Contents list available at IJRED website
International Journal of Renewable Energy Development
Journal homepage: https://ijred.undip.ac.id
Research Article

Socio-Economic Prospects of Solar PV Uptake in Energy Policy Landscape of Pakistan

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Abstract. Despite global calls for climate change and its impacts in past decade, energy sector of Pakistan has remained highly dominated by high-cost carbon-intensive resources. Although a significant number of policies have been put forward by both provincial and federal government in last three years, the ground-level implementation of these policies is non-existent, and Pakistan's progress is still far behind the developed countries. This study therefore performs a socio-economic analysis of solar PV potential in Pakistan and how recent policies can be mobilized to upscale the utilization of solar PV both as an on-grid and off-grid generation source. This also links to solar potential for corporate sector engagements in their Net-Zero Pathways. The methodological approach uses a Low Emission Analysis Platform (LEAP) model designed for Pakistan's Power System supplies under three different scenarios i.e., Energy Transition Scenario, Conventional Generation Scenarios, and Business as Usual Scenario. Indicative Generation Capacity Expansion Plan (IGCEP 2021) along with recent policies is used as the leading data source for driving the capacity additions. The results obtained from the model indicates that despite having a large potential, under currently policies the share of solar in total grid power generation will remain under 2% by 2030. Under Energy Transition Scenario, the model runs under a least cost optimization plan leading to a higher uptake of solar power. As per this scenario, the share of renewable increase beyond 2030 to achieve a share of around 50% by 2045. This can lead to cumulative carbon reductions of around 2000 Mt by 2030 and economic savings of around $ 5 billion. Based on the model results, this study also identifies the possible pathways for upcoming iterations of Pakistan IGCEP plan that builds around solar PV.

Keywords: Solar Energy; Energy Planning; Energy Policy; LEAP; Energy Generation;

Received: 24th April 2022; Revised: 8th June 2022; Accepted:16th June 2022; Available online: 28th June 2022

1. Introduction

Past five years have observed a marked increase in the use of clean energy sources across the globe (IRENA, 2022). Despite global economies being bent under the weight of COVID19, the share of renewable energy especially Wind and Solar has grown rapidly (IEA, 2021b). The energy landscape in coming decade appears to be more "just", "efficient", "affordable" and "clean". Renewable energy technologies are increasingly becoming the more focused area of investments and technology exchange (IRENA, 2020). As economies shift away from the fossil fuel technologies, understanding the role of renewables in decarbonization is key for a smooth pathway to net zero targets (Lin & Jia, 2020).

As per the recent report of International Energy Agency, addition of renewables in global electricity supply is on track to meet the targets of Paris Agreement. Driven by Solar Photovoltaic (PV), 290 GW of renewable energy capacity was commissioned in 2021. This is 3% more than the capacity added in 2020 and solar PV is responsible for more than half of it (IEA, 2021a). Regionally, China has been the largest contributor, accounting for almost 43% of total capacity, followed by EU, USA, and India (ibid). These four countries combine to constitute almost 80% of the total capacity additions.

Policy support for renewables have also mobilized the public sector spending in clean energy. Renewables have accounted for 11% of total economic recovery (COVID-19) spendings on clean energy (Ling *et al.*, 2022). An approximately $42 billion are expected to be injected this sector led by Solar PV. It has been further estimated that with right policy and regulatory support, approximate $400 billion of investments can be mobilized (ibid).

While the global progress on renewables is promising, the major challenge rests in capacity expansion plan of the developing countries (IRENA, 2018a). With decrease in coal prices, developing and underdeveloped countries are looking to coal as the cheaper and more affordable option. Policy support for making a shift towards renewables has also been lacking due to outdated grid infrastructure and lack of fiscal space to make a rapid just transition (UN-ESCAP, 2020). While this has been

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true for many countries, this study mainly focusses on the energy landscape of Pakistan.

Pakistan's Energy and power sector are facing a severe and multifaceted energy crisis, mounted with climate and socio-economic risks. As per the latest 'Long Term Climate Risk Index' study (Eckstein *et al.,* 2019), Pakistan was among the top ten most afflicted and susceptible countries to global warming from 2000 to 2019. Pakistan's overall percentage of global CO_2 emissions kept below 1% in the past (MoCC, 2021). However, since 2015, its contribution to Greenhouse gas emissions (GHG) and CO_2 have risen sharply due to rapid investments in coal fired power plants (Zia *et al.*, 2020).

Even though coal appears to be economical for energy landscape of the country, it, however, has higher direct and indirect costs as compared to renewables, through transition risks, accelerating threats from climate change, and asset locking (Analytics, 2020). The continued development in coal mining and power plants is presented in the recently released "Integrated Generation Capacity Expansion Plan (IGCEP) 2020-2047 & 2021-30", which envisages the future energy mix dominated by coal and renewable energy mainly the hydropower (NTDC, 2021). Similarly, the long-term power plan (IGCEP) suggests adding nearly 4.8 GW of gas-based power capacity within the next two decades to meet the demands of residential and industrial sectors. This increased coal utilization will be a serious impediment to the growth of clean and cheap energy resources in the country (Nicholas, 2020).

Currently the power sector of Pakistan is suffering from major inefficiencies including surplus power, demand side management issues, low energy access, and financial burden (NEPRA, 2021). A major reason for the recent troubles has been the past reliance on fossil fuels (Aslam et al., 2021a). Renewables face a major challenge due to significant lack of awareness among the masses. Individuals are reluctant to buy solar PV and off-grid power generation sources due to less awareness, high capital cost, lower comparative output and lifecycle (Jan *et al.*, 2020). All these factors add up to decrease people's willingness to adopt solar PV and its market among the people of Pakistan has not been able to flourish. This study has attempted to enlist the steps to transform policies and limitations due to which the quality of imported solar PV is being compromised in Pakistan. To overcome the issues of limitations and policies, comparison is required with the strategies and policies being adopted by both developed and developing countries.

Substantially, studies have reviewed the potential of solar PV on a large scale (Lea *et al.*, 2021). Delossa *et al.* analyzed the impact of Solar PVs on power distribution facilities (Dellosa, 2016). Guno at el. Discussed the integration strategy of solar PV systems in residential building through a case study of Philippines (Guno et al., 2021). In industrial sector, a detailed review of solar integration was performed by Wattana *et al.* (Wattana & Aungyut, 2022). For user-end appliances, solar energy analysis was conducted by Suherman et al. (Suherman *et al.*, 2020). Now although similar studies have also been conducted in Pakistan, but their implementation and utilization in the policy landscape is very limited, thus leading to a low market in both demand and supply sectors.

In order to enable economic growth, the Pakistani government began a thorough restructuring of the power sector in 2013, facilitating independent power producers' entry to the power industry and implementing a multi-billion-dollar investment plan to expand power generation (Hina Aslam, Vaqar Ahmed, Michael Williamson, Faran Rana, Ubaid Zia 2020). As a result of these activities, new power plants with a combined capacity of more than 7,000 MW, including 1,700 MW of solar and wind, were operational by 2018 (NEPRA, 2018). In 2019, the national annual installed power generation was 35 GW, and load shedding due to capacity restrictions came to an end as a result of the additional generation capacities (Aslam et al., 2022).

