>2</sub>eq), followed by a substantial increase to (77 MtCO<sub>2</sub>eq) in 2030, while it will reach zero by 2050. The integration of electric vehicles and hydrogen power transport can potentially reduce emissions and can be helpful in not relying on total electricity in the transport sector. The hypothetical plan to integrate electric and hydrogen-based transport systems aims to significantly reduce emissions in Pakistan's transportation sector by 2050. The plan includes a phased adoption of electric and hydrogen-powered vehicles across various transport modes, including road and rail. By 2030, the strategy targets achieving 30 % electric vehicle (EV) adoption for cars, scaling this up to 50 % by 2050, while also introducing hydrogen-powered cars to make up the remaining 50 %. Similarly, the plan envisions that two- and three-wheelers,

which are significant contributors to urban pollution, will transition to 50 % electric and 50 % hydrogen-based models by 2050. In public and freight transportation, the plan proposes a balanced shift to electric and hydrogen technologies. By 2050, the target is for buses to be equally divided between electric and hydrogen, each making up 50 % of the fleet. For trucks, a similar distribution is planned, reducing dependency on fossil fuels and ensuring a sustainable supply of clean energy for heavy transport. Furthermore, the electrification of railways and the integration of hydrogen-based trains, each making up 50 % of rail transport by 2050, is intended to decrease emissions from long-distance and freight rail travel. This comprehensive approach will drastically cut carbon emissions in the transportation sector by reducing reliance on conventional fossil fuels and encouraging a transition towards cleaner energy alternatives. The dual strategy of electric and hydrogen adoption not only diversifies energy sources but also provides flexibility in tackling different transportation needs and infrastructures. Such initiatives are expected to help Pakistan meet its emission reduction goals, ensuring the sector's alignment with the broader national decarbonization targets.

Emissions from the commercial sector remain relatively stable and low throughout the projection period. There is a slight increase from 2020 to 2025, followed by stability or negligible emissions thereafter. Meanwhile, Emissions from the "Others" sector exhibit a mixed trend, with an increase until 2025 followed by a decline towards zero emissions by 2050. The sector shows a gradual decrease in emissions over the projection period. Furthermore, emissions from agriculture remain minimal and relatively constant throughout the projection period. There is little to no change in emissions from 2020 to 2050. Substantially, industrial emissions show a decreasing trend from 2020 to 2050, reflecting significant reductions in manufacturing and industrial activities. After peaking in 2025 reaching (89 MtCO<sub>2</sub>eq), emissions decline substantially, approaching (0.1 MtCO<sub>2</sub>eq) by 2050. While some sectors experience fluctuations or minimal changes in emissions, others show consistent and significant reductions over time. These trends reflect the effectiveness of sector-specific mitigation strategies and the transition towards cleaner and more sustainable practices across various sectors.

Emissions from electricity generation exhibit a noticeable decrease over the projection period by installing CCS (Carbon Capture and Storing) technologies, hence this sector showed the high emission in the NDS scenario. After peaking in 2025 and reaching up to (83 MtCO<sub>2</sub>eq), emissions decline substantially, reaching minimal levels up to (0.2 MtCO<sub>2</sub>eq) by 2050. The "Installed Capacities" in Fig. 8 illustrates the projected transformation in Pakistan's energy mix from 2015 to 2050 across several key energy sources: thermal power plants, hydropower, nuclear, renewables, and imported energy. A noticeable trend is the substantial increase in hydropower capacity, reflecting Pakistan's focus on cleaner energy to reduce emissions from conventional thermal plants.

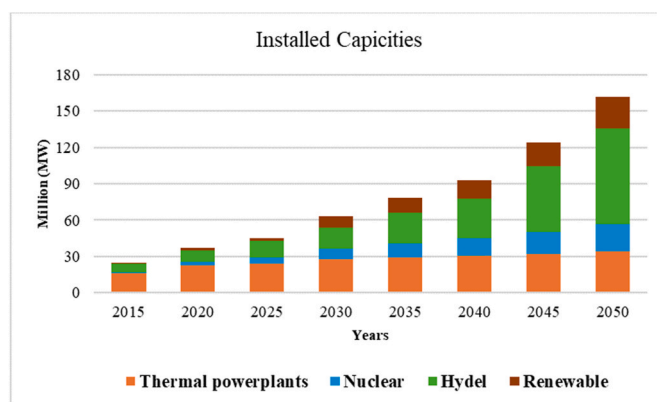


Fig. 8. Projected installed capacity mix in Pakistan's power sector (2015–2050).

