MODELLING AND ANALYSIS

Long-term optimal power generation pathways for Pakistan

Sikander Ali Abbasi1 | Khanji Harijan2 | Muhammad Waris Ali Khan3 | Abdullah Mengal4 | Faheemullah Shaikh5 | Zubair Ahmed Memon5 | Nayyar Hussain Mirjat5 | Laveet Kumar2

Abstract
Pakistan has faced an electricity shortfall for over two decades despite various efforts taken at different levels. Though electricity supply in recent times has crossed the demand, the supply-side stresses and deciding optimal power generation pathways have always been a challenge for policymakers and researchers. In this study using a LEAP energy model, following the sectoral electricity demand forecast, four supply-side scenarios have been developed and analyzed for the study period 2017-2055. In each scenario, referred to as Business as Usual (BAU), Renewable Energy Technologies (RET), Coal Power Penetration (CPP), and High-Efficiency Low-Emission (HELE) scenario, electricity generation, installed generation capacity, cost of production, and GHG emissions are estimated and compared for seeking long-term optimal energy pathways for Pakistan. The study results reveal that for the end year (2055), RET is an environmentally sustainable scenario with an estimated electricity generation of 2421 TWh, which is enough to meet the electricity demand of 2374 TWh. The GHG emissions under the RET scenario are estimated to be 857 million metric Tons, which are around 50% less than CPP and 40% less than the BAU scenario. However, the cost of generation is higher than BAU and CPP scenarios. The CPP scenario emerges to be cost-competitive, however with the highest GHG emissions. This study thus suggests that convergence of RET with the CPP scenario could be an appealing option for Pakistan to meet increasing demand with energy security and environmental sustainability.

KEYWORDS
electricity demand forecast, electricity supply projections, GHG emissions, LEAP, Pakistan

1 | INTRODUCTION

A clean, affordable, and reliable electricity supply is crucial to economic growth, human development, and environmental sustainability. Pakistan, like many developing countries, is striving to attain self-sufficiency in power supply to meet its growing electricity demand. The regional electric power system has gained significant importance with the social-technical evolution of decentralized power systems.1 The poor planning and policy initiatives in the electricity sector have played a key role in augmenting the energy crisis in the country.2 Studies focusing on
the cost and benefits of the renewable resources for power generation lack environmental and externality cost estimation which makes Business as Usual scenario as a least-cost option in Pakistan. Pakistan is a country of 212 million people, with 21% of its population living below the poverty line. The population growth rate of Pakistan is about 1.9% while the per capita GDP is around 1482 US$. It is estimated that 51 million people in the country have no access to electricity. As such, the national electrification ratio is 71%. The country has witnessed prolonged power outages over the last two decades consistently experiencing a deficit of around 5000 MW of electricity. The electricity shortage did not appear suddenly. It is the result of weak energy policies coupled with institutional and governance failure. The situation was further aggravated by financial constraints, lack of transparency, and political will. With socioeconomic and sociopolitical uncertainties, the electricity demand could not be anticipated. During the last few years, the generation capacity surpassed the electricity demand however subsidy to consumers, high transmission, and distribution losses, flawed power policies have given birth to circular debt which is restricting power plants to generate rated power resulting in continuous power outages. In the total energy mix, renewable energy (RE) contributes only 3.9% against the country’s recent policies that aim to increase the share of the RE up to 30% by the year 2030. According to recent estimates, the global energy demand will increase by 28% between 2015 and 2040, with a growing share of developing countries. Unless this demand is made in significant part with renewable energy sources, this trend might constitute a threat to climate and energy security. Moreover, the economics of the RE sector has become more competitive with fossil fuels particularly oil, even if the oil prices fluctuate. The world economic forum reports that since 2010, the benchmark price for solar has dropped 84%, offshore wind by more than half, and onshore wind by 49%. The report highlights that new renewable power generation projects now increasingly undercut existing coal-fired power plants IRNA 2020 Pakistan’s dependence on natural gas for power generation also had reached an all-time high at 50.4%. In the year 2019, however, the reliance dropped to 34.6% in the wake of the decline in domestic gas deposits and consumption of Liquefied Natural Gas (LNG) since 2015. The share of imported LNG, as such, increased from 0.7% in the year 2015 to 8.7% in 2019. Nevertheless, the electricity generation sector in Pakistan is currently dominated by imported oil and natural gas. The total thermal share of electricity is 63.37%, followed by hydro, nuclear, and renewables as 28.00%, 3.88%, and 4.45%, respectively, as shown in Figure 1. According to the Pakistan Economic Survey 2018-19, the installed electricity generation capacity reached 34,282MW in 2018-19 compared with 33,433MW in the corresponding period of the previous year, recording a growth of 2.5%.

