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Modeling of Electrical Grid Systems to Evaluate Sustainable Electricity Generation in Pakistan

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MODELING OF ELECTRICAL GRID SYSTEMS TO EVALUATE SUSTAINABLE ELECTRICITY GENERATION IN PAKISTAN

A Thesis Presented

by

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ABSTRACT

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Pakistan has always had a history of severe energy shortfalls, which rose up to an alarming 33% in 2013. This situation was countered by investments in the energy sector through the China Pakistan Economic Corridor (CPEC), which were unfortunately largely based on brown fuels. Although beneficial in the short term, these investments do not bode well for the climate scenario of Pakistan, with various parts of the country already having experienced temperatures rise of 1-3°C. To ensure that the current situation doesn't exacerbate and is tackled in a timely manner, this research aims to examine how the untapped potential of renewable energy in Pakistan can be better utilized by modelling the entire electrical grid system for multi-portfolio based sustainable electricity generation, in line with the sustainable development goals chalked out by Pakistan with the United Nations (UN). Delving further into the matter, a gap is observed that demands coalescence between sustainability and portfolio-based generation in the context of Pakistan, since the prevalent narrative is of Business As Usual (BAU). The research methodology implemented is a cross sectional case study employing qualitative and quantitative data collection methods and outcomes, in which the entire grid system of Pakistan is studied and sustainability metrics are defined; followed by a comprehensive use of Multi-Criteria Decision Methodology in decision making process. Portfolios defined are a combination of different generation technologies, each simulating a possible avenue of policy, and are then evaluated for a range of sustainability metrics to understand the tradeoffs involved to arrive at a set goal. The process decision framework developed shall enable the Pakistani energy sector in meeting the energy demands by providing the decision-makers with various routes to do so, while informing on the sustainability impact of their decisions.

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CHAPTER 1

INTRODUCTION

The purpose of this research is to introduce a multi criteria decision analysis-based framework for sustainable energy production for Pakistan, in line with the UN Sustainable Development goals of clean energy production and climate change.

Through this research we design an electricity model for Pakistan, which evaluates viable alternatives for tackling the country's energy deficit in a sustainable manner. Taking into consideration pertinent policy opinions, we define a set of generation portfolios that can serve as alternatives to the current Business as Usual scenario and act as a viable alternative to the coal-dominated CPEC projects. Using the country's enormous renewable potential and changing stakeholder behavior towards climate change, we define and evaluate energy alternatives with high amount of solar and wind energy in the mix as opposed to the coal-oil nexus currently dominating the generation mix of the country. Using Multi Criteria Decision Analysis, we then analyze different possible energy futures with respect to economic, social, technical, environmental and societal factors.

Pakistan is situated in the heart of South Asia, with an area of 341,000 sq. miles and a population that exceeds 200 million. An agriculture-based economy, Pakistan is heavily reliant upon conventional energy generation sources to meet its electricity demands, which stand at 35,000 MW as of 2019. Being a developing country, Pakistan has been experiencing a constantly increasing energy shortfall issue, mainly due to ever increasing demand and less than adequate investment in energy sector. In 2012, the average shortfall hit a record high of 7000 MW; however, it kept hovering in the 4000MW-6000MW zone otherwise. The shortfall had disastrous impacts on the economic and social development, which led the government to make shortfall reduction a priority. With the main sources of power being two hydropower dams built in 1970s, Pakistan's energy mix comprises oil (diesel, HFO etc.), LNG, natural gas, coal, nuclear energy and hydropower. Recently, natural gas took precedence and the fast depleting reserves made the government enter into a 15-year LNG import agreement with Qatar in which 3.75 million tonnes of liquefied natural gas will be supplied annually. In addition to that, Oil has taken up 36% of the total share which has drastically impacted the climate, as well as the country's economy due to volatile international markets and trade deficits.

With the growth in industrial sector, the energy sector has experienced an increase of 5% in demand [1]. From 2000 to 2015, there has been a compound annual growth of 4.6% of energy consumption in the power sector of the country. Similarly, the country's GDP is expected to grow at a rate of 5% due to rapid industrialization, inducing ever-growing energy needs [2]. Similar to other developing countries, the socio-economic development of Pakistan is strongly associated with energy access [3]. About 25% of the current population (207 million) remains without access to electricity, of which 80% are above the poverty line who could conceivably pay for electricity but do not have access due to structural issues [4]. The difficulty in access to modern energy adversely affects literacy rate, health services, development of inclusive societies, educational advancements and sustainable growth of the country.

Although Pakistan is one of the lower contributors to the global greenhouse gas (GHG) emissions, the Global Climate Risk Index has placed Pakistan on the fifth spot on the list of countries most vulnerable to climate change in its annual report for 2020 [1]. The report also states that the country has lost 9,989 lives, suffered economic losses worth $3.8 billion and been witness to 152 extreme weather events from 1999 to 2018. Moreover, it is one of the few unfortunate nations, which face a disproportionate burden of the threats posed by climate change, contributing only 0.90 metric tons of CO2 per capita [6], while being ranked 5th amongst the countries most vulnerable to the impacts resulting from it. The country's largest sources of emissions are energy (45.8%), agriculture (43.5%), and industrial applications (5.2%) [8]. The emissions have been reportedly increasing at an annual rate of six percent, or 18.5 million tons of carbon dioxide (CO_2) equivalent. Moreover, the country lacks technical and financial resources to combat the adverse impact of climate change which would have serious implications on Pakistan's water, food, health, and environment.

A World Bank report focusing on South Asia's Climate Hotspots relates that national temperatures in Pakistan are already above their optimal values, southwestern Pakistan having experienced one of the largest increases in the regions, with annual average temperatures rising by 1.0°C to 3.0°C (1.8°F to 5.4°F) from 1950 to 2010 bearing some serious implications for the country's agricultural productivity and livelihood standards.

A recent study carried out at Duke University estimates the CO2 emissions from new energy projects to be developed under the China Pakistan Economic Corridor (CPEC) to be about 51 million metric tons annually; a figure that doesn't bode well for the 20% emission reduction targets set by Pakistan as its Nationally Determined Contribution (NDC) to the Paris Agreement. Furthermore, the government's plan to generate 18000 MW of renewable energy by 2030 is in direct conflict of the more than 5000 MW capacity coal fired projects in the pipeline.[2]

In comparison, the renewable potential of the country holds a lot of promise and the development of these distributed energy sources could be the solution our policy makers should be focusing on. Citing the Alternative Energy Development Board, Pakistan has an estimated annual solar potential of 2.9 million MW, a wind energy potential of 340,000 MW and another 100,000 MW of generation potential from untapped hydropower resources.[3].

It is therefore vital that this immense potential for clean energy be utilized in combination with other energy sources to arrive at the optimal energy mix which is both economically and environmentally viable. In light of the aforementioned, the usage of renewable energy resources for meeting energy demands becomes a necessity.

CHAPTER 2
LITERATURE REVIEW

In this section we conduct a systematic literature review starting with sustainability and its definition, possible sustainability metrics and indicators to be used in energy evaluation and its modelling, and multi criteria decision making analysis techniques and its implementation. Then we discuss the usage and efficacy of Business as Usual as a base energy scenario in Section 2.2. The structure of the Electricity Sector in Pakistan, including generation, transmission, distribution and retail are detailed in Section 2.3. Section 2.4 discusses existing literature regarding sustainability metrics and portfolio-based generation in Pakistan, thereby validating the existing research gap.