Hydropower expansion plays a crucial role in stabilizing the country's energy supply and minimizing carbon emissions. At the same time, renewable energy shows the most significant capacity growth, aligning with Pakistan's Alternative and Renewable Energy (ARE) Policy 2019, which targets 20 % renewable generation by 2025 and 30 % by 2030 ("20 × 25" and "30 × 30"). This rapid expansion of renewables like solar and wind highlights the country's commitment to reducing its carbon footprint and transitioning to cleaner energy sources.

Meanwhile, nuclear energy's contribution remains relatively small but stable, indicating a modest increase in capacity over the years. This is likely due to the high costs and extended timelines associated with nuclear projects. In contrast, thermal power plants show a decline in their share of the energy mix, marking a shift away from high-emission energy sources towards cleaner options. Moreover, the limited and relatively stable role of imported energy suggests Pakistan's strategy to minimize dependence on external energy sources while focusing on building domestic generation capacity. By reducing thermal reliance and increasing the share of renewables and hydropower, the country aims to achieve significant emission reductions by 2050. This comprehensive approach to capacity planning and diversification aligns with the decarbonization goals and supports the broader efforts to achieve a sustainable energy future.

The integration of Carbon Capture and Storage (CCS) technology is crucial to Pakistan's strategy for mitigating greenhouse gas (GHG) emissions from existing thermal power plants. The Asian Development Bank reports that Pakistan plans to install 600 MW of CCS capacity by 2025, capturing approximately 3.13 million tons of CO<sub>2</sub> annually—around 8 % of the country's GHG emissions baseline from 2015. This technology captures carbon dioxide from thermal plants before it is released into the atmosphere, storing it underground or repurposing it for industrial use.

By incorporating this technology, Pakistan aims to reduce carbon emissions while continuing some thermal power generation during its transition to renewable energy. The deployment of CCS capacity represents a significant investment in maintaining energy security, supporting sustainability, and aligning with global decarbonization efforts. It also allows for a gradual phase-out of high-emission energy sources without disrupting the power supply, complementing other strategies such as expanding hydropower, nuclear energy, and renewable capacity as outlined in the ARE Policy 2019. In the broader context of Pakistan's decarbonization plan, CCS serves as a bridge technology, minimizing the environmental impact of remaining thermal power plants while contributing to emission reductions. This approach will significantly reduce emissions by 2050, even as thermal power is phased out in favor of renewables and hydropower.

The Asian Development Bank (ADB) has proposed installing Carbon Capture and Storage (CCS) technology with a capacity of up to 600 MW by 2025. This installation is expected to cost around (1.2 million US\$). Essentially, the implementation of this CCS capacity could make a significant contribution to lowering Pakistan's carbon footprint in the coming years. We have estimated that if Pakistan installs CCS technologies along with renewable energy for carbon reduction it will cost approximately (11 billion US\$) to cope remaining 30 % of emissions.

According to Asian Development Bank [84] by replacing 20 % of the imported coal used (Box 1) in power plants, Pakistan can save over US\$ (147 million US\$) of the amount used for coal imports in 2021 (i.e., 1466 million US\$). It is enormous, given the pressures on our foreign reserves. Jamshoro Coal Power Plant is planning to employ SC's new boiler(s) to use imported sub-bituminous coal blended with local coal in a ratio of 80:20 as its fuel [84]. As power generation through local coal is much cheaper than imported coal, our findings suggest that Pakistan needs to promote local coal-based plants along with CCS technologies which can be more sustainable in contrast to moving to renewable energy options in the long term. According to the study done by [85], the cumulative investment cost to meet the electricity demand of (3091 PJ) by 2035 is estimated to be 170 billion USD in the BAU scenario, resulting

in 181 million tons of GHG emissions. In contrast, the most environmentally ambitious scenario, known as RE-40, would require an investment of 179 billion USD, leading to 96 million tons of GHG emissions. The Coal-40 scenario, characterized by heavy reliance on coal, would generate the highest greenhouse gas emissions, totaling 339 million tons, and necessitate an estimated investment cost of 185 billion USD.