Pakistan's transition and a shift towards renewable energy go beyond just replacing fossil fuels with solar and wind energy. A true transformation of the country is embedded in the fundamental way the energy system is structured. This requires understanding the opportunities, strategies, and present case studies both within and outside the country to understand the most suitable models. In 2021, supported by policy deadlines, wind energy was all set to depict the largest global increase of 17% (growing by 275 TWh) in renewable power generation as compared to its 2020 levels (IEA, 2020). Along with being clean and sustainable, wind energy was the most cost-effective solution for many countries (IRENA, 2020). In recent years, Pakistan has taken a shift towards clean energy by adopting ambitious targets for its energy and climate outlook. Pakistan's "Alternate and Renewable Energy (ARE) Policy 2019" approved by Cabinet Committee on Energy (CCOE) has mentioned a target of achieving 30% share of renewables by 2030 on a least cost basis (AEDB, 2019b). Along with revised Nationally Determined Contributions (NDCs), the approved version of Pakistan's Indicative Generation Capacity Expansion Plan (IGCEP) 2021 has also clearly mentioned that by 2030, almost 60% of Pakistan's total energy generation will be through renewable energy sources (including Hydro) (NTDC, 2021).

However, among these plans, the potential of harnessing energy from solar power recently has been overshadowed in Pakistan. In 2021, solar energy contributed to less than 1% of the total generation in the country (NTDC, 2021). Even as per the IGCEP 2021, solar energy will only have a power generation share of 1% and capacity share of only 2% by 2030. As opposed to this, most research studies have highlighted that solar energy has a vast potential in Pakistan particularly in the province of Sindh and Balochistan (Bank, 2021).

According to "Variable Renewable Energy Locational Study" carried out by the World Bank Group, Pakistan has a potential to add 8726 MW of solar capacity by 2025 (without any grid investments) and 13,546 MW of solar capacity by 2030 (with grid investments) (Bank, 2021). Recent study on "Green Recovery of Energy and Power Sector in Pakistan " by Sustainable Development Policy Institute (SDPI) indicates that an increased reliance of Pakistan's power sector on Solar and Wind energy can lead to annual savings of $9 billion by 2040 (Aslam *et al.*, 2022). SDPI's research in collaboration with UNESCAP on Reform priorities for Pakistan's energy sector also indicates that as opposed to associated challenge of time and cost over-runs with Hydropower, solar has a comparatively very short period of installation and significantly lower cost over-runs (Hina Aslam, Vaqar Ahmed, Michael Williamson, Faran Rana, 2020).

Further, the corporate sector of Pakistan is also looking to adopt solar energy to incorporate sustainability into their development Agendas (Intelligency, 2022). Even at the informal sector, solar is being extensively used to provide off-grid energy access to the marginalized communities (UNDP, 2021). Along with energy security, it also leads to rural empowerment and local job creation. As per SDPI's study on "Supporting Economic Recovery ", $1 spent on fossil fuels has the potential to generate 2.7 jobs whilst the same amount spent on wind or solar can potentially produce 7.5 jobs (Javed, 2021).

But despite a large potential as indicated above, many stakeholders have previously highlighted that the challenge for solar upscale in Pakistan lies in the outdated power evacuation capacity for intermittent resources, lack of technically and economically feasible solutions, regulatory constraints, developing structured accounting mechanisms for the corporate sector, lack of indigenous production, and capacity to handle the resulting electronic waste (Ahmed *et al.*, 2021; Sher & Qiu, 2022).

Given the identified gaps mentioned above, this study will perform a socio-economic assessment of solar PV, explain how a solar driven market can help Pakistan overcome its major energy sector challenges, and how it can act as a big step in achieving Pakistan's Nationally Determined Contributions (NDCs). The key objectives of the study include analyzing the economic and environmental prospects of solar PV under different government plans such as ARE policy, IGCEP 2047 and 2021, and its NDCs through scenario-based modeling, and then using a Low-Emission Analysis Platform (LEAP) model to prepare a solar based energy outlook and sustainability framework that can assist government in making a clean energy transition.

2. Existing Policy Landscape of Solar PV in Pakistan.

Initially, Pakistan's "Policy for Power Generation 2002" was the major power policy, with the goals of providing sufficient power capacity at the lowest possible cost, encouraging, and ensuring the use of country's own resources, and ensuring that the interests of all relevant stakeholders are incorporated (GOP, 2002). Then the Energy Security Action Plan was designed to meet Pakistan's Vision 2030 objectives for dependable and high-quality energy sources (MoPD&R, 2014). It improves energy supply by building more focus on RE sources especially the hydropower. The government also took part in energy conservation through supporting energy conservation techniques and significant energy savings at the national level (ENERCON, 2006). While the focus of all these policies has been on increasing the share of clean energy sources, the implementation hand of government was always lacking and mainly the administrative targets have been met (Raza *et al.*, 2022). As also highlighted previously, the strongest support for solar PV uptake in Pakistan came through the introduction of Alternate and Renewable Energy Policy (2019) which targets a share 30% energy generation from renewables by 2030 (AEDB, 2019a).

2.1. Supporting studies by the World Bank Group

The uptake of renewables in Pakistan is hindered by challenges of operational flexibility and technical capability of national grid to absorb intermittent renewable energy resources (Jan *et al.*, 2020). Furthermore, despite an energy surplus, line capacity constraints and low electrification rates in rural areas are still a pressing issue (Kabala *et al.*, 2021). To overcome these bottlenecks, the National Transmission and Despatch Company (NTDC) requested the World Bank to aid with analyzing the optimal integration and maximum technical possible level of wind and solar power in Pakistan's long-term grid expansion plan 2030. In response, the World Bank published the "Variable Renewable Energy Integration and Planning Study" which answers critical questions such as the optimal energy mix that Pakistan could adopt over the next two decades while considering economic, technical, and environmental factors and how Pakistan's current grid infrastructure can handle the intermittency of wind and solar energy (World Bank, 2020). The integration and planning report was soon followed by a 'VRE locational study' which draws its recommendations and data insights from a detailed study on Renewable Energy mapping of wind and solar particularly in different provinces of Pakistan (Bank, 2021). It identifies the most suitable zones for solar and wind development across the country and analyzes the realistic potential of different provinces to absorb and transmit VRE based on the capacity of their grid networks. Figure 1 highlights the technically useable potential of solar PV across Pakistan based on existing grid network.

In 2022, the World Bank also put forward a "Variable Renewable Energy Competitive Bidding Study" and a draft document on Mini-Grids for Electrification of off-Grid Communities in Pakistan (Bank, 2022). Both reports also extensively highlight the significance on utilizing solar energy.

Giving these opportunities and challenges, it is very critical to realize the existing challenges that exist in uptake of solar PV, and what could be the socio-economic impacts of a large-scale transition towards solar PV in the country. While the potential of solar PV has been highlighted in various studies, the existing policy landscape has not been incorporated in the analysis. Capacity expansion in most scenario modeling studies is theoretical without taking into account the committed energy sector projects. This study takes them into scenario building by adopting the targets mentioned under the recently approved capacity expansion plan, and then compares it to a least cost scenario. This would lead to potentially more realistic results in the national context of Pakistan.