2.1 Multi-Criteria Decision Making Methodology

The Brundtland Commission Report [9] defines sustainability as “Ability to meet needs of the present without compromising the ability of future generations in meeting their needs”. After United Nation’s sustainable development goals and signing of Paris Climate Change agreement [10], countries around the world have started working on increasing the efficacy and sustainability of their electricity systems, particularly focusing on employing renewable energy techniques for environmental protection. However, evaluating the sustainability metric is an uphill task that carries a lot of qualitative and quantitative factors, which are involved in decision making process. With the increase in complexity of decisions, the difficulty of sustainability metric in choosing optimized solution increases progressively. Delving into the literature, it was seen that although there are a lot of authors that have recommended the need to identify sustainability indicators, there has been a limited number of studies regarding their mathematical modeling [11].

Energy evaluation is a layered activity that contains various social, economic, political and environmental factors that are both qualitative and quantitative in nature. While looking at it from a sustainability perspective, the foremost task is to determine the indicators, which not only should be holistic in nature; but also cater to the interaction of the associated subsystems. [12]

Kaya and Kahraman [13] suggest that in some energy studies, the MCDM evaluation criteria was used and the factors considered are given as follows:

- Technical issues such as efficiency of the energy system, the energy ratio, reliability and safety of the system
- Economic issues which include capital investment, operational and maintenance cost, payback period, useful service life etc.
- Environmental issues such as oxides of Carbon, Nitrogen and Sulphur, particulate emission, pollutants, land deterioration, noise etc.
- Social issues such as benefits, creation of new jobs, acceptability etc.

Lior [14] remarked that sustainability of a system hinges on diversification of the energy sources so that environmental performance can be ensured. Moreover, the author seconded the idea of defining a sustainability indicator, which includes social, economic, environmental and technical factors; since the energy systems are generally large and complex in nature.

Afgan, et al. [12] and Begić and Afgan [15] in their research works selected the energy indicators by taking into account the actual system values and the variables were calculated under different weighing scenarios. It can be seen from the literature that MCDM technique has been extensively used in context of energy issues, as indicated by Zhou, et al. [16], Wang, et al. [17]. The latter proposed the idea of grouping the problems into social, economic, environmental and technical factors.

A comparison between social, economic, environment and technical cost of small scale energy technologies to a larger scale alternative was conducted by Burton and Hubacek [18]. Afgan, et al. [19] assessed the use of natural gas in energy sector. Techniques of axiomatic design and AHP were used by Kahraman, et al. [20] in the selection of the most appropriate renewable energy variable in a fuzzy environment. Furthermore, Kaya and Kahraman [13] used fuzzy AHP and another method known as VIKOR (Multicriteria Optimization and Compromise Solution) in planning renewable energy combinations, followed by San Cristóbal [21] in form of fuzzy VIKOR.

In energy sector, there are numerous studies in literature related to the implementation of MCDM. One of the earliest studies related to energy planning on a multi-criteria basis is presented by Hämäläinen and Karjalainen [22], in which AHP was used to examine the weightage of evaluation criteria in Finland's context. In context of Greece, the use of MCDM was proposed by Georgopoulou, et al. [23] in energy planning issues, along with the usability of ELECTRE III technique. In case of geothermal energy production, the energy evaluation and ranking was done using a fuzzy extension of PROMETHEE method by Goumas and Lygerou [24]. Beccali, et al. [25] present an application of ELECTRE method to assess an action plan for the diffusion of renewable energy technologies at regional scale. Haralambopoulos and Polatidis [26] propose the use of PROMETHEE II in renewable energy projects and apply the decision framework to a geothermal resource usage case in Chios island.

Patlitzianas, et al. [27] propose an integrated approach regarding the suitability of multi-criteria methods in the context of renewable energy planning. They also present a comparative matrix with various multi-criteria techniques for renewable energy planning.

Although there are different MCDM methods and developed models applied in the area of energy, the literature review indicates that AHP, ELECTRE and PROMETHEE methods are the most widely used ones for energy planning, RES evaluation and RES site selection [28].

MCDM is a widely employed technique but requires extensive computation. In renewable energy case, the techniques of Fuzzy VIKOR and fuzzy TOPSIS are widely used. Support vector machine, particle swarm optimization, quantum particle swarm optimization, honey bee optimization, cuckoo search optimization, ant colony optimization are all machine learning tools which helps to unravel the mystery behind the data and accurately predict the possible outcomes. These are now being used in renewable energy sector for control systems, grid applications, emission reduction, to name a few. [29].

AHP though has come in for a lot of criticism for its uni-directional relationship characteristic and rank reversal properties. Some of the criticism levied at AHP include the following:

Author & Year	Criticism
(Abu Taha & Daim, 2013)	Although AHP is easy to use and apply, its unidirectional relationship characteristic cannot handle the complexity of many problems.
[5] (Velasquez & Hester, 2013)	AHP has experienced problems of interdependence between criteria and alternatives. The general form of AHP is susceptible to rank reversal. Due to the nature of comparisons for rankings, the addition of alternatives at the end of the process could cause the final rankings to flip or reverse.
[6] (Konidari & Mavrakis, 2007)	It does not allow [individuals] to grade one instrument in isolation, but in comparison with the rest, without identifying weaknesses and strengths.
[7] (Pérez, Jimeno, & Mokotoff, 2006)	The addition of indifferent criteria (for which all alternatives perform equally) causes a significant alteration of the aggregated priorities of alternatives, with important consequences. In hierarchies with four or more levels, rank reversal may happen. Since in almost all applications of AHP the set of criteria is not fixed ex-ante but is variable and is constructed in accordance with reasons of relevance and simplicity, almost all applications of AHP are potentially flawed.
[8] (Weiss & Rao, 1987)	Realistic decision problem typically will involve several levels within the hierarchy and large numbers of attributes at each level. Thus, the number of pairwise judgments needed for calibrating the hierarchy will be extremely large. Consider the decision problem of allocating resources to four competing alternatives in a corporation with five types of duplicate attribute will give more importance to those alternatives that score highly in that attribute, This increase in importance occurs because the weight given to the duplicated attribute is greater.

Author & Year	Criticism
[9] (Carmone, Kara, & Zanakis, 1997)	A major drawback of the AHP is that at each level in a large hierarchy of n alternatives, n(n-1)/2 pair comparisons must be evaluated. For a few levels and sublevels, the AHP can be applied in a straightforward, timely manner to derive the weights. As the size (n) of the hierarchy increases, the number of pairwise comparisons increases rapidly. The completion of n(n- 1)/2 comparisons can become a very difficult task for the decision maker when applied to all levels of the hierarchy

Table 1: AHP Criticisms

Hence as such, for the purpose of this research, we are utilizing Multi Objective Decision Analysis (MODA). This method effectively serves our purpose and is widely utilized in methods eliciting stakeholder preferences and decisions.

2.2 The concept of a "Business as Usual" Scenario

The definition of BAU given by Oxford Reference is given as follows:

A scenario for future patterns of activity which assumes that there will be no significant change in people's attitudes and priorities, or no major changes in technology, economics, or policies, so that normal circumstances can be expected to continue unchanged.