## 5. Bridging policy and economic dimensions towards net-zero emission

Overall, the current study offers a long-term pathway extending up to 2050. To maintain this positive trajectory, it underscores the importance of ongoing policy support and technological innovation. Specifically, within Pakistan, the comparison between the BAU scenario and the NDS and NZES offers valuable insights into the country's efforts to combat climate change and reduce GHG emissions. The analysis is essential, given Pakistan's vulnerability to the impacts of climate change, including extreme weather events, water scarcity, and threats to agricultural productivity and ecosystems. This achievement is especially crucial for Pakistan's commitment under the Paris Agreement to reduce its emissions intensity and transition to a more sustainable growth pathway.

In 2021, the revised National Coaching Certification Program (NCCP) was launched, connecting climate action and economic development with durable attention to mainstreaming and climate change integrating with other policies [86]. There have been several other meaningful developments. For example, several new sectoral policies that support decarbonization efforts have been adopted. For instance, the 2019 Alternative Renewable Energy (ARE) Policy [87] aims to create an environment and agenda for the sustainable growth of Pakistan's ARE sector. The advancement of the generation of domestic energy is frequently expected to give advantages to the economy through, for instance, further developed energy exchange equilibrium and occupations made. In any case, the financial effects of energy improvement situations are not restricted to the energy area, and the leaders should think about the effects on the whole economy [88]. The enhancement of energy efficiency and conservation has gained strong support from the Strategic Plan for Energy Efficiency & Conservation (2020–2023), while the 2019 National Electric Vehicle Policy for 2020–2025 is actively promoting the growth of the transportation supply chain. For instance, it has reduced import duties on batteries and charging equipment to encourage the adoption of electric vehicles [89]. Collectively, these initiatives, along with various reforms and policy adjustments, unmistakably indicate a renewed commitment to addressing the challenges and crises related to climate change within the country. The government also acknowledges the critical importance of integrating decarbonization, resilience, and green growth into all sector-specific and provincial-level programs to facilitate climate mitigation and adaptation. Although mainstreaming these principles has been government policy for more than a decade in principle, there has been no established institutional mechanism to implement them across sectors or to coordinate policies between the federal and provincial governments.

To tackle these challenges, the Updated NDCs propose an extension of the National Action Plan (NAP) as a foundational framework. This NAP aims to facilitate the integration of medium and long-term climate-change initiatives into the national sectoral policies, strategies, and programs, fostering a coordinated approach across different levels of government [17]. Launched in March 2021, the two-year NAP is currently in the process of being developed, with support from the UNEP and a total funding of US\$2.7 million from the Green Climate Fund (GCF). Concurrently, Provincial Adaptation Plans are being formulated for each province. Although there were some initial delays, the implementation of the NAP finally commenced in August 2022. Furthermore, the government has initiated the formulation of a long-term low-emissions development strategy in response to Article 4.19 of the Paris

Agreement and the Glasgow Climate Pact. The effort is supported by the 2050 Pathways Platform.