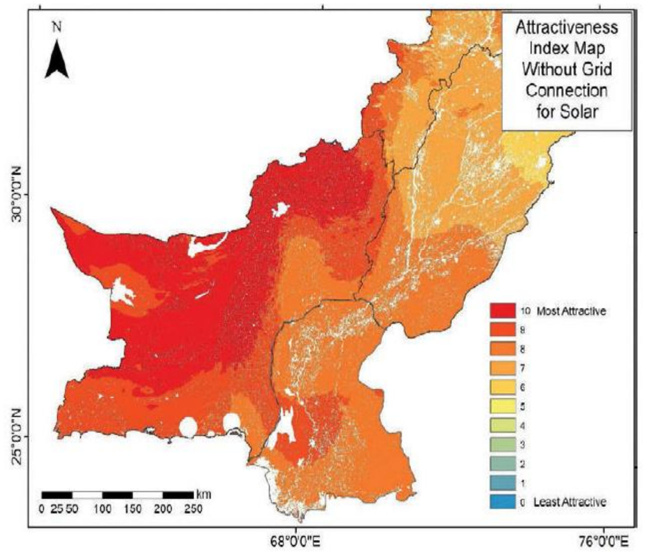

Fig. 1 Financial attractiveness of solar PV potential excluding transmission and grid connection costs (Bank, 2021).

3. Methodology and Data Collection

The methodological section of the study is divided into two main categories i.e., Primary Data Collection and Secondary Data Collection. The secondary data analysis is mainly based on analyzing the results obtained from literature review while the primary data analysis is based on the model development for predicting the outcomes under different scenarios of solar PV development using LEAP tool.

3.1. LEAP Model Development

LEAP is an internationally recognized tool which comes with the benefits of being accessible without cost and enabling the feeding for Excel based data into the model with user friendly interface easily (SEI), 2022). The future outlook part is modelled by extrapolating energy demand and supply by sectors by type of energies, with looking into future social economic development pattern, to match the development demand in a country or region. Development of the LEAP model relies on a large amount of data to support the bottom-up analysis (C.G, 2016; Hu *et al.*, 2019; Mirjat *et al.,* 2017a, 2017b, 2018). The LEAP model does have the benefit of being more easily understood by policymakers, which is an important consideration when using a quantitative modelling tool to aid policymaking (Zia *et al.*, 2019). LEAP is a term to refer to long-term modelling tool that is built around the idea of scenario analysis. Scenarios are self-contained narratives that depict the evolution of an energy system through time. Policy analysts can use LEAP to design and analyze different scenarios by comparing their energy needs, socioeconomic costs and benefits, and environmental implications. A. Amo-Aidoo et al. used the LEAP model to perform the policy level implementation of solar energy in Ghana, and depicted that a visionary supply scenario can meet the 2030 renewables target through solar (Amo-Aidoo *et al.,* 2022). Dewei Yang also used to LEAP to design critical pathways for energy substitution in China (Yang *et al.*, 2021). For Pakistan, Figure 2 presents the framework of LEAP-Pakistan.

Few major components of LEAP include energy consumption assessment, energy conversion techniques, environmental impact assessment and cost analysis for who energy value chain. The LEAP software's built-in calculations give a wide choice of modelling approaches inside each item. It generates a large number of results that can be seen as graphs, tables, or even maps. Energy demand, for example, is computed in five basic dimensions: fuels, years, scenarios areas, and branches (i.e., the sectors and subsectors of the analysis) (SEI, 2005). The user just selects the dimensions to be displayed on axis of each chart. The unit can be changed easily, and the chart format can also be adjusted. LEAP uses a set of functions to perform scenario-based modeling. Output values are predicted using linear regression technique to an exponentially growing model (ibid).

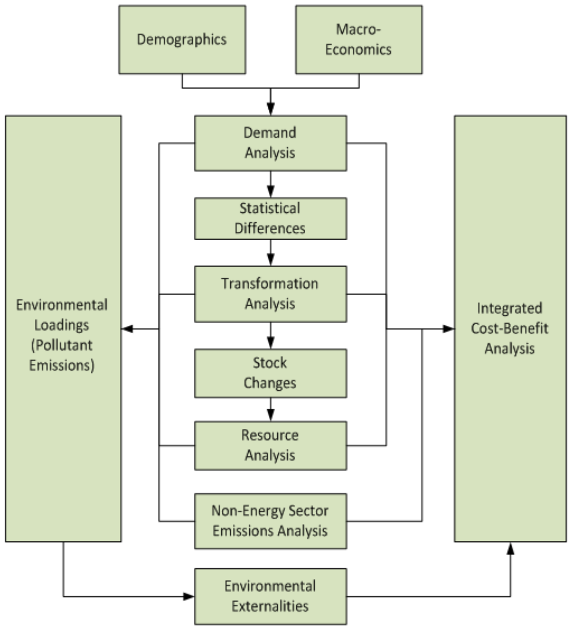

Fig. 2. LEAP Modeling framework ((SEI), 2022)*

Table 1
Critical drivers and parameters under different scenarios

Scenario	Abbreviation	Description
BAU	Business as Usual	BAU scenario was designed to serve as the reference base for other two policy scenarios. The BAU scenario is based on the targets as prescribed in Pakistan's recent capacity expansion plan **i.e.,** IGCEP. The GDP growth beyond 2021 is maintained at a 4.5% target as per the IMF Country Report 2021 (IMF, 2021). The population growth and urbanization are projected through a rate of 2% and 2.7% respectively (*Pakistan Economic Survey 2020-21*, 2021).
CGS	Conventional Generation Scenario	The demand drivers in this scenario are same as that in BAU scenario. The major different is that energy generation mix of Pakistan is expected to remain same, as to analyze the existing threat that the implementation arm of government is not in line policy making hand. The penetration of solar will remain same as it is.
ETS	Energy Transition Scenario	In this scenario, the demand growth patterns are same, however, for demand sectors, the energy intensity is improved in line with NEECA's strategic plan (NEECA, 2020). In power capacity expansion, this plan follows a least cost model while initially taking capacity from the committed projects. After 2030, this model will take a higher intake from solar and wind since there is no constraint of following IGCEP after 2030 (NTDC, 2021).

* The LEAP Model used in this study can be accessed through the following link: https://drive.google.com/drive/folders/15c3X_e68FBdP2GTrxfh6lj99SkRa3__a?usp=sharing

Table 2
Power Capacity Additions (NEPRA, 2018)

	2015	2017	2019	2020	2022	2024	2025
Ultra-super critical	0	0	0	0	660	660	660
Gas based powerplant	2902	2905	2905	2905	2905	2905	2905
Oil based STPP	4705	4164	3623	3352.5	2811.5	2270.5	2000
Combined Cycle plant	9200	9200	16193	16613	16613	16613	16613
Subcritical	150	480	810	2130	5263	5263	5263
Supercritical	0	810	3450	3450	3780	5100	5100
Solar	400	400	400	400	400	400	400
Wind	306	785	785	785	785	785	785
Bagasse	146	280	280	280	280	280	280
Nuclear	752	1689	2783	3330	4424	5518	6065
small Hydro	556	556	556	556	556	556	556
big Hydro	6774	6774	6774	6774	6774	6774	6774
Oil based Diesel Engine	1730	1730	1730	1730	1730	1730	1730
RLNG CCPP	0	1260	5670	6500	6500	6500	6500

3.2. Scenario based Modeling

Scenario analysis in this study depicts the capacity expansion plan and resulting profiles which each scenario must follow to achieve a set of policy target. The scenarios are modelled using LEAP with key assumptions such as electricity cost, per unit emissions from different sources, GNI/capita kept constant. A complete demand-supply equilibrium has been modelled using a top-down approach for key demand sectors i.e., Transport, Residential, Commercial, and Industrial Sector. The energy demand in each sector is driven by the increase in Gross Domestic Product (GDP), increase in population and urbanization, and other sector specific parameters. A total of three scenarios are modelled as defined in Table 1.