Various national governments utilize BAU as a reference scenario for its climate change mitigation policies. In 2009, the Indonesian Government used BAU as a reference for its climate mitigation targets by announcing that it will, through unilateral actions, reduce Indonesia's emissions by 26% from the BAU scenario, and in the case of a full international support, it can further reduce emissions from the BAU scenario by 41%. [30]

Fei and Shuang-Qing [31] suggested a without policy scenario with a clear base year as definition of BAU, as such a definition will set an objective benchmark to assess mitigation efforts pertaining to climate change in developing countries. Mets, et al. [32] used BAU as a benchmarking strategy that aids in moving towards a sustainable future by setting the bare minimum limits. Aized, et al. [33] have used various strategies to assess the validity of different parameters in Pakistan's electricity generation context, in which BAU has been used based on existing government policies and plans. Similarly, work by Gul and Qureshi [34] suggests that BAU is an excellent comparative criteria in context of studying energy generation practices in Pakistan. Therefore, in this research, we plan to use it as a benchmarking strategy in power generation context.

2.3 Pakistan Electricity Generation Structure

The electricity utility infrastructure in Pakistan currently comprises of an unbundled state owned and controlled monopoly, with the generation sector open to competition from Independent Power Producers (IPPs). Prior to the unbundling and structural reforms of 1998-2002, electricity generation, transmission and distribution in Pakistan was being controlled by two vertically integrated public electrical utilities, Water and Power Development Authority (WAPDA) and Karachi Electric and Supply Company (KESC). KESC's jurisdiction was limited to Karachi and its nearby areas only in the southern province of Sindh, while WAPDA was responsible for electricity supply to the rest of the country. Unbundling efforts began in 1998, when generation was first opened to Independent Power Producers and an Independent regulator, National Electric Power Regulatory Authority (NEPRA) was set up to regulate the price and quality of electricity for public entities. For generation from the private sector, the Private Power Infrastructure Board was established (1994).

In 2002, WAPDA was disaggregated into 4 thermal based generation companies (GENCOs), 9 distribution companies (DISCOs) and a single transmission company, National Transmission and Distribution Company (NTDC). KESC was privatized in 2005, with its name changing to K-Electric and continues to be a vertically integrated utility generating and supplying electricity to its service area. To coordinate the unbundling efforts and ensuring a smooth transition for the unbundled public entities, the Pakistan Electric Power Company (PEPCO) was formed. [10][11]

After unbundling, the power wing at WAPDA is now responsible for Hydro Power Generation and Operation & Maintenance (O&M) of power houses.[12] Thermal generation is being managed by the GENCOs and IPPs. Nuclear generation comes under the jurisdiction of Pakistan Atomic Energy Generation Commission, while renewable electricity generation is mostly a function of the IPPs. On the transmission front, NTDC constructs, operates, maintains 500/220 kV lines/grid stations, purchases power from generators and sells it to DISCOs. These market operations and all transactions are carried out by the Central Power Purchasing Agency, a government entity responsible for power procurement, settlement and financial affairs for NTDC. [13] The DISCOs construct, operate, maintain 132/66 kV lines & grid stations and 11/0.4 kV distribution system and are responsible for the ultimate supply of electricity to the consumers. National Power Control Centre, a subset of NTDC is responsible for the operation of the generation and transmission system, including balancing supply and demand, load forecasting and economic dispatch of thermal power generation. [14]

2.4 Existing Literature on Modelling of Sustainable Scenarios for Electricity Generation in Pakistan

Work on modelling sustainable scenarios for electricity planning in Pakistan is limited. However, two recent publications provide useful background.

Mirjat [15] use the AHP methodology in Multi Criteria Decision Making (MCDM) methodology for determining the sustainability of four alternation power generation scenarios for the country. The Long Range Energy Alternative Planning (LEAP) model was used to develop these scenarios based on different fuel mixes and technologies. The Reference scenario envisioned a supply mix using the government's current energy policies and regulations. The Renewable Energy technologies scenario included maximum supply using renewable energy resources. The Clean Coal Maximum scenario, based power generation on a widespread use of clean coal technologies and the Energy Efficiency and Conservation scenario focused on reduced electricity consumption and demand assuming that an energy conservation and efficiency objective was adopted. The research used a combination of four main and seventeen sub criteria upon which AHP methodology was applied to evaluate each scenario's sustainability. The scenarios were then ranked according to the stakeholder preference mechanism, whereby based on responses from a variety of stakeholders in the energy planning process, weightages were assigned to each sustainability criteria, and then scores were computed for the performance of each of the alternative scenarios under these criteria. The portfolio scoring the highest was then ranked the best.

Mengal [36] took a similar approach in using the LEAP model for development of four alternative scenarios namely the Reference scenario based on the government's current power policy with an emphasis on coal and compared it with alternative scenarios which included more hydro power, a combination of more hydro-nuclear power and a scenario which modelled an increased penetration of all renewable resources (solar, wind, biomass and hydro). This study is however limited in its analysis as it only uses GHG emissions as an evaluating criteria for ranking each of these scenarios.

Our research builds upon these two research papers and expand into additional alternative scenarios with varying ratios of each power generation technology. Our portfolios are developed so as to effectively model policies and scenarios currently under discussion in various forums of potential decision makers. The electricity model created is an hourly demand based model, incorporating hourly demand growths and working on satisfying them across the year as opposed to the prior works, which are limited to annual demand growth rates. The aim of our research is not to arrive at one best portfolio but to rather help policy makers understand the trade-offs between different sources of energy generation and to provide them with a wider array of scenarios which could be used to achieve the country's commitment to sustainability. Both of the papers use 2015 as the base year but our research assumes 2022 as the base year, so that the effect of adding extensive coal power plants to the energy mix can be also be simulated. Moreover, our study makes use of 'Levelized Cost of Energy' as the criteria for economic sustainability which hasn't been done before.

CHAPTER 3
RESEARCH METHODOLOGY

The primary objective of this research is the modelling of the electrical grid system of Pakistan to evaluate the sustainability of electricity generation, considering a set of different energy portfolios.

The research encompasses the following activities:

- Definition of Generation Portfolios:
  A set of energy futures for Pakistan are defined using different generation technologies and capacities, which serve as an alternative to the defined Business As Usual (BAU) portfolio
- Electricity Generation Model:
  The model evaluates the different portfolios by calculating the energy generated by each technology in that portfolio up to its constrained limit and whether the portfolio meets demand or not
- Definition of Sustainability Metrics:
  A set of sustainability metrics are defined, so as to evaluate the portfolios considering the impact of both energy and capacity
- Sustainability and MCDM Model:
  To better understand the trade-offs involved in achieving the various sustainability metrics, an MCDA analysis is pursued and the portfolios are evaluated in terms of various stakeholder preferences and policy scenarios

3.1 Definition of Generation Portfolios

The portfolios are defined as a combination of different available power sources as per the year 2025. The year 2025 has been selected, as the majority of the already commissioned CPEC Power projects will be operational and providing electricity to the main grid, which are currently in various phases of implementation and have very high chances of being operational as the contracts have already been signed and agreed upon. It is also a good year to form as the basis as NEPRA's state of industry report of 2018 [16] does not foresee any renewable energy plants based on wind and solar after 2021, in stark contrast to the stated policy of the Federal Government.

The portfolios set up are evaluated against the projected hourly energy demands of 2025 using current available data.

We first define a reference BAU portfolio, which is based on the information available in NEPRA's State of the Industry Report 2018,[17] that provides year-wise capacity additions in the pipeline till 2024. Then we discuss how we will define the set of other portfolios to be evaluated.

3.1.1 Reference Electricity Generation Portfolio

A BAU portfolio is defined as the reference case. It predicts and models the 2025 portfolio of the country by utilizing information provided by NEPRA of capacity additions till 2022. Average capacity additions for each technology for the five-year period (2018-2022) are calculated to predict capacity additions from 2023-2025. The BAU portfolio is shown in Figure 1B below. This can be contrasted with the current (2018) portfolio in Figure 1A.