Electricity generation, however, varies due to the availability of input and other constraints; as such, the same has only increased from 85 552 GWh in 2017-18 to 87 324 GWh in 2018-19 with a growth of 2.1%. The share of hydropower in the generation mix of Pakistan has declined from 51% in 1985 to 26% in the year 2017. The decreased share of hydropower in the total energy mix is the result of a misunderstanding between the provinces about water distribution, the shortsightedness of policymakers, and fiscal constraints. To enhance energy security, Pakistan is also aiming to utilize indigenous coal for electricity generation; however, this trend is against the global transition of encouraging the utilization of carbon-neutral technologies. It is also a matter of fact that the per capita electricity consumption of the country is lowest compared with many neighboring countries such as India, Iran, and Sri Lanka. As per World Bank report (2014), Pakistan’s per capita electricity consumption is only 448KWh. The electricity consumption of India, Iran, and Sri Lanka is 805 KWh, 3022 KWh, and 531 KWh, respectively. The world average electricity consumption is also sufficiently higher and reported to be 3132 KWh. This severely low per capita consumption is alarming and highlights that Pakistan is lagging in electricity consumption by all sectors. With increased population, urbanization, and anticipated growth of the economy, it is anticipated that electricity demand will increase many folds in the future.

Many studies have been conducted in developing as well as developed world regarding demand and supply-side projections using LEAP model such as Venezuela, Panama, Pakistan, India, Nigeria, Iran, Indonesia, China, Africa, and South Korea. While each of these studies has applied the LEAP model as the primary accounting and scenario management tool, their
perception, choice, and data methodology differ. Each study examines the energy system in a different country with distinct energy system data and under different scenarios. As such, all such studies vary in scope, targeting either the city or countrywide energy system, and include either a specific part or whole integrated supply and demand system. All above studies have applied LEAP for sectoral electricity demand forecast, whereas this study has covered sectors with their sectoral GDP and subsectors (end users) so that electricity growth trend can be identified at the receiving end. On the supply side, three important aspects such as use of high-efficiency low-emission technologies in fossil fuel power plants and coal deployment in CPEC projects have been modeled to compare the reliability, cost-effectiveness, and environmental sustainability of supply side. In the backdrop of the global energy transition from fossil fuels to renewable energies, Pakistan’s move to coal and RE simultaneously display conflicting perspectives and this is the motivation of this study to examine how the energy landscape of the country would look like on a long-term horizon.

This study thus has attempted to forecast long-term sectoral electricity demand to investigate the sectoral growth pattern. Long-term power generation projections with alternative scenarios are made to seek optimal energy pathways for Pakistan. The development of alternative scenarios is based on emerging developments in Pakistan that provide interesting and contrasting generation pathways between electricity availability, cost of electricity, and environmental sustainability. Moreover, the results provide choices for careful selection and decision on the part of policymakers to formulate sustainable and optimal electricity generation pathways for Pakistan.

To attain this objective, the structure of this paper follows such that section 2 discusses the methodology used in the electricity demand forecasting and generation projections. The scenario development is presented in section 3. Results and discussion are presented in section 4, while the conclusions of the study are contained in section 5 of the study.