3.3. Base Year Data Collection

Table 2 below shows the installation capacity of Pakistan planned before IGCEP 2047 was launched. In 2017, power generation is 114 TWh, while it was 89 TWh in 2010, increasing by 28%(NEPRA, 2018). Renewable energy accounts for 34% (including Hydro) while the share of nuclear was 4%. Installed capacity in 2017 was 29.57 GW which had increased by 30% as compared with that in 2013 (ibid). Due to high demand and cost issues, coal fired power generation is expected to increased quickly, especially with the collaboration with China (*CPEC Projects Progress Update*, 2019). The total installed capacity of the hydropower is about 7320 MW, in which 3767 MW is in NWFP, 1698 MW in Punjab, 1036 MW in AJK, and 93 MW in the Northern Areas.

The generation sector of Pakistan is moving towards a reliable supply system, as planned by NEPRA, turning from oil-based energy towards large base-load power plants using indigenous and imported coal, highly efficient gas-based plants, hydro power plants and renewable energy.

3.4. Emission Factors of different sources

Coal fired power plants dominates life cycle GHG emissions, with a range of 674 – 1688 g CO_2eq / kWh. And ranges for oil and gas fired power plants are 511 – 1171 g CO_2eq / kWh and 291 – 931 g CO_2eq/kWh respectively (IPCC, 2014). New coal fired power plants have emissions ranging from of 711 – 952 g CO_2eq/kWh, whereas NGCC plants have emissions range of 412 – 653 g CO2eq/kWh (ibid).

Some power generation technologies have very low lifecycle GHG emissions. Equipped with CCS is expected to reduce GHG emissions to 73–291 g CO_2eq/kWh for coal fired power (99–393 g CO_2eq/kWh). For gas fired power generation technologies, the range is 121–172 g CO_2eq/kWh (IPCC, 2014).

3.5. Modeling Assumptions and Limitations

While the modeling techniques has taken into consideration the national data and all the recent developments happening in policy landscape of Pakistan's energy sector, some limitations and modeling assumption might change the actual outlook of the country:

- The capacity expansion has been planned through a demand-supply equilibrium. The outlook of power capacity by 2030 and 2040 might change if the demand of country does not increase at the projected rates due to poor economic growth, industrial development, or increase in GNI/capita.
- The projected GDP growth is taken as per the estimations of IMF. The final demand leading to capacity increase might reduce in a low GDP growth scenario
- The cost calculations for power generation are based on Levelized Cost of electricity. It does not describe the cost that will be charged from the consumers.
- The environment intensities are grid emissions and does not quantify the emissions resulting from exploration of materials or land clearing.

- The expansion plan used as a basis of modeling in this study is indicative in nature. The upcoming iterations may have revised figures for the capacity expansion.
- The least cost optimization does not include the cost required for improvements in transmission and distribution system of Pakistan to integrate intermittent energy sources on the grid.

4. Results

Energy and climate are the core challenges for Pakistan, and if not addressed and managed properly, could easily jeopardize the sustainable development. However, despite these challenges, Pakistan is no exception to a new and emerging Global Energy Economy. We have many of the technologies and solutions to reach Net Zero as renewables, EVs, efficiency and other technologies progress, along with international and national collaborations in innovation and digital society to transform the world. However, country's vulnerability to climate change impacts, exacerbated by COVID19 pandemic, requires strengthening the capacity to develop and execute various sector specific interventions that address the adverse effects of climate change, contribute to reducing greenhouse gas emissions, and improve the country's ability to attract climate finance.

Given the numerous challenges and opportunities associated with the transition to RE around the world, Pakistan must carve out a route for green energy transition. It will not only assist the government in meeting its climate goals, but the constantly falling price of RE has also made it more economically feasible. This section summarizes the findings from the study's desk review and quantitative analysis.

4.1. Key Takeaways from Secondary Analysis

Policy formation has been done in Pakistan in the past, according to the literature, however there is a significant gap between design and execution due to a lack of planning (Raza et al., 2022). Both the provincial and federal governments are working to develop an energy portfolio. However, there is a need for harmonization of efforts between the provincial and federal administrations, as well as across different federal divisions, in terms of the entire country. When regional governments discuss about renewable energy, they have their own viewpoints, whereas the federal government has its own policies for obtaining a 30% renewable energy share without consulting the provincial governments (Alam, 2021). Provinces must produce power planning development studies and appropriate papers in order to select sites and technologies. On-grid and off-grid options can then be prioritized once these have been created. After the board of investment and the government have created a document that meets all standards, projects should be prioritized for the following 10-15 years, after which the board of investment and the government can bring them forth for private investment.

Pakistan is expanding its electricity producing capacity to satisfy rising energy demand as the country's energy surplus grows. Pakistan is boosting its generation capacity based on indigenous resources in order to lessen its reliance on imported fuel in the electricity sector, according to current power plans (NTDC, 2021). Hydropower, coal power, and renewable energy sources will all play a larger role in implementation. The initially suggested strategy, according to IGCEP 2047, is to boost coal power generation by 47 percent by 2040, in addition to other fuel-operated thermal power plants (Aslam, 2020). Despite the low cost and domestic availability of renewables, Pakistan's growth plans previously favored fossil fuel-fired power generation. Pakistan was expected to add 26,894 MW of power generation capacity using domestic coal alone by 2047, according to the proposed IGCEP plan (ibid). This is roughly 27.7% of total capacity additions between 2030 and 2047.

Pakistan's energy system is set up in such a way that costs are constantly rising, despite the need to switch to cleaner energy sources. Rather than an energy transition network, the country currently has an energy addition network, in which supply chains, logistics, and other equipment are constantly being added. However, this expanded network comes at a cost, and the system's implementation in Pakistan has resulted in increased capacity payments (1500 billion by 2023) as a consequence of the system's implementation (Aslam et al., 2022). As a result, it is critical for the country to resume its energy transition by enhancing energy sustainability.

Investments and interest in renewables in Pakistan have increased slightly in the past due to the trend and new policies. In 2018, non-hydro renewables accounted for only 4% of total power, a figure that is predicted to gradually rise (NEPRA, 2018). According to the IRENA renewable energy preparedness report for Pakistan, there is significant wind potential in the Baluchistan and Sindh corridors (IRENA, 2018b). The Chinese are the largest investors in wind projects, having installed roughly 400 MW (37%) of wind plants completed between 2014 and 2018 (Aslam et al., 2021b). The Quaid-e-Azam solar plant is now operating with a capacity of 400 MW, with future additions planned. A total of 550 MW of solar projects are now under construction in the country (ibid).

Hydro power now has a large share of the entire energy mix (25 percent), and it is predicted to grow to around 30% by 2030 (NTDC, 2021). As a result, achieving a total of 60% (30 from hydro and 30 from wind, solar, and biomass) would be a huge achievement for Pakistan's power sector [88]. Currently, renewables (solar and wind) account for only 4.9 percent (1698 MW) of total power generation, with wind accounting for 67.5 percent, 13.4 percent from solar, and 19 percent from Bagasse. By 2025, Pakistan has the capacity to generate roughly 8726 MW from solar and 3755 MW from wind, respectively (Bank, 2021). This value is expected to rise to roughly 23,801 MW by 2030. Hydel energy accounts for 21.3 percent of Pakistan's power generation mix and 7.8 percent of the country's total energy supplies.