The total power generation capacity of Pakistan currently stands at 36,946 MW, the breakdown of which is shown in Table 2 below. By 2022, NTDC forecasts Total Installed Capacity to go up to 50,852 MW. Extrapolating the trends to 2025, gives us our BAU portfolio, where the total installed capacity is predicted at 67,757 MW.

The majority of the predicted generation additions are coal power projects contributing upward of 13000 MW, Hydro Power around 7000 MW and Nuclear around 3500 MW. In contrast, only 1500 MW of solar additions and 1600 MW of wind energy is expected to go online in this period. The rest of the projects are mostly small scale bagasse or natural gas projects.[17]

As per Government predictions and forecasts, the BAU model of 2025 is expected to meet demand, however if during experimentation the BAU portfolio fails to meet demand, a modified BAU portfolio will also be established where energy capacity will be added until all demand is met.

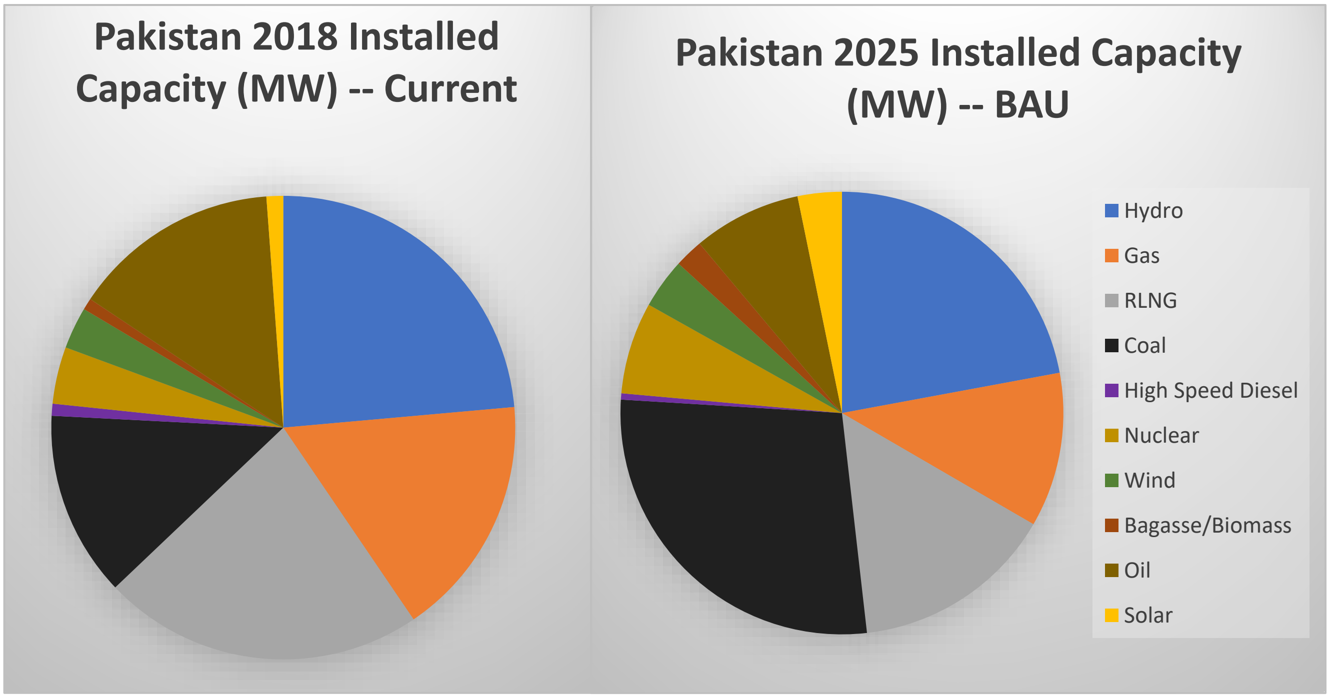

Figure 1: Pakistan 2018 (NTDC) (1A) & 2025 Installed Capacity Mix (1B)

3.1.2 Alternate Energy Generation Portfolios

In this section, we describe our method for defining the alternative portfolios to be evaluated.

Each portfolio is a combination of installed generation capacity of different technologies. For an ideal portfolio, it is required to satisfy the demand of electricity for the year in concern as per the demand projections of 2025. However, we allow some portfolios to not meet demand (as this is a reality in Pakistan). If the demand is not met, Energy Not Supplied (ENS), which is the difference between the Energy Demand for a given time t and the electricity generated by the portfolio for time t, is evaluated as an output for these portfolios. The governing equation below is utilized in our modeling:

$$ENS_i = \sum (ED_t - EG_{t,i})$$

where ENS_i is the sum of the electricity not supplied for a portfolio i, where ED_t is the electricity demand during time-period t and $EG_{t,i}$ is the electricity generated by portfolio i at time t.

The following subsections and Table 2 below, describe the portfolios that are constructed.

PORTFOLIO	CAPACITY (MW)											Satisfies Demand	Description
	Hydro	Gas	Nuclear	Coal	Wind	Solar	Regassified Liquified Natural Gas (RLNG)	Oil	Bagasse/ Biomass	High Speed Diesel	Total Gen. Capacity		
Current Portfolio	8713	6253	1467	4774	1078	430	8271	5350	301	309	36946	NO	2018 Capacity Mix
Business as Usual	14963	7653	4547	18820	2478	2180	10039	5350	1418	309	67757	YES (expected)	BAU 2025
1	↑ 14963	7653	↑ 4547	10000	↑ 2478	↑ 2180	8271	3000	↑ 1418	0	70924	YES	Indigenous Energy Sources + Contracts (meets demand)
2	14963	6253	4547	0	2478	2180	8271	5350	1418	309	45769	NO	Zero Coal, Constrained Oil and Gas
3	↑ 14963	0	↑ 4547	18820	↑ 2478	↑ 2180	0	0	↑ 1418	0	75820	YES	Zero Oil & Gas, Constrained Coal (meets demand)
4	13177	7253	3667	14807	↑ 2478	↑ 2180	7000	3350	1099	309	63662	NO	13 GW Renewable by 2025
5	14963	3827	2274	9410	6479	6082	5020	2675	1418	155	52302	NO	50% reduction in Thermal by 2025
6	↑ 14963	3827	2274	9410	↑ 6479	↑ 6082	5020	2675	↑ 1418	155	63361	NO	60% Renewable Energy Policy
7	↑ 14963	3827	↑ 2274	9410	↑ 6479	↑ 6082	5020	2675	↑ 1418	309	75941	YES	60% Renewable Energy Policy (meets demand)

Table 2: Portfolio Descriptions

GREEN arrows indicate capacities that will be increased in successive iterations till ENS=0 is achieved or a set constraint is reached.

3.1.2.1 *Indigenous Energy Sources*

In this portfolio, local sources of energy, such as indigenous coal, wind, solar, hydroelectric power and natural gas are utilized to study the economic impact such a portfolio has on the national spectrum.