2 | METHODOLOGY

LEAP energy model is employed in this study for the forecast of long-term sectoral electricity demand and generation projections for the study period 2017-2055. LEAP energy modeling framework has been developed by the Stockholm Environment Institute and is widely used for power sector scenario analysis. Since it is an integrated model that can be used to track energy consumption, production, and resource extraction in all sectors of an economy, supports bottom-up macroeconomic modeling of demand and its functions support a long-range projection and analysis. On the supply side, it provides a range of accounting and simulation methodologies for modeling electricity generation and expansion planning. In this study, the demand-side data are structured based on sectors (domestic, industrial, commercial, agriculture, and others). The key parameters such as population growth, number of households, household size, number of consumers, urbanization, and GDP of each sector are considered in LEAP. The LEAP methodological framework for electricity demand is shown in Figure 2. The GDP of each sector is considered as per base year (2017) data. However, the summative GDP of 11 years is considered in key assumptions. The consumer growth rate of domestic and industrial is taken as 4.1% and 3.1% respectively followed by agriculture, commercial, and others as 5.42%, 2.1%, and 5.33%. This study, as such, is the first to deliberate RE policy 2019 and coal in focus as enunciated by CPEC energy projects. Secondly, the supply-side projections are made on a long-term basis.

Key assumptions and model input parameters for electricity demand are given in Table 1.
2.1 | Key assumptions

The basic assumptions considered in the electricity supply model are given in Table 2.

In addition to the above, Table 3 provides the various input parameters employed in this study model which include power generation capacity of each generation method, installed generation capacity, the amount of fuel consumed, electricity generated alongside fixed and variable costs as well as efficiency, availability in percentages, lifetime, and merit order for the base year (2017).21-23 It is pertinent to mention that the electricity generation in 2017 was 94.8 TWh which is just 6% of projected electricity generation (2374 TWh) in 2055.

It is pertinent to mention that the biomass power generation is negligible and not connected to the national grid; therefore, fuel consumed is not provided in Table 3.

The model input parameters and adopted power generation technologies in Pakistan (Table 3 and Table 4) were used in the model to project power generation up to the year 2055 (end year) under various scenarios. The following section elaborates study scenarios with main resources considered and various policy narratives.

3 | Scenario Accounts

An energy scenario refers to a set of energy pathways that are purposefully designed to address a specific policy narrative. The objective is to highlight the effects of the various scenario accounts. Through the process of developing calculated scenarios, and measuring the scenario results, different narratives would generate new understandings that can enable electricity planning more appropriately.

In this study, the reference scenario of demand forecast and four supply-side scenarios have been enacted to project demand and supply for the study period (2017-2055). The four supply scenarios illustrate official policy and policy interventions. The further explanation of supply scenarios is explained in Table 5 and sections 3.2.1 to 3.2.4.

3.1 | Demand forecasting

3.1.1 | Business as usual (BAU) scenario

The business-as-usual scenario reflects government policy without policy intervention. GDP, number of electricity consumers, population growth, number of households, household size, and rate of urbanization have been applied in LEAP to project the sectoral demand for electricity up to the year 2055. It is worth mentioning that a demand forecast has been made on the electrified households, and it is noted that the remaining non-electrified population is in remote areas which are opting for solar power on account of governments reluctance to connect them through the national grid.

3.2 | Supply projections

The summary account of four supply-side scenarios is given in Table 4.
Further explanation of the above scenarios follows as under:

3.2.1 | Business as usual (BAU) Scenario

It is assumed that power capacity additions will be implemented as per government plans without any policy interventions. In this scenario, source-wise capacity addition is considered as planned by the government of Pakistan under CPEC, Indicative Generation Capacity Expansion Plan (IGCEP), National Power System Expansion Plan (NPSEP, 2011), and Vision 2025. Existing oil-based power plants will retire, and no new oil-based power plants will be added after 2030.

3.2.2 | Renewable energy technology (RET) scenario

RET scenario portrays the government’s effort to increase the share of renewable in the total energy mix. As per the plan, Pakistan intends to add a 30% share of renewable by 2030. To effectively increase the share of renewable energy, the resource potential of RE present in the country, and alternative and RE policy 2019 have been considered.