A thorough economic analysis reveals that fossil fuel investments are not inexpensive in the long run. It has a higher direct cost than renewables, and even its indirect cost includes transitional risk and exacerbated climate change dangers. Reducing Pakistan's reliance on coal will free up enormous financial resources (Aslam et al., 2021b). Between 2013 and 2020, Pakistan's coal imports nearly tripled, from less than 3 billion tonnes to nearly 18 billion tonnes (Pakistan, 2020). It accounts for 2.75 percent of overall imports, which amount 1.4 billion dollars each year. This sum is equal to the cost of insulating 1.4 GW of solar power. As a result, it's important to understand how much coal we import and how much it increases our reliance.

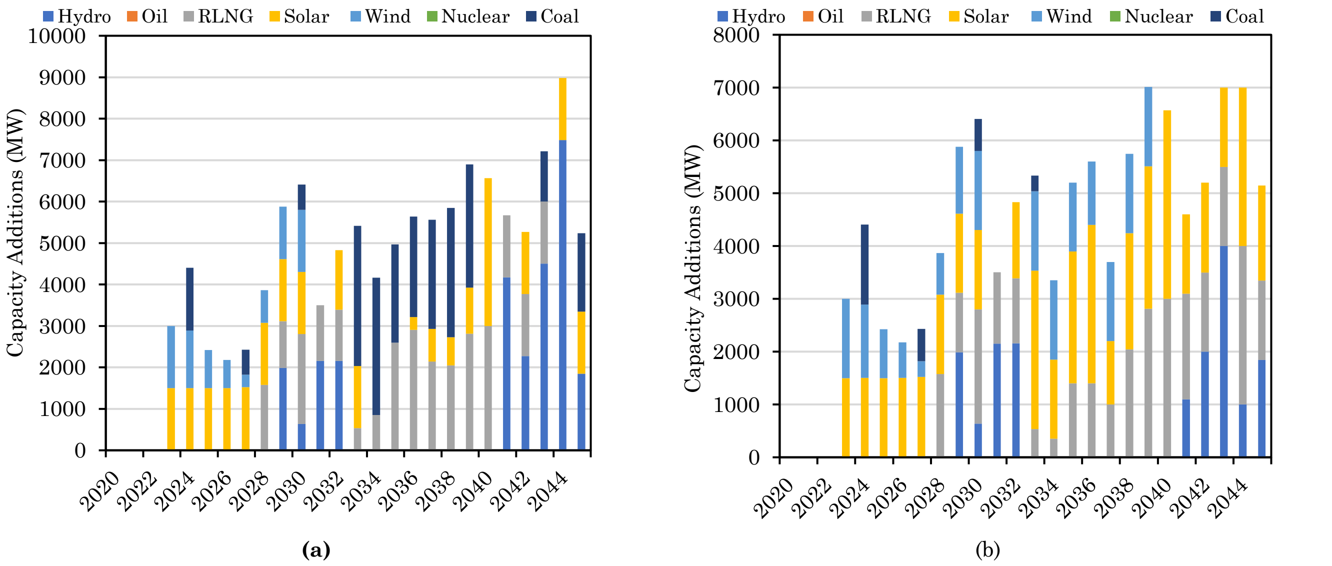

Fig. 3. (a) Capacity additions in BAU scenario, (b) Capacity additions for Energy Transition Scenario

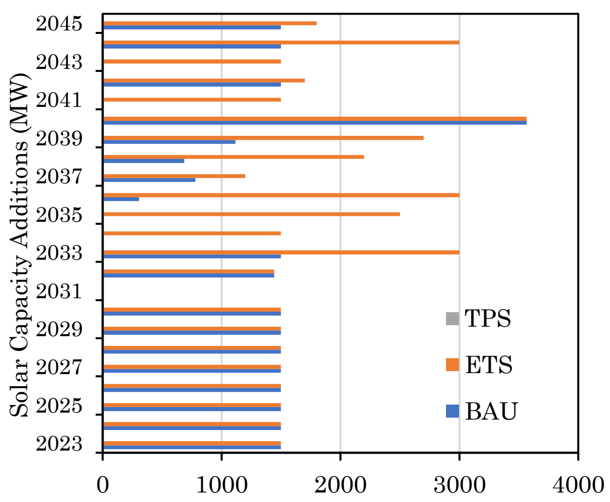

Fig.4. Capacity additions of solar power under different scenarios

Many economies have constructed their energy portfolios by relying on coal at first and then leveraging it as a conduit for renewable investments. As a result, what makes financial sense is heavily dependent on the policy goals. If the overall cost of the facility or the debt burden are the most important factors, the existing CPEC structure with its strong coal reliance makes sense. In that sense, even natural gas is a viable alternative. This investment, however, should not be considered environmentally friendly. If the goal is to maintain the LCOE (including emission value) low in the long run, however, cheaper and greener choices can be considered.

4.2. Capacity Additions under different scenarios

Power capacity additions under BAU scenario are shown in Figure 3a. It represents that the share of solar increase has not increased at a rapid rate since 88% of projects under Pakistan's capacity expansion plan are committed. This gives a little room for model to run on a least cost basis. From a total of 61,112 MW of capacity additions, only 13,685 MW is from solar and wind. It represents that if current policies of Pakistan are realized then renewables will occupy a combined share of 22% by 2030 from which 13% will be from solar.(Natarajan et al., 2020)

In energy transition scenario, the models run on a least cost basis as soon as the constraints of IGCEP are lifted. Thus beyond 2030, the model intakes a very high share from renewable energy sources i.e., wind and solar. Over 60% capacity share of Pakistan by 2040 under this scenario is occupied by wind and solar.

Figure 3b represents capacity additions in energy transition scenario. In the conventional generation scenario, total capacity expansion required is met from exactly the same sources as that in 2021. Gas and Furnace Oil will occupy the major share closely followed by hydro power.

4.3. Solar Power Additions

Figure 4 shows the addition of solar power in each year under three different scenarios. It can be clearly analyzed that solar penetration has been largest in Energy Transition Scenario as compared to the other two. The graph does not depict the conventional generation scenario since there is no addition of solar power.

4.4. Power Generation Mix under different scenarios

For getting more insights into the energy transition scenario, this section describes the share of different sources under each scenario. However, apart from capacity additions, Figure 5a is based on energy generation from different plants.

Power generation profiles are very much a reflection of total capacity share. However, the share of renewables particularly solar and wind is lower as compared to that of their capacity additions share. This is mainly due to lower capacity factor and intermittency nature of the renewable energy sources. Figure 5b represents the power generation mix under ETS. For conventional generation, the share is majorly dominated by oil and RLNG resources. The share is shown in the Figure 6.