- **Motivation:**

  High amount of crude oil and coal is imported by the government leading to international debt and uncertainty. The total import of the crude oil of the country during 2017-18 was 10.33 million tons at a cost of US$ 4,903.65 million. The total coal imported during 2017-18 was 13.68 million tons, at a cost of Rs. 154,795 million. Projecting these values to 2025 further compounds the costs, as thousands of MW of imported coal plants are set up as well as the CASA pipeline for 1000 MW of natural gas from Iran also joins the capacity mix in 2021, in addition to some 2000 MWs of Gas, being imported from Qatar on a 20 year deal. Oil imports are one of the major reasons for current account deficit for Pakistan. Strategies to cut current account deficit require reduction in oil imports and hence as such, electricity generation through oil. [14] Pakistan also has some existing policy limitations and system constraints for its portfolio definition. For example, 66pc energy for Regassified Liquid Natural (RLNG) projects are on a 'take or pay basis'. These RLNG contractual obligations and fuel contracts are also studied in the portfolio for their impact on the future energy mix.

- **Portfolio Definitions:**

  Portfolio 1: Constrained imported coal, oil and natural gas; includes all (2025 BAU) alternative sources such as indigenous coal, hydroelectric power, solar and wind projects -- This portfolio allows for those imported sources, where supply deals have already been agreed upon. It is a more practical approach towards promotion of indigenous sources, while ensuring that already agreed upon international transactions and contracts are abided by. In addition to the Generation Capacities of indigenous sources, this Portfolio also abides by the coal, gas and LNG supply agreements already signed by the government. The portfolio is then made reliable, by adding wind and solar energy capacity in equal proportions as well as nuclear capacity for base loads, until demand is met.

3.1.2.2 *Climate Change Mitigation*

- **Motivation:**

These portfolios try to incorporate greater amounts of solar and wind energy into the energy mix in place of brown energy sources such as coal, oil and natural gas. These portfolios are ones proposed by climate change mitigation policy initiators and act as a good reference for greener energy mixes by 2025 and the possible economic and social impact such a portfolio instigate. Different ideas explored under this criterion include getting rid of coal altogether, and various levels of minimization for thermal sources. Another portfolio tries to minimize the utilization of the Independent Power Producers (IPPs) at the earliest possible stage, to study the impact such a model will have on the national economy and other sustainability metrics.

- **Portfolio Definitions:**

Portfolio 2: Zero Coal, Constrained Oil and Gas at 2018 levels. Demand is tried to be satisfied by using hydro, solar, wind and nuclear projects by 2025 and the existing oil and gas projects in 2018. No new investment in oil and gas is entertained in this portfolio. ENS is an output for this portfolio.

Portfolio 3: With Zero Oil & Gas and constrained Coal at 2025 levels, this portfolio tries to model the idea of ending the reliance on Oil and Gas and moving towards a coal dominated, reliable energy mix. This portfolio is made reliable by adding hydro, solar and wind power, so as to accurately predict the impact of a renewable-coal nexus, as envisioned by the incumbent government.

3.1.2.3 *Renewable Energy (RE) Policies by 2030/40*

- **Motivation:**

The government under its 2019 Renewable Energy Policy, announced plans to scale up the share of renewable resources (solar, wind, micro-hydro and biomass) in the national generation mix to 30% by 2030. A target for increasing hydro-power contribution to the mix by 30% has also been setup, bringing total renewable energy share in power generation to up to 60% by 2030.[18] Another current proposal is the phasing out of thermal projects in the next 20 years. Another possible policy being discussed is the tripling of total energy generation by 2047 and replacing all thermal sources by Renewable Energy. This proposal is a part of the IGCEP report and is currently under discussion on policy forums.[19]

- **Portfolio Definitions:**

Portfolio 4: This portfolio builds on the information available by NTDC till 2022 and only adds Renewable energy (Solar & Wind) to try and meet the demand in 2025. This portfolio studies the impact on the generation mix of Pakistan of having 13 GW of renewable energy by 2025 and can be analyzed as a parallel to the '18000 MW of renewable energy by 2030' policy. This portfolio is expected to meet demand, however if it fails to do so, ENS will be an output for this portfolio.

Portfolio 5: 50% reduction in thermal projects by 2025. Building on Portfolio 4, Portfolio 5 not only adds 13 GW renewable energy by 2025, but also reduce all thermal projects by 50% of its 2022 capacity. Energy Not Supplied is an output for this portfolio.

Portfolio 6: This portfolio analyses the 60% renewable energy policy, where 30% of the generation mix is hydro-power and 30% is renewable energy through wind, solar, and bagasse. Building on Portfolio 5, this portfolio also reduces thermal generation by 50%, while ensuring that the policy percentages are met. If the portfolio fails to meet demand, which does look likely, **Portfolio 7** will be introduced to make it reliable by adding Nuclear, Hydro, Solar and Wind Power capacities.

3.2 The Energy Model

The energy model calculates energy generated by each source by trying to mimic the dispatching rules set by National Transmission and Despatch Company (NTDC), Pakistan. The National Power Control Center (NPCC) under NTDC decides upon the operation and load dispatch of the power plants in the country except for the plants which come under the jurisdiction of Karachi electric supply company (K-Electric) in Sindh. K-Electric has its own merit-order dispatch system, the data for which is publicly available [35]. The merit-order system for dispatch of thermal generation plants is based upon fuel efficiencies and the variable component of power plants, including the fuel cost and variable operation & maintenance, where power plants with the lowest specific cost are dispatched first. This economic merit order list includes a fuel cost/kWh and an O&M cost/kWh, which are then added to achieve a specific cost in Rs./kWh, which forms the basis of the economic merit order list issued by NTDC.[20]

In cases where new thermal capacity is added to a portfolio and specific costs are not available, it is estimated by averaging the costs of existing projects of same technology. This helps us accommodate new thermal projects within the NTDC dispatch system for electricity generation.

It is also pertinent to note that hydroelectric plants are dispatched as per Indent (water outflows) given by WAPDA to NTDC and is optimized over the 24-hour period. Whereas, solar, wind and nuclear are must-run plants and dispatched irrespective of merit. Such a situation exists particularly due to the fact that the current contribution of solar and wind to the Pakistani energy mix stand at a meagre 2-3%. Hence as such NTDC simply dispatches any energy output it receives from such sources, without the need to accommodate it in its Merit Order Dispatch system.

3.2.1 Electricity Generation Model

The electricity model estimates the amount of energy generated by each source in the portfolio, up to its constraints as specified in the portfolio definitions. Utilizing the dispatching rules set below, our model outputs the total energy supplied, the capacity factor for each technology and the average power.

Similar to Nock and Baker [21], a merit order dispatch flowchart (Figure 2) is utilized by the model to evaluate whether hourly demands are adequately met after a generation technology is deployed up to its maximum constraint. Our model tries to mimic the trends observed in the NTDC merit order dispatch list [22] and translates the project based list into percentages of available technology dispatched in precedence over another. Hence as such Nuclear power is given precedence over solar, wind and other fuels. While NTDC utilizes Hydropower for peaking loads, lower costs associated with hydro energy gives it precedence over other fuels. It is also pertinent to note that with almost 30% of the generation mix composed of Hydropower, it would be impractical to reserve all of it for peak loads. Hence as such, by utilizing the data provided by NTDC in its' State of the Industry report, half of the available hydropower for electricity generation is dispatched earlier for every time period (t), with the rest reserved for peak loads.

All thermal fuels (Gas, Coal, Oil, Bagasse) are dependent on the NTDC despatch merit order list which takes into account the specific cost of each power plant, including Fuel and O&M costs to rank the projects for dispatch. Our model generalizes the observed trend, and hence as such follows the following dispatch order, where in thermal fuels, natural gas is dispatched first followed by half of the available coal capacity and Biomass respectively. This is followed by half of the oil capacity in a portfolio, the remaining coal capacity, RLNG, the remaining Oil capacity & High Speed Diesel respectively.