3.2.3 | Coal power penetration (CPP) scenario

Pakistan has discovered vast reserves of 175 billion tons of lignite coal in the Sindh province of Pakistan. The country intends to exploit this coal to increase power generation in the total energy mix. Under the plan, Pakistan aims to increase coal-based electricity up to 18% by 2025. Various priority projects based on imported coal under CPEC are in the execution phase or the planning phase. All such initiatives by the government of Pakistan have been considered in this scenario.

3.2.4 | High-efficiency low-emission (HELE) scenario

Pakistan aims to add coal power generation to the total energy mix in the coming years, since coal power generation has substantial environmental consequences. Therefore, in the HELE scenario, it is assumed that high-efficiency low-emission technologies in coal-based power plants can reduce GHG emissions and increase the efficiency of the power plants. Three technologies, such as
supercritical with Carbon Capture and Storage (CCS), ultra-supercritical, and Integrated Gasification Combined Cycle (IGCC), have been considered in this scenario.

The modeling results for each of these scenarios for the considered parameters, that is, electricity generation, installed generation capacity, cost of production, and GHG emission are provided in the proceeding section.

4 | RESULTS AND DISCUSSION

The results of this study are organized as a sectoral demand-side projection under the reference scenario and four supply-side scenarios, which include electricity generation, installed capacity, cost of electricity production, and GHG emissions. The electricity demand projections by sector are made with LEAP, as shown in Table 5.

### 4.1 | Demand-side projections

Electricity consumption in the base year (2017) was 94.8TWh. The final electricity demand is estimated to be 2374TWh under the business-as-usual scenario in 2055 (end year).

The demand projections from 2017 to 2055 undertaken using the LEAP model are shown in Figure 3. The electricity demand in the domestic sector is expected to increase 23-fold. The 34-fold increase in electricity is anticipated in commercial sector during the study period (2017-2055). A 20-fold increase in electricity is projected in the agriculture sector during the study period. In the industrial sector, a 25-fold increase is estimated from the base year to the end year. The annual growth rate of electricity demand for the study period is estimated to be 8%. Manifold increase in electricity demand is attributed to moderate

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**TABLE 4** Summary of supply-side scenario alternatives

| Scenario | Focus | Main resources |
|----------|-------|----------------|
| BAU      | In this scenario, official policy is followed | As per official policy |
| RET      | Renewable energy technologies are added as per renewable energy policy 2019 and the resource potential of RE | Hydro, solar, wind, and biomass |
| CPP      | Indigenous coal and imported coal are preferred | Indigenous coal and imported coal |
| HELE     | Modern technologies (supercritical with CCS, ultra-supercritical, and IGCC) in coal-fired power plants are considered. | Indigenous and imported coal |

**TABLE 5** The sector-wise electricity demand, (TWh) (2017-2055)

| Category | 2017 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 | 2055 |
|----------|------|------|------|------|------|------|------|------|------|
| Domestic | 48.0 | 61.5 | 92.8 | 140.2 | 211.9 | 320.0 | 483.4 | 730.3 | 1103.1 |
| Commercial | 7.9 | https://doi.org/10.4 | 16.5 | 26.3 | 41.9 | 66.8 | 106.3 | 169.3 | 269.5 |
| Agriculture | 9.2 | 11.7 | 17.4 | 25.8 | 38.3 | 56.9 | 84.4 | 125.4 | 186.2 |
| Industrial | 24.0 | 31.0 | 47.5 | 72.7 | 114.4 | 170.6 | 261.3 | 400.2 | 613.0 |
| Others | 5.7 | 7.6 | 12.2 | 19.4 | 31.1 | 49.6 | 79.3 | 126.8 | 202.6 |
| Total | 94.8 | 122.2 | 186.4 | 284.5 | 434.5 | 663.9 | 1014.8 | 1551.9 | 2374.4 |

**FIGURE 3** Electricity demand forecast (2017-2055)
GDP, an increase in the population, rapid urbanization, improved living conditions, infrastructure development, and industrialization. All the supply-side scenarios are subsequently developed to examine the growing trend of electricity supply under various assumed conditions.