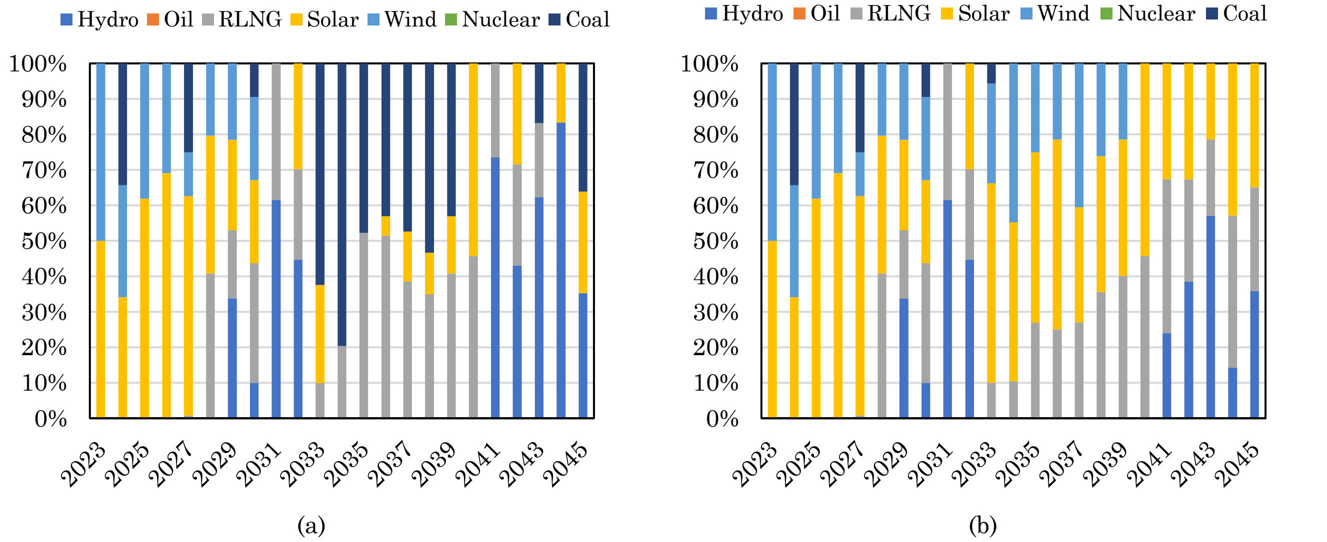

Fig 5. (a). Power Generation Mix of different sources in BAU scenario., (b) Power Generation Mix of different sources in Energy Transition Scenario

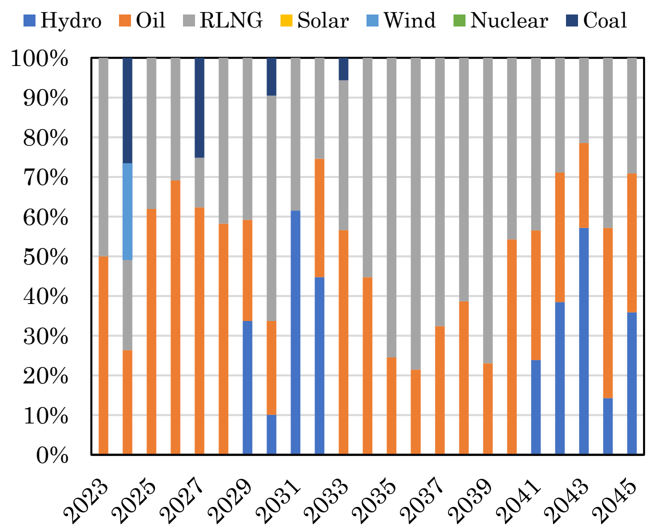

Fig. 6. Power Generation Mix of different sources in Conventional Generation Scenario

4.5. Investments for Each Scenario

This section describes the total cost of power generation. The cost has been calculated considering the per unit generation cost from each scenario. It should be noted that the cost calculations are performed irrespective of the LEAP model. An excel sheet has been used in which the total generation of each technology is multiplied with its per unit cost as per the latest NEPRA's tariffs (Average value). Figure 7a depicts the total generation cost from each category of plant in a particular area. As already mentioned in the literature and methodology section, the cost of renewables is already lowest in Pakistan. Further, these calculations also include per unit emission cost. Now although initially including the emission cost in generation of Pakistan might make the basket price much higher, however, in a long-term, it will save Pakistan from expensive power and large capacity payments. Figure 7b depicts the total cost of power generation in ETS. A comparison of both scenarios depicts that with increasing penetration of renewables the cost of power generation is coming down. Among the three scenarios, the lowest cost is obtained in energy transition scenario while the highest cost in CGS as shown in Figure 7c.

Since depicted in previous two sections as well, till 2030 the cost of ET and BAU will remain same since following the targets of ARE policy seems to be the most realistic approach for Pakistan. However, after 2030 the difference starts since the IGCEP based scenario starts decreasing the penetration of renewables. Figure 8 shows a comparison of total generation cost under each scenario.

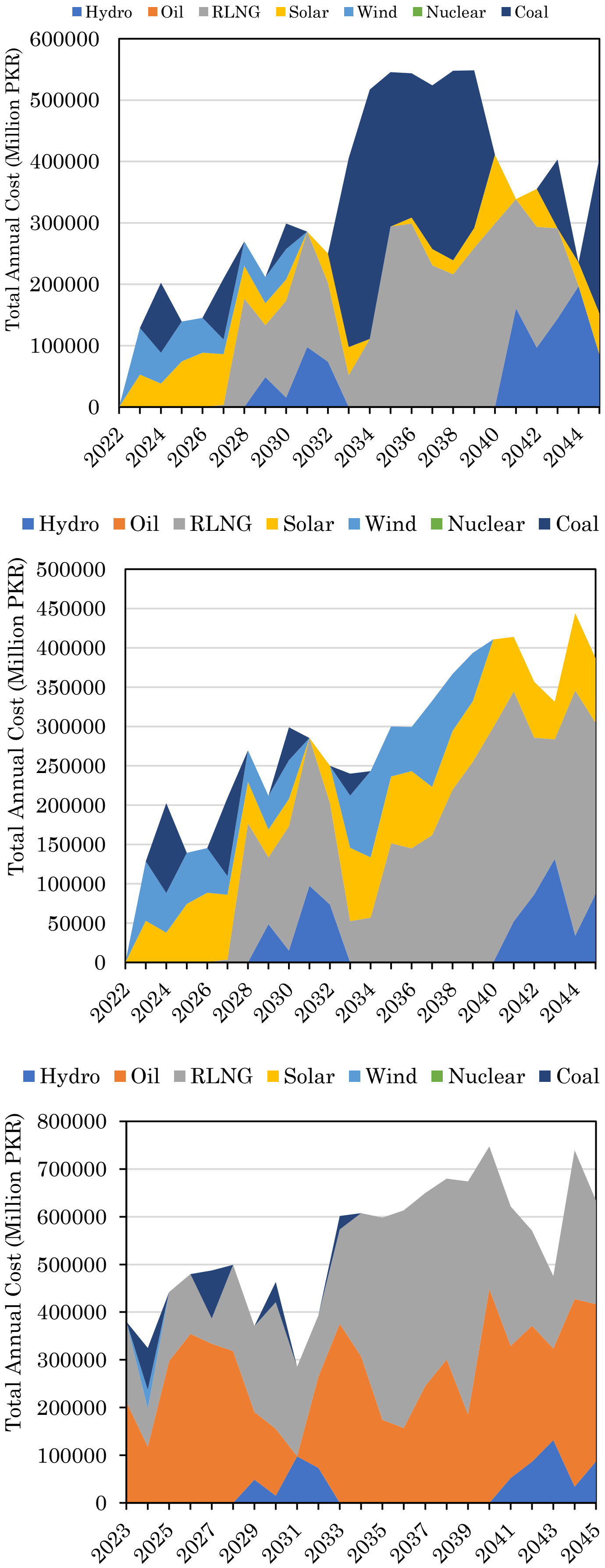

Fig. 7(a). Total Annual Costs (Added Capacity) of Power Generation in BAU Scenario, **(b).** Total Annual Cost (Added Capacity) of Power Generation in ET Scenario, (c) Total Annual Cost (Added Capacity) in Conventional Generation Scenario

4.6. Environmental Profiles for each scenario

Figure 9a represent the emissions from power sector of Pakistan due to capacity additions. It can be seen that the share of emissions is entirely contributed by Coal and RLNG based energy sources. Solar, Wind, and Hydro does not contribute to CO2 emissions. Hence a higher penetration of renewables can significantly alter the emission profiles in Pakistan.