Each technology is limited by their capacity in the portfolios. Solar irradiation hourly data, wind speeds data, nuclear outages and hydro availability for electricity generation are utilized in the calculation of generation by each technology up to its maximum capacity in a particular portfolio.

The dispatch order observed is displayed in Figure 2 below. For every hour t, the dispatch sequence below is followed, until the demand for time t is met or all capacity in the portfolio is utilized without meeting demand and ENS value is recorded for that iteration.

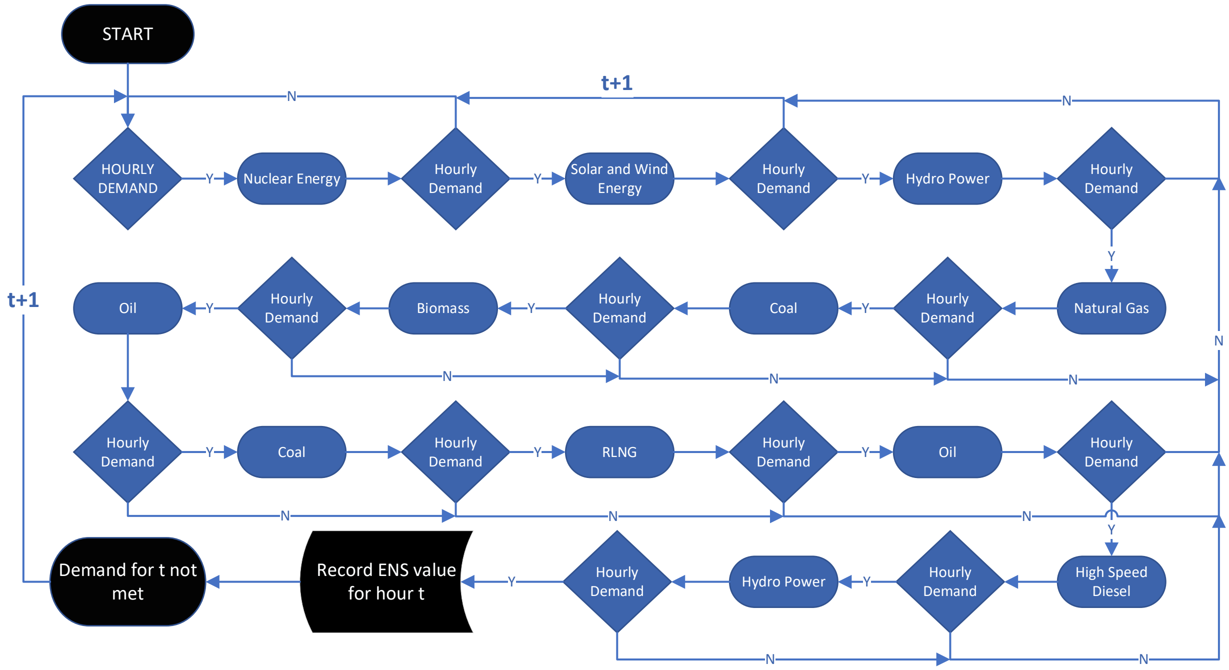

Figure 2: Merit Order Dispatch Flow Diagram

3.3 Projection of Demand

Future demand projections are generated based upon the hourly growth rate calculated by the hourly demand data of the last five years provided by NTDC [36, 37]. The demand for 2025 is predicted by using historical data from 2015-2018, and is displayed in Figure 3 below. Visible seasonal peaks are observed in the summer months whereas similar daily trends are observed in summer and winter months respectively.

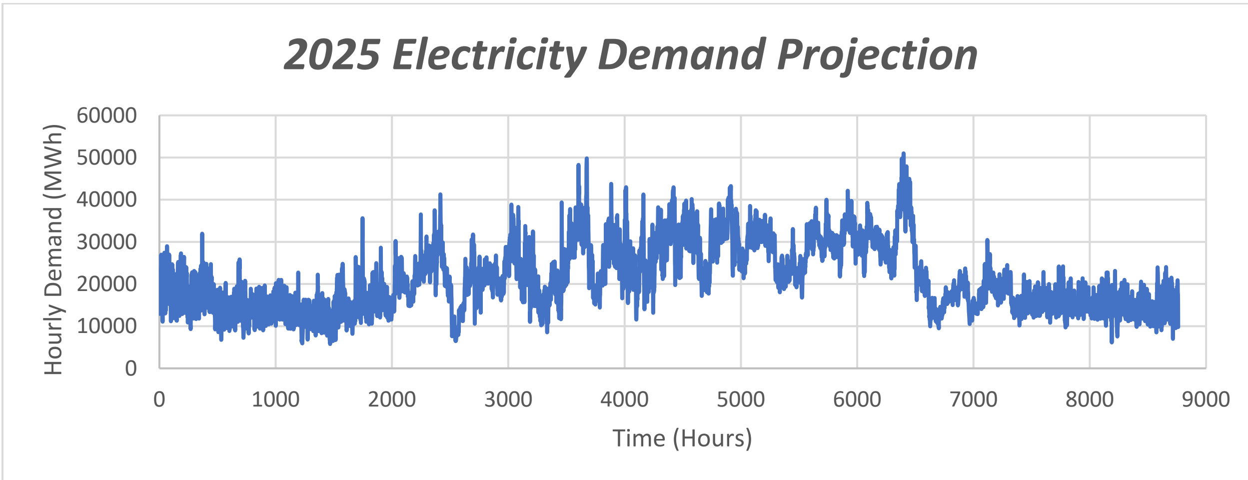

Figure 3: Pakistan's hourly Electrical Demand Projection for 2025

3.4 Sustainability and MCDM Model

Using MCDM, we evaluated each portfolio over a set of defined metrics below. Each generation technology in each portfolio is assigned a certain score for every defined metric. These scores are based on both the installed capacity and the generated energy. Thus, each metric is divided into its per capacity and per energy components, similar to Nock and Baker [21]. Some metrics such as land use etc. are based on a fixed or per capacity basis and are calculated per MW whereas variable or per energy metrics such as Greenhouse Gas Emissions and LCOE are calculated on a per kWh scale. The total value of a metric is calculated by combining the two values as follows:

$$x_{i,j,t} = \frac{F_{j,t}}{hCF_{i,t}} + V_{j,t}$$

where x_{ijt} is the total value of metric j for technology t in portfolio i, F_{jt} and V_{jt} is the fixed and variable value for technology t for metric j respectively, h is the no. of hours in a year and CF_{it} is the capacity factor of technology t in Portfolio i.

Each portfolio, which is a combination of different generation technologies, is then scored using a weighted averages methodology. In a weighted sum method, all the data for a particular metric is brought into a comparable form by normalization. This is done by defining the maximum, minimum and preferred value for each metric, such that

$$Z_{i,j} = \frac{X_{i,j} - X_{min}}{X_{max} - X_{min}}$$, where X_{max} is preferred value, and

$$Z_{i,j} = \frac{X_{max} - X_{i,j}}{X_{max} - X_{min}}$$, where X_{min} is preferred value

where, $X_{i,j}$ are the raw scores of portfolio i for metric j, and $Z_{i,j}$ are the normalized scores for portfolio i, for metric j.

The normalized scores are then multiplied by preference weights, and weighted sum method is utilized to arrive at a final score.

$$Y_i = \sum_{j=1}^{n} (w_j * Z_{ij})$$

where i = 1,2,3,...,m, w_j is the relative weight of significance of a metric and Z_{ij} are the normalized scores for portfolio i for metric j. Then, the total Weighted Sum Method score of a portfolio is denoted by Y_i. Note that the $\sum_{j=1}^{m} w_j = 1$.