4.2 | Supply-side projections

In supply-side projections, the electricity generation, cost of production, and GHG emissions of all scenarios are provided and discussed in the following sub-sections.

4.2.1 | Business as usual (BAU) scenario

Electricity generation

In the BAU scenario, the total electricity generation is projected to be 2382.3 TWh in 2055. The share of oil in the electricity generation mix in 2017 was 29.9%, (35.4 TWh) which will be exterminated to 0% by the year 2030 and onwards as per the government policy. The share of hydro in 2017 was 29.3% (34.6 TWh) which is projected to be 16% (383 TWh) in 2055. The nuclear share in 2017 was 3.9% (4.6 TWh) and is anticipated to be 5.2% (123 TWh) in 2055. The share of coal, natural gas, and biomass in 2017 was 0.2% (0.1 TWh), 35% (41.4 TWh), and 0.5% (0.6 TWh), respectively. In 2055, the share of coal, natural gas, and biomass are expected to be 27.4% (652 TWh), 42.4% (1010 TWh), and 0.9% (22 TWh), respectively. Similarly, the share of wind and solar power in 2017 is 1.09% (1.3 TWh) and 0.1% (0.2 TWh), respectively, while their share in 2055 is projected to be 5% (119 TWh) and 3.03% (72.4 TWh), respectively. The source-wise electricity generation projections from 2017 to 2055 are shown in Figure 4.

Installed capacity

The installed generation capacity of oil, hydro, nuclear, and coal in 2017 was 6.8 GW (26%), 7.1 GW (27%), 0.8 GW (3%), 1.5 GW (5.7%), respectively, whereas the installed generation capacity of natural gas, biomass, wind, and solar in 2017 was 8.9 GW (34.2%), 0.1 GW (0.38%), 0.7 GW (2.6%), and 0.4 GW (1.5%), respectively. In the end year (2055), the installed capacity of oil is zero as the government plan to close oil-based power generation after 2030. The installed capacity of hydro, nuclear, coal, and natural gas is anticipated to be 52.4 GW, 18.7 GW, 108.5 GW, and 210.5 GW, respectively in 2055. The generation capacity
of biomass, wind, and solar is projected to be 0.1 GW, 0.7 GW, and 0.4 GW, respectively. The overall installed capacity in BAU scenarios is estimated to be 478 GW in end year. The installed capacity of the power generation mix in the BAU scenario is given in Figure 5.

**Cost of production**

The production cost covers capital cost, fixed and variable maintenance, and operational costs. In the BAU scenario, the cost of production in 2017 was 1 billion US$. The cost of production in 2055 is estimated to be 65.7 billion US$. The share of capital cost in 2055 is 41 billion US$ (62%), followed by fixed O&M costs of 17.9 billion US$ (27.2%) and variable O&M costs of 6.8 billion US$ (10.3%). The cost of production in the BAU scenario is shown in Figure 6.

**GHG Emissions**

In the BAU scenario, the GHG emissions of oil, coal, and natural gas were 32.1 and 0.2 and 18.1 million metric tons of CO$_2$ equivalent in the base year. The total GHG loadings were 50.5 million metric tons of CO$_2$ equivalent in 2017. The GHG emissions of coal and natural gas are anticipated to be 998.6 and 440.9 million metric tons of CO$_2$ equivalent respectively in 2055. The total GHG emissions are expected to be 1439.4 million metric tons of CO$_2$ equivalent at the end year. The considerable increase in GHG emissions is attributed to the rapid additions of coal-fired power plants under CPEC and the use of natural gas during the study period. The GHG emissions in the BAU scenario are shown in Figure 7.

### 4.2.2 Renewable energy technologies (RET) scenario

**Electricity generation**

RET scenario portrays the government’s effort to increase the share of renewable in the total energy mix. As per the plan, Pakistan intends to add a 30% share of renewable by 2030. To effectively increase the share of renewable, the government of Pakistan has announced an alternative and renewable energy policy, 2019, which
encourages private investors to invest in wind and solar projects. In this scenario, the same growth trend of renewable power after 2030 has been considered for electricity supply projections up to the year 2055 (end year). Similar growth has been considered based on RE prices which are becoming competitive with fossil fuels in the coming years. The electricity generation projections are shown in Figure 8.