In Business-as-Usual Scenario, between 2020-2045, there will be cumulative increase of around 4300 Mt of CO2 emissions from the power sector. However, as compared to this, in energy transition scenario, this increase can be limited to 2370 Mt. This represents that a cumulative value of around 2000 Mt can be saved by following the pathway of Energy transition scenario as also depicted in Figure 9b.

Conventional generation represents a much larger share off emissions from multiple sources. However, if Pakistan does not build upon its targets of renewable energy even by 2030, the cumulative emissions by 2045 might increase by around 8000 Mt which puts Pakistan completely off-the track from its NDC commitments. Figure 9c represents the total emissions in CGS.

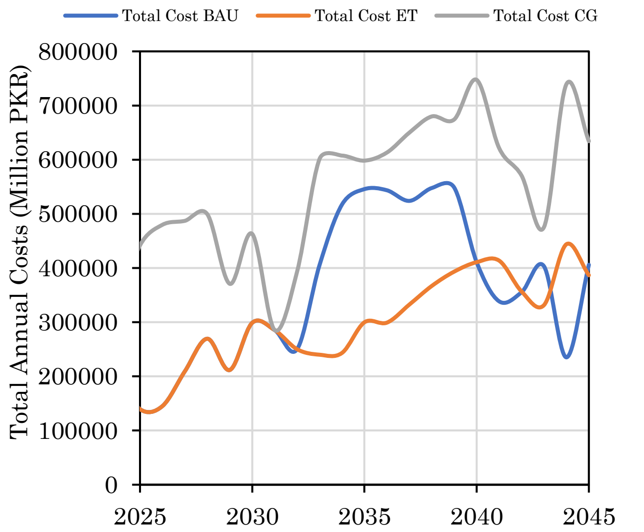

Fig. 8. Comparison of Total Generation Cost (Added Capacity) in Each Scenario

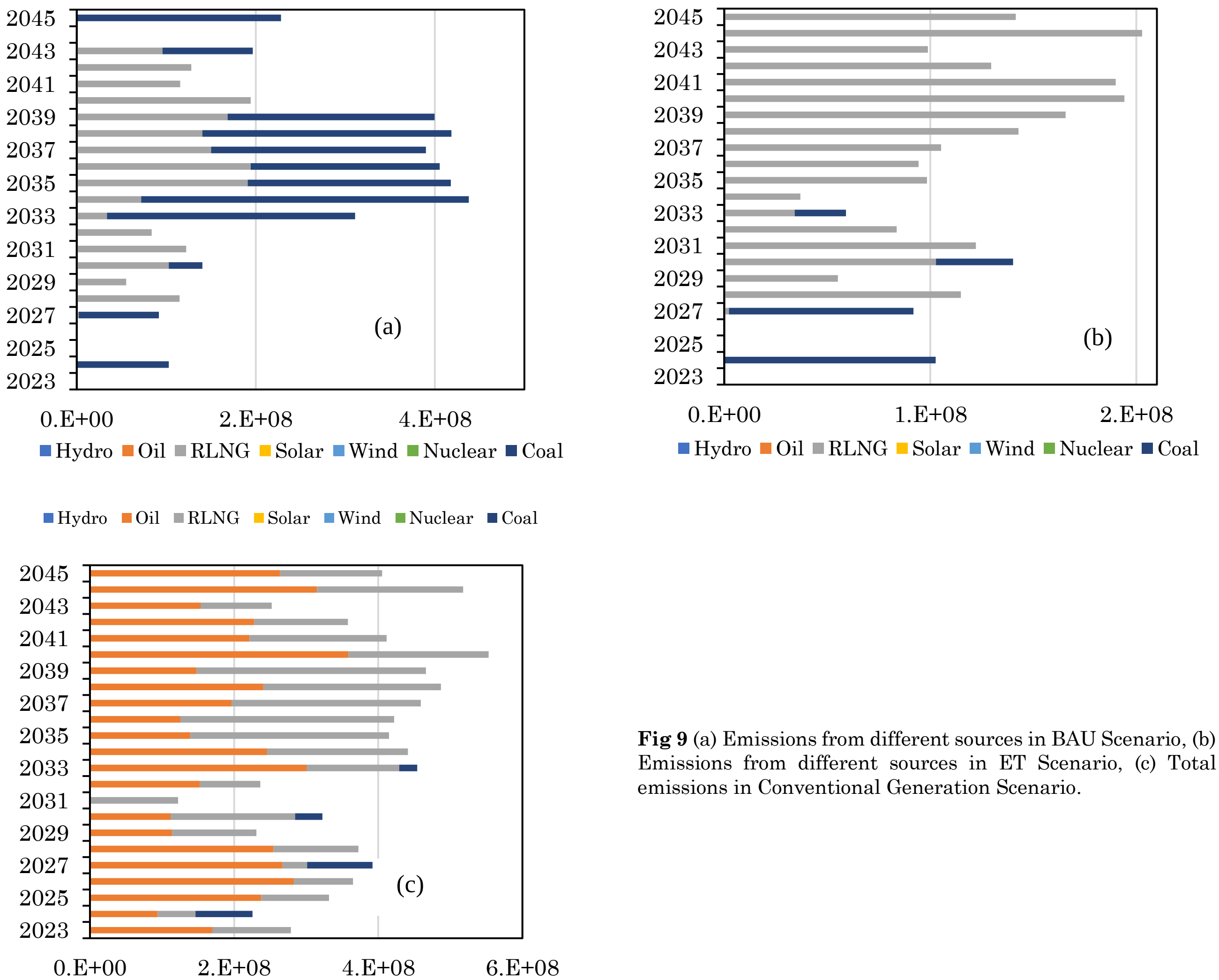

Fig 9 (a) Emissions from different sources in BAU Scenario, (b) Emissions from different sources in ET Scenario, (c) Total emissions in Conventional Generation Scenario.

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5. Discussion

While the results mentioned in previously sections very clearly highlight the socio-economic significance of solar energy upscale, it would require massive support to overcome the existing challenges. Although the renewable energy policy has several beneficial aspects, its core activities have not been adequate to fuel significant growth in Pakistan's renewable energy sector. This is a direct result of AER policy's inability to adequately address a few key difficulties, despite the fact that these issues have been acknowledged in the policy framework

5.1. Outdated Grid Infrastructure

The government has undertaken a large and difficult endeavor to develop solar energy, although Pakistan's national grid is now in poor condition (Zafar *et al*., 2016). Due to its variability and intermittency, it has not yet been technically upgraded to absorb renewable energy more effectively. A large chunk of Pakistan's industrial state relies on the captive plants due to extensive grid losses (Khalil & Abas, 2014). Pakistan has also had nationwide power outages as a result of a shaky distribution system, which has had serious consequences. Grid expansion and modifications are required to scale up variable RE production so that power systems may utilize high-quality solar and wind resources that are typically located outside of existing power transmission. Fundamentally, there is no limit to how much fluctuation a power grid can manage because technical remedies for voltage and frequency exist (Shahzad *et al*., 2017). However, everything comes at a price, and in Pakistan, investments in the T&D industry are far outweighed by investments in the power producing sector.