3.4.1 Ranking of Generation Portfolios based upon stakeholder preferences

Once the generation portfolios are formulated, their performance over the defined sustainability metrics are computed. Each portfolio is then ranked according to stakeholder preferences for our given sustainability metrics using the weighted sum method. Different preference weights represent potential decision maker scenarios. Trade-offs between different metrics are observed and suggestions made to help policy makers arrive at a better informed decision.[38]

3.4.2 Defining Sustainability Metrics

Our sustainability metrics are defined under the following categories:

- Technical Sustainability: Specifically, Energy Not Supplied (ENS) as defined for a portfolio in Section 3.1.2. This is a measure of mismatch between supply and demand of electricity.
- Environmental Sustainability;
  - Greenhouse gas emissions of the portfolios – including emissions from the installation and operation of the enterprise (CO_2eq/kWh). This metric has both a fixed and variable component as some technologies such as fossil fuels are heavily dependent on plant operation while others such as solar and wind result in GHG emissions in their construction and production phases. Operational Greenhouse Gas Emissions (CO_2, N20 and CH_4) for all technologies is calculated in terms of CO_2eq by utilizing data available and sourced as per Appendix B. These values incorporate all these gasses using EPA standards for Global Warming Potential (GWP) and equations. For calculation of emissions during installation, international trends and data are utilized to calculate the emission data for similar ventures. Life Cycle Assessments are utilized for technologies such as Natural gas and oil, and EPA emission factors, inventory guidance, standards and equations are utilized in these calculations. [21] [22]

- Quantification of pollutants (Sox and NOx) as a result of construction and operation of a particular portfolio (g/kWh). Again, this has both a fixed and variable component similar to GHG emissions and the sum of the total life cycle emissions would be the air pollution associated with a portfolio. The source of the input data is defined in Appendix B.
- Life Cycle Land Use by Technology – Calculated per MW for every technology, this metric includes the land used during resource production, by energy plants, for transport and transmission, and to store waste materials. Both one-time and continuous land-use requirements are considered.[25]

- Economic sustainability;
  - Levelized Cost of Electricity, which will take into account all fixed and variable costs of electricity generation over the life cycle of a generation technology ($/kWh), where for a particular generation technology T in a portfolio;

$$LCOE_T = \frac{AC_{Cap,T} + AC_{fixed,T} + AC_{var,T} + AC_{fuel,T}}{AE_{gen,T}}$$

where,

Levelized Cost of Energy for a particular technology T in a portfolio is the sum of Annualized Capitals Cost for that technology ($AC_{Cap,T}$), Annual Fixed Costs ($AC_{fixed.T}$) such as fixed O&M costs, Annual Variable Costs ($AC_{var,T}$) such as Variable O&M costs and Annual Fuel Costs ($AC_{fuel,T}$), per Annual Energy Generated by the Technology T ($AE_{gen,T}$), for our year in concern (i.e. 2025). Annual Capital Cost will also include an annuity factor (f) such that,

$$AC_{Cap,T} = TC_{Cap,T} * f$$

and,

$$f = \frac{z\,(1+z)^t}{(1+z)^t - 1}$$

to account for discount rate (z), over the lifetime of a power plant (t in years).[26] A lifetime of 30 years has been taken for all technologies to ensure consistent results across different metrics and a discount rate of 5% has been assumed. A sensitivity analysis is also to be performed on the Discount rate, as Tariff documents issued by NEPRA assume a 10% Discount Rate. Pakistan is also heavily reliant on foreign funding and loans for setting up energy projects and hence as such, Overnight Capital Cost i.e. the investment required for a particular energy project becomes an important preference for some stakeholders. To effectively model that, we also evaluate how LCOE changes for our portfolios with a Discount Rate of 10% and 15%.

- Socio-Political sustainability;
  - Safety of the portfolio in terms of fatalities incurred per GWh for a portfolio including construction and operation. This is another metric that assumes fatalities to be wholly variable. It looks into the fatalities occurred during the construction phase of the projects, as well as the operational safety numeric of a power plant.
  - Jobs created quantified by utilizing statistics available sourced in Appendix B. This is a per capacity (fixed) calculation and is calculated for each technology by using the total job opportunities created by a project per MW of Capacity. A majority of jobs are generated through the construction process of energy plants and operational jobs are of a fixed nature as well. The data available through government CPEC projects does account for indirect jobs created for enabling an operational plant, as well as direct construction and operation jobs. This data can be extrapolated across the projects for different technologies.

3.5 Data Collection and Calibration

Demand data is obtained for the Pakistani grid system from the planning department of National Transmission and Despatch Company Pakistan. Data is also required for daily generation and supply for wind, solar, hydro and other sources, and the dispatching rules defined by the Planning Department. The NTDC issues an annual State of the Company document, which not only gives important data such as the annual energy mix, generation by source, demand data, peak surplus/deficit etc. but also predicts the energy mix for the next five years. A task force on Energy is currently working to propose immediate, medium and long-term policy interventions with the aim to provide indigenous, affordable and sustainable energy. NTDC has submitted an Indicative Generation Capacity Expansion Plan (IGCEP) 2018-40 to National Electric Power Regulatory Authority (NEPRA), the electricity regulator. This expansion plan is a part of the Integrated Energy Plan, which includes power, as well as petroleum demand and supply plans until 2047. This plan is targeting transformation of power generation sector from thermal production to renewables and nuclear power.[27]

Ten-minute site data is also available for both solar and wind power for multiple locations through World Bank projects, and has been obtained. This is utilized in calculating output for current and future wind and solar energy projects of Pakistan. Annual reports of ministries of Climate Change, Environment and Industry and Production are important sources of information for data required in calculation of sustainability metrics. Annual reports of NEPRA and data elicited by officials at NTDC are valuable sources for metrics data as well. The sources and the values for our energy model and our sustainability criterions are detailed in Appendix A and B.

3.6 Limitations

The developed mathematical model is theoretical in nature and requires validation through application in a real-time power generation scenario. Limitations will also exist in the entrenchment of such models in policy making decisions, due to the complexity of these models and the poor understanding of policy makers in such technical areas. In addition, this model will be based on generation capacity, further limitations will exist in implementing this on ground due to transmission and distribution constraints as well. The model also assumes new projects and uses 2025 as our target year with high dependence on the completion of the CPEC projects for the formation of the base scenario and continuation of government policies. The portfolios have been developed based on the existing energy policies in Pakistan. These power policies however, are highly volatile and subject to change depending upon the political climate and incumbent government of the country. A lot of demand and supply data is also extrapolated using currently available data and NTDC predictions. Due to lack of available data, some of our sustainability inputs (Appendix B) are sourced from Global and US sources and may not be an exact representation of the situation in Pakistan. Since the focus of this study is to evaluate the general tradeoffs that occur by favoring different generation technologies over each other, and not to obtain exact values, the generalization however serves the intended purpose of this research.