The total electricity generation is projected to be 2421 TWh in 2055. In the RET scenario, the share of hydro and nuclear is anticipated to be 13.3% (322 TWh) and 10% (264 TWh), respectively. The share of coal, natural gas, and biomass is projected to be 18% (443 TWh), 17% (410 TWh), and 1.5% (36.7 TWh), respectively. The share of wind and solar is estimated to be 21% (503 TWh) and 18% (440 TWh), respectively. It is pertinent to note that the share of renewable in 2017 was 1.8% which is anticipated to be 40.5% in 2055. The electricity generation is projected to grow at 8% annually with a 20-fold increase in electricity generation in the end year.

**Installed generation capacity**

In the RET scenario, the total installed capacity from all sources in 2055 is estimated to be 688.4 GW from 26.2 GW in 2017. The installed capacity of wind, solar, and biomass is projected to be 171.4 GW, 287.8 GW, and 5.2 GW respectively in 2055. The installed generation capacity of hydro, nuclear, coal, and natural gas is anticipated to be 43.5 GW, 40.6 GW, 70.3 GW, and 69.5 GW, respectively. Renewable energy would play a significant role in the end year. The higher value of installed capacity is attributed to the low-capacity factor and intermittent nature of renewable energy. The projections of installed capacity from 2017 to 2055 in the RET scenario are shown in Figure 9.

**Cost of production**

The production cost in the RET scenario was 1 billion US$ in 2017, which is estimated to be 81.5 billion US$ in 2055. The cost of this scenario is 16 billion US$ higher than the production cost of BAU scenarios. The higher cost is the result of the high initial investment cost of wind turbines and low plant capacity factor owing to its intermittency in nature. With these limitations, the large power plant size and higher installed capacity will increase the overall cost of production. However, the cost is calculated on the base year price, which is bound to come down; therefore, the actual cost of the RET scenario in the end year will be much less than anticipated.
In the RET scenario, it is assumed that alternative and renewable energy policy 2019 and utilization of resource potential shall be implemented. The culprits of GHG emissions in the RET scenario are coal and natural gas power plants. The GHG emissions of coal and natural gas are anticipated to be 677.9 and 179.3 million metric tons of CO₂ equivalent, respectively, in 2055. The total GHG emissions are projected to be 857.1 million metric tons of CO₂ equivalent at the end year. There is a 40% reduction in GHG emissions in RET compared with the BAU scenario. Such profound reduction can help achieve environmental sustainability in the power generation sector of the country. The GHG emissions from 2017 to 2055 are shown in Figure 10.

4.2.3 Coal power penetration (CPP) scenario

Electricity generation
The electricity generation projections in the CPP scenario are shown in Figure 11. The CPP scenario depicts the government’s intentions to utilize indigenous coal for attaining self-sufficiency in electricity generation. The government intends to attain an 18% share of coal in the total energy mix by 2025. China Pakistan Economic Corridor (CPEC) energy projects would also run on imported coal. Under this scenario, the total electricity generation mix is projected to be 2491.6 TWh in 2055. The share of coal in the end year is estimated to be 33% (824 TWh) in the total energy mix of Pakistan. This substantial share would lessen the burden of imported oil and enhance the energy security of the country. However, there would be a substantial increase in GHG emissions at the end year. The share of hydro, nuclear, and natural gas is projected to be 13% (325 TWh), 3% (74 TWh), and 42% (1057 TWh), respectively. As such, the share of biomass, wind, and solar is anticipated to be 1% (23 TWh), 4.6% (116.2 TWh), and 3% (70.8 TWh) respectively in 2055.