5.2. Baseload Power

The notion of base load electricity, which requires plants to be able to operate for months without requiring to be pulled down for maintenance, has long been an impediment to increasing RE penetration in Pakistan (Dondariya *et al*., 2018). The economics of such facilities dictate that the fuel cost should be low and plentiful, therefore local coal appears to be the best option. It is difficult to rely solely on renewables to supply consistent energy demands without an adequate energy storage system already in place, especially for large-scale systems.

5.3. Cost of Energy Additions

One of the main reasons for RE's moderate expansion in the country appears to be its financial competitiveness with traditional energy generators. Despite the fact that the cost of renewables RE has dropped dramatically over the last decade, Pakistan's energy sector is structured in such a way that costs are constantly growing, and the country's energy addition network is constantly adding to supply chains, logistics, and other equipment (Liu *et al*., 2018). This comes at a higher price, and the increased capacity payments are the outcome of the system's implementation in Pakistan. The Covid epidemic has drained the country's financial reserves even more. Pakistan's economic boost was estimated to be around 1.2 trillion dollars. Despite having a lower value than predicted, the stimulus was not in line with the green recovery (NREL, 2020).

5.4. Data Unavailability

On-the-ground data of at least one year is necessary for wind and solar PV generating installations. However, just a few feasibility assessments for project implementation have been conducted. In Pakistan, more than 40 wind masts have been constructed to collect data (Bhutto *et al*., 2012). Similarly, while World Bank studies have found the theoretical and technological potential of solar and wind on various sites, actual realities change rapidly over time, and externalities must be taken into consideration. Furthermore, there is a dearth of knowledge on how to collect technical data linked to renewable technology, which is becoming a major impediment to the development of renewable energy projects.

5.5. Lack of Policy Support and Coordination

For persons living in remote and far-off regions, limited awareness initiatives have been developed to educate the public about the benefits of renewable technology (Aslam *et al*., n.d.). There is a lack of organizational coordination, communication & advocacy, and involvement of various government bodies, organizations, energy departments, and creditors, as well as a lack of fiscal and regulatory structure to encourage local industry participation. Instead, the cost of importing solar panels has lately surged. For the awarding of licenses and the installation of net-metering, there are lengthy processes and a lack of cooperation from government institutions. For the construction, commissioning, and proper maintenance of renewable projects, there is also a lack of both competent labour and technical training facilities. Nationally funded technology transfer mechanisms/policies are lacking, and academic/R&D institutes lack technical testing and certification labs.

5.6. Heavy Reliance on Coal-based Projects

China has emerged as a significant international coal power investor in recent years, investing up to USD 21-38 billion in foreign coal power projects (Aslam et al., 2021b). Coal, along with other energy supplies, has laid the groundwork for the "Belt & Road Initiative (BRI)" member countries, as well as China, to begin energy cooperation. Saudi Arabia, the United Arab Emirates, Pakistan, Kazakhstan, and Russia have proven to be the best locations for Chinese energy investment, combining resource potential and financing environment (Isaad, 2020). Many resource-rich countries, on the other hand, have insecure economic frameworks, political limits, environmental challenges, and a scarcity of applicable technologies, placing investments at risk.

5.7. The Way forward for Solar Uptake in Pakistan

Based on the model results and extensive literature around key aspects of the study, this paper recommends the following key points for rapid uptake of solar PV industry in Pakistan:

- To increase people's willingness to adopt, there is a need to build capacity among all relevant stakeholders (Policy makers, parliamentarians, consumers, manufacturers etc.) and educate the common people about the benefits offered by solar energy.
- To overcome the existing gaps in energy sector planning, there is need for close coordination between all government entities (Federal, provincial and district-level) including ministries, DISCOs, GENCOs, with the private sector developers.
- Purchasing potential of sola in off-grid areas of Pakistan especially the province of Balochistan (and areas where expansion of national grid is not economically feasible) must be subsidized to increase the demand of solar. Local banks and multilaterals can be tasked to ensure that microfinance options are available for the people.
- To ensure provision of electricity and clean cooking to the rural communities, Pakistan needs to mobilize the window of regional cooperation. On a Macro-level, this includes development of regional on/off-grid VRE solutions, regional electricity trade, transmission lines through cross-border trade programs, and developing regional power markets and exchanges. On a micro-level, this could also include quality assurance and control standards.
- To achieve clean energy targets as mentioned in Pakistan's revised Nationally Determined Contributions (NDCs), there is a need to attract financing from international donors and build around funding opportunities such as Global Carbon Funds. As opposed to same financing terms and conditions, international communities, donors, banks, and multilaterals must differentiate between the financing schemes and have separate benchmarks for a coal and renewables-based project.
- Pakistan must develop plans to promote local manufacturing and transfer of technology as this would play a key role in easing and lowering the tariff of electricity.
- To upscale the adoption of renewable energy, policy makers can focus on revision of the Grid Code where Renewable energy projects can be brought under the "Must Run Projects" category.
- To provide an enabling environment to the private sector, government entities must develop a "Principal of Subsidiarity" where it should delicate what can be done efficiency at the consumer scale. Similar barriers and challenges must be addressed for the international and local investors by providing the ease of business.

Leading from this discussion, there is a considerable potential to design a model that also covers the cost of grid expansion and improvement. For future studies, there is also a need to design a shadow IGCEP which does not put a modeling constraint of committed projects. This would provide a much better renewable portfolio even till 2030. Since the capacity expansion plan of Pakistan is Indicative in nature, it might change in upcoming iterations. Along with a deterministic modeling approach (such as the one adopted in this study), there is a need to develop a model based on a Probabilistic modeling approach. Such modeling activities can further be expanded to cover other renewable energy sources such as Wind, biomass, or mini-micro hydro. This would provide a complete holistic picture of renewable energy landscape in Pakistan.

6. Conclusion

Through a deep dive into policy landscape and socioeconomics, this study has identified the major challenges and critical factors that play a leading role in upscale of renewables (particularly solar) in energy mix. The most critical factors that is hindering the growth of solar in generation mix of the developing countries is their committed projects and their long-term power purchase agreements. Fossil fuel projects (mainly coal) that started in the 21st century cannot be bought or decommissioned and till their commitments are not over, the power generation from these plants will remain online leading to increase in capacity payments. The second barrier for renewables capacity addition is its intermittent nature due to which the plants are not deemed suitable for base load requirements.

Therefore, despite being the cheapest source of energy, power evacuation capacity and existing grid infrastructure have limited the capacity of developing or under-developed countries to transition their power sectors. Same was the case of Pakistan where the recent Capacity Expansion Plan i.e., IGCEP was 88% committed in nature till 2030. Candidate projects barely constituted for 12% of capacity increase. Under such conditions, the Capacity expansion plans should incorporate benefits that are not priced such as use of indigenous resource, energy security, and carbon emission. In a least cost generation plan, renewables should have a level playing field and dispatch or distribution companies needs to bring transparency about how energy prices are set.

Once these challenges are removed, the economics of renewable energy is well suited for all countries to follow the global transition. On one hand where renewable energy is the most environment friendly alternative, it also makes the economic and social case for most countries through its low cost and resulting impact on the national GDP. This however requires policy support through ambitious but realistic targets, subsidies and incentives for RE generation and technology upscale, harmonization between federal and provincial governments, and ensuring a "just" transition pathway that caters for the need of both renewable and fossil fuel industry.

Conflicts of Interest: The Authors state that there is no conflict of interest.

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