Pakistan's central bank, the State Bank of Pakistan, introduced guidelines requiring financial institutions to monitor their climate risk exposure at a portfolio level and encourage them to mitigate the risks they identify [90]. The State Bank of Pakistan also provides an incentive scheme for renewable energy through three distinct categories for borrowing. While there is no such incentive scheme available for fossil fuel-based projects [91,92]. An independent emissions modeling framework has projected a peak temperature rise of 1.8 °C, reinforcing the idea that if countries fulfill their commitments, global warming could be held just below the 2-degree Celsius threshold. However, achieving the more ambitious goals of limiting warming to "well below" 2 °C or even 1.5 °C requires immediate policy actions aimed at achieving substantial reductions in emissions during these decades. These actions should be in alignment with achieving a global net-zero carbon emissions target [93]. However, achieving net-zero emission via the road-map policy is somewhat challenging because of the country's current economic crises, i.e., the devaluation of local currency. Currency devaluation has an expansionary effect, enhancing economic growth at the cost of increasing energy consumption and GHG emissions. Currency depreciation has an alarming impact on carbon emissions [94]. Therefore, the government should pursue regulations and an exchange rate policy to control GHG emissions. The study's findings indicate that exchange rate depreciation positively affects carbon emissions. According to the NDCs report and literature, renewable energy resources and electric vehicles are the baseline technologies to achieve net-zero carbon emissions [95]. These policies are not fruitful under severe stress, with low foreign reserves, depreciating currency, and high inflation [96].

## 6. Final remarks concerning policy Suggestions

Mitigating GHG emissions within the global energy system is imperative for addressing climate change. Every region needs to formulate long-term strategies and enact policies that facilitate the transition toward sustainable energy. This involves assessing the effects of current energy policies and considering enhancements to their NDCs [97], Pakistan Updated-NDCs play a significant role in the worldwide effort to limit global warming and tackle the climate crisis. By setting ambitious emission reduction targets across various sectors, Pakistan contributes to the collective goal of keeping global temperature rise below 1.5 °C, as outlined in the Paris Agreement. To demonstrate Pakistan's commitment to being a responsible global citizen and reinforces the importance of every nation taking meaningful actions to combat climate change. The current study NDS scenario is aligned with its Updated NDCs submitted under the Paris Agreement. The NDCs serve as a pledge by countries to decrease their GHG emissions and acclimate to the influences of climate change.

The NDS scenario, emphasizing emission reductions and sustainability measures, reflects an enhanced climate ambition, signaling Pakistan's willingness to go beyond its initial commitments and contribute more to the global effort. The significant emission reductions in the NZES scenario by 2050 signify Pakistan's commitment to transitioning towards a net-zero carbon economy. This long-term goal is essential to achieving a sustainable and climate-resilient future. The modeling in this study primarily focuses on energy-related CO<sub>2</sub> emissions across the power, transportation, industry, and residential sectors. Non-CO<sub>2</sub> emissions (e.g., methane and nitrous oxide) and emissions from agriculture and land-use changes are not explicitly accounted for within the current framework. By setting this target, Pakistan is taking proactive steps to mitigate the impacts of climate change, protect vulnerable communities, and ensure the planet's long-term health. Current policies emphasize a transition to clean and renewable energy sources. By reducing dependence on fossil fuels and increasing the share of renewables in the energy mix, Pakistan is curbing emissions, improving energy security, and reducing air pollution. Pakistan is pursuing a low-carbon

and climate-resilient pathway by integrating climate-friendly policies into economic planning and development strategies. This approach helps reduce emissions, enhances the country's resilience to climate impacts, and fosters socio-economic growth. Pakistan requires adequate climate finance and international support to fully implement the current policies and recommended measures to achieve its emission reduction targets. As a developing nation, Pakistan seeks financial resources, technology transfer, and capacity-building assistance from the international community. Enhanced collaboration and partnerships with developed countries and international organizations are essential to support Pakistan's climate action initiatives. While focusing on emission reductions, Pakistan also recognizes the importance of climate adaptation and resilience-building. Climate change impacts are already being felt in the country, and adaptation measures are crucial to safeguarding vulnerable communities, ecosystems, and infrastructure from the effects of climate change. By setting ambitious emission reduction targets, aligning with international climate commitments, and aiming for a net-zero carbon future, Pakistan is positioning itself as a proactive and responsible player in the fight against climate change. The current study presents a roadmap for sustainable and long-term climate-resilient development, offering opportunities for economic growth, improved energy security, and enhanced environmental protection.