Installed generation capacity
The installed generation capacity projections from 2017 to 2055 in the CPP scenario are shown in Figure 12. The total generation capacity in 2055 is estimated to be 457 GW.
The highest share is from natural gas with 187.4 GW (41%) followed by coal with 128.7 GW (28%). Such a substantial share of coal reflects the government’s vision to penetrate coal power under CPEC power projects and utilization of indigenous coal of Thar. The share of hydro and nuclear is estimated to be 43.7 GW and 11.3 GW, respectively. The share of wind, solar, and biomass is projected to be 37.9 GW, 44.9 GW, and 3.3 GW, respectively. The total share of renewables exclusive of hydro is 18% of the total installed capacity of the country in 2055.

Cost of production
In the CPP scenario, the production cost is estimated to be 65.1 billion US$ in 2055. The share of the capital cost is 39.4 billion US$ (60%), whereas the cost of fixed and variable operating and maintenance costs are projected to be 18.4 (28%) and 7 billion US$ (10.7%), respectively in 2055. The cost of production is less compared with other scenarios as the initial investment cost, and fuel cost is less than the other sources of electricity generation. The cost of production from 2017 to 2055 is shown in Figure 13.

GHG emissions. In the CPP scenario, it is expected that many imported and indigenous coal-fired power plants will be commissioned in the country. Since coal-fired plants are carbon-intensive, therefore they will emit more GHG emissions. In this scenario, the GHG emissions of coal and natural gas are projected to be 262 and 461.5 million metric tons of CO₂ equivalent, respectively in 2055. The total GHG emissions are estimated to be 1723.5 million metric tons of CO₂ equivalent at the end year. 284 million metric tons of CO₂ more emissions are projected in CPP compared with the BAU scenario. The GHG emissions (2017-2055) are shown in Figure 14.

4.2.4 | High-efficiency low-emission (HELE) scenario

Electricity generation
In 2011, roughly half of all new coal-fired power plants used HELE technologies in the world, mainly supercritical and ultra-supercritical coal combustion units. However, about 75% of all operating units today use non-HELE technology. In the HELE scenario, the electricity generation projections are estimated to be 2404 TWh in 2055. The share of hydro, nuclear, and coal is anticipated to be 14.6% (351.8 TWh), 4.7% (113.4 TWh), and 25.4%
(609.6 TWh), respectively. As such, the share of natural gas, biomass, wind, and solar would be 42% (1009.9 TWh), 1.0% (23.4 TWh), 5.3% (128.5 TWh), and 3.1% (75.5 TWh) respectively, since high-efficiency low-emission technologies such as supercritical with CCS, IGCC, and ultrasupercritical have been supposed to be employed in the future when economics dictates. Since these technologies are expensive, therefore their share is low and is estimated to be 0.5% (14.4 TWh), 1.4% (936 TWh), and 1.7% (42 TWh), respectively. The electricity generation projections from all sources are shown in Figure 15.

**Installed generation capacity**
The installed generation capacity in the HELE scenario was 26 GW in 2017, and it is anticipated to be 503 GW in 2055. The year-wise projections from 2017 to 2055 are shown in Figure 16. The highest share is from natural gas 210.5 GW (42%) followed by coal 100.3 GW (25.4%).
share of hydro, nuclear, and biomass is 47.8 GW (14.6%), 17.7 GW (4.7%), and 3.3 GW (0.9%) respectively. As such, the share of wind, solar, supercritical with CCS, IGCC, and ultra-supercritical are projected to be 41.9 GW (8.3%), 47.9 GW (9.5%), 8GW (1.5%), 12 GW (2.3%), and 14 GW (2.7%), respectively. The installed generation capacity of the HELE scenario is higher than BAU, and CPP scenarios, however 165 GW less than the RET scenario. The installed capacity from 2017 to 2055 is shown in Figure 16.

**Cost of production**
The production cost in the HELE scenario is estimated to be 73.6 billion US$ in 2055. The capital cost is projected to be 48.1 billion US$, which is 65% of the total cost. The share of fixed and variable O&M costs is 18.3 billion US$ (24.8%) and 7.2 billion US$ (9.7%), respectively, at the end of, year. The cost of production under the HELE scenario is highest compared with BAU and CPP scenario; however, it is less than the RET scenario. The cost of production is shown in Figure 17.