CHAPTER 4

RESULTS

4.1 Energy Model Results

Figure 4 shows the outputs of the energy model. It is observed that the composition of the portfolio dictates the energy contribution and in turn the capacity factors for each technology in a portfolio. Relatively high capacity factors were observed in almost all the portfolios for both wind (35%) and solar (23%) energy. This reflects well on the match between available wind and solar resources and the demand profile of the country and highlights the possible role of these sources in any future generation mix for Pakistan. However, given the intermittent nature of the Renewable sources, any portfolio with high renewable energy requires more capacity investments compared to fossil fuels to effectively meet demand. Also, all portfolios that meet demand had lower capacity factors for Oil, High Speed Diesel and RLNG, compared to portfolios not meeting demand. This means that these portfolios are not using the fossil capacity efficiently, but on the other hand, may have less air pollution and emissions. This also emphasises the importance of Renewable energy in any reliable portfolio, where it reduces the dependence on thermal generation sources. Retiring some technologies in certain portfolios leads to greater capacity factors and effective utilization for the remaining generation technologies, as is observed in Figure 4 below. For example, *BAU 2025* and *Zero Oil and Gas* portfolio have similar installed capacities of Coal, but the energy generation percentages differ by almost 7%.

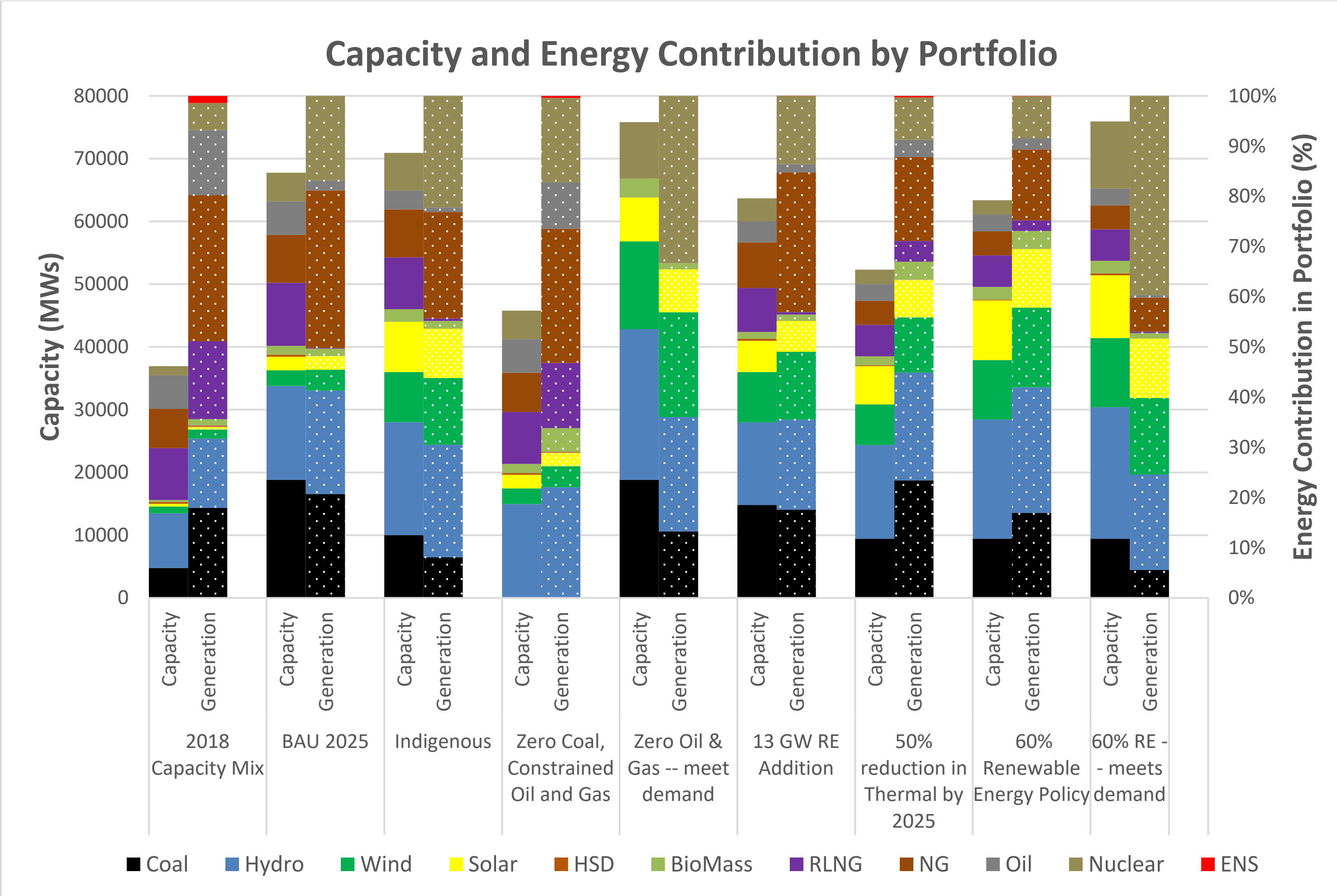

Figure 4: Capacity and Energy Contribution by technology

The left bars (solid) for each portfolio demonstrate the breakdown of capacity by technology, whereas the right bars (dotted) indicate the percentage generation by each technology in that portfolio. ENS is displayed on the generation bar in a solid red color

As observed in Table 3 below and Figure 4 above, the *BAU 2025* meets the projected demand for the country in 2025 and reassures the government's claims of planning to end load-shedding by 2025. If, however, no capacity is added to the *2018 Capacity Mix* portfolio, an ENS of 2634 GWh is observed, with the demand not being met in 757 hours for the year 2025.

The portfolios that do meet demand other than the *BAU 2025* include the *Indigenous Sources*, *Zero Oil and Gas* and the *Reliable 60% RE* portfolios. As observed from Table 3 below, all reliable portfolios require a greater total installed capacity than the *BAU* to meet demand. This is due to the high amounts of Renewables promoted in each of these portfolios. The *Indigenous Portfolio*, while having less coal and RLNG compared to the

BAU, meets demand due to the higher amounts of renewable energy being promoted in this portfolio, with almost 4 times the capacity for both solar and wind, compared to the *BAU* portfolio. The other two portfolios -- *Zero Oil and Gas* and *Reliable 60% RE* require even more RE capacity additions compared to the *Indigenous Portfolio* to meet demand. This can be attributed to the availability constraints and lower capacity factors of the RE technologies being promoted in these portfolios. The *BAU* is a thermal- and coal-heavy portfolio and hence as such is not faced with such challenges.

Another takeaway is the reliance on Nuclear energy for two of our reliable portfolios. For both, *Zero Oil & Gas* and *Reliable 60% RE* portfolio, nuclear generation stands between 35% to 40% of the total generation. This can be attributed to the fact that Nuclear energy dispatches first in the Pakistani grid and provides a good alternative for base loads compared to other thermal sources.

Portfolio	Total Installed Capacity (GW)	ENS (GWh)	Max. ENS in an hour (GW)	No. of hours ENS is observed (h)
2018 Capacity Mix	37	2634	20	757
Zero Coal, Constrained Oil and Gas	46	743	16	226
50% reduction in Thermal by 2025	52	536	15	164
60% Renewable Energy Policy	63	93	10	39
13 GW Renewable by 2025	64	10	3	5
BAU 2025	68	0	0	0
Indigenous	71	0	0	0
Zero Oil & Gas -- meet demand	76	0	0	0
60% -- meets demand	76	0	0	0

Table 3: Total Installed Capacity and ENS statistics for each portfolio

Among those portfolios that do not satisfy demand, the lowest mismatch is observed in the *13 GW Renewable Energy* portfolio, which fails to meet demand in only 5 hours for the whole year. Having a total installed capacity less than the *BAU*, as highlighted in Table 3, it presents itself as a realistic option along with the demand-meeting portfolios. This portfolio still has high amounts of Coal and