While Pakistan is making significant strides toward emission reductions, it is evident that achieving net-zero carbon emissions by 2050 may be challenging for some sectors with current policies as shown in the NDS scenario. Specific sectors need more focused mitigation measures and accelerated efforts to bridge the gap and achieve long-term goals are recommended in the NZES scenario. The electricity generation sector is a critical area for achieving net-zero emissions. While the NDS scenario emphasizes renewable energy deployment, there might still be challenges in completely phasing out fossil fuel-based power plants, especially for meeting peak demand. To address this, Pakistan must prioritize investing in advanced clean energy technologies like Carbon Capture and Storage (CCS) for existing fossil fuel power plants which can curb emissions in the long term. Shahid et al. [24] emphasize the pronounced cost-effectiveness of electricity generation from renewable sources, showcasing a fivefold reduction in costs compared to conventional methods. Rehman et al. [23] predict a substantial transformation in the energy fuel mix, foreseeing oil as the dominant energy source and estimating it to account for 38.16 % of the total consumption. These findings collectively underscore the economic advantages and shifting dynamics within the energy sector, urging a closer examination of renewable sources for a more sustainable and cost-efficient energy future. This will be followed by natural gas at 37 %, electricity at 16 %, coal at 7 %, and LPG at 1 % by the year 2035. Additionally, it suggests that nuclear power could serve as a viable alternative for Pakistan's sustainable energy future. In contrast, importing coal for power generation is not recommended; instead, the promotion of domestic coal, coupled with clean coal technologies, is encouraged. Moreover, promoting grid integration of renewables, energy storage solutions, and demand-side management can enhance the sector's decarbonization. Industries remain a significant source of emissions in Pakistan. The industries sector needs comprehensive measures to transition to low-carbon production processes to achieve net-zero carbon. The government should incentivize and support industries adopting energy-efficient technologies, process optimization, and waste reduction strategies. Collaboration between industries and research institutions can lead to the development and adoption of breakthrough technologies that substantially cut emissions. Conversely, the domestic and building sectors show a declining emission trend, but further efforts are needed to achieve net zero. Emphasizing energy-efficient building design, retrofitting existing structures, and promoting sustainable building materials can reduce emissions in this sector. Raising awareness among the public and incentivizing the adoption of energy-efficient appliances and renewable energy systems can also play a pivotal role in achieving net-zero carbon in buildings. Unfortunately, the transport sector is been

neglected because of no vehicle retirement policy availability which poses a serious threat to the environment, also hydrogen fuel is been introduced by other countries for future transport which is more environmentally friendly.

Addressing these sectors' emission challenges requires a combination of effective policies, technological innovation, financial incentives, and collaborative efforts. The government, private sector, civil society, and international partners must work together to accelerate mitigation measures and advance the transition to a sustainable, low-carbon economy. By focusing on these sectors, Pakistan can make considerable progress towards net-zero carbon emissions and contribute to the global effort to combat climate change.

We acknowledge in our analysis the uncertainty associated with projecting future energy and carbon emission routes because of shifting economic, policy, and technological conditions. Considering how complicated energy networks are, long-term projection is by its very nature unpredictable. To tackle this, we employ scenario analysis within the LEAP model, investigating multiple scenarios with varying assumptions. This enables us to show a variety of potential results, from positive to negative. Although our work attempts to provide informative assessments, we acknowledge that real trajectories might differ because of uncontrollable outside influences. We raise awareness of potential changes in future outcomes by communicating the limitations of our projections through our discussion of uncertainty. We use rigorous techniques like scenario analysis and sensitivity testing to address and highlight the difficulties in estimating notwithstanding inherent uncertainty.

#### CRediT authorship contribution statement

**Riaz Ahmad:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Genyuan Liu:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Syed Aziz Ur Rehman:** Software, Resources, Formal analysis. **Rizwan Fazal:** Software, Methodology, Investigation. **Yuan Gao:** Validation, Data curation. **Duo Xu:** Resources, Methodology. **Feni Agostinho:** Writing – review & editing, Resources, Methodology. **Cecilia M.V.B. Almeida:** Writing – review & editing, Formal analysis. **Biagio F. Giannetti:** Writing – review & editing, Methodology.

#### Declaration of competing interest

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

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2024.134075>.

#### Data availability

Data will be made available on request.

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