**GHG emissions**
HELE scenario depicts the deployment of high-efficiency low-emission technologies in coal-fired power plants to reduce emissions and enhance efficiencies. Supercritical with CSS, ultra-supercritical, and IGCC technologies have been considered. In this scenario, the GHG emissions of coal, natural gas, supercritical with CSS, ultra-supercritical, and IGCC are anticipated to be 522.3, 246.9, 6.7, 19.6 million metric tons of CO₂ equivalent, respectively. The total GHG emissions are estimated to be 795.5 million metric tons of CO₂ equivalent in 2055. By deploying these modern technologies, a 50% reduction of GHG emissions can be achieved compared with the BAU scenario. The GHG emissions (2017-2055) are shown in Figure 18.

### 4.2.5 Cost analysis

This study has calculated the NPV cost of all scenarios at various discount rates of 5%, 7%, and 10%, as shown in Figure 16. Since a 5% discount rate is nearer to the announced rate of the State Bank of Pakistan therefore, the NPV cost of this rate has been considered in the cost analysis. The NPV at all discount rates is shown in Figure 19.

It is found that the CPP scenario has the lowest cost with 271 billion US$ compared with BAU, RET, and HELE.
scenarios with 320, 341.8, and 357.7 billion US$, respectively. The NPV of the CPP scenario is lowest under all three discount rates. This low value of the CPP scenario is attributed to the low capital, fixed, and variable O&M cost of coal-fired power plants. The summary results of all scenarios are given in Table 6.

From Table 7, it is observed that the electricity generation projections of this study are comparable with other studies conducted in Pakistan. One of the studies has projected the power generation up to the year 2050 as 1706 TWh which is comparable with this study with 1730 TWh. No other study has projected electricity generation beyond 2050.
Pakistan has made modest economic progress over the last two decades which has resulted in a substantial increase in electricity demand. To estimate the electricity demand, sectoral electricity demand has been forecasted from 2017 to 2055 with LEAP. The electricity consumption in the base year was 118TWh which is projected to be 2374 TWh in 2055. The electricity demand has shown 8% growth annually with a 20-fold increase in the end year. Electricity generation, installed generation capacity, cost of production, and GHG emissions of each supply scenario have been projected up to the end year. The results revealed that under all scenarios, the generation projections will meet the anticipated electricity demand at the end year. In the BAU scenario, with 2382 TWh of electricity generation, the GHG emissions are estimated to be 1444 million metric tons of CO₂ eq with a modest cost of 65.7 billion US$ in the end year. The NPV cost with a 5% discount rate is calculated to be 320.5 billion US$. In the RET scenario, the electricity generation is projected to be 2421 TWh with GHG emissions of 857 million metric tons CO₂ eq which is 40% less compared with BAU and 50% less compared with the CPP scenario. The substantial decrease in GHG emissions will improve the environmental sustainability of the power system. However, the cost of production is 81.5 billion US$ which is higher than all other scenarios. The NPV cost of the HELE scenario is anticipated to be 357.7 billion US$. From the results of various scenarios, it is revealed that RET and CCP have contrasting performances from an economic and environmental point of view. The financial performance of RE has a critical influence on the future development of the RE sector as profitability is related to their success in attracting private investment for infrastructure development. However, the cost of RE is continually falling; therefore, the ultimate cost is expected to be competitive than anticipated at the end year. Coal on the other hand has less production cost owing to the abundance of the indigenous resource. The NPV analysis recommends the CPP scenario compared with all other scenarios. With the results obtained and comparing all the scenarios, it is established that electricity demand will continue to grow with around a 20-fold increase due to societal, economic, and demographic changes undergoing in Pakistan. Secondly, any single scenario on the supply-side does not fulfill the objectives of affordable, reliable, and sustainable power supply to consumers on a long-term basis. Therefore, the merger of RET and CPP scenarios can provide an optimal energy pathway for Pakistan to meet the future needs of electricity.

CONFLICTS OF INTEREST
The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

ORCID
Faheemullah Shaikh https://orcid.org/0000-0003-4469-828X
Laveet Kumar https://orcid.org/0000-0001-6932-1695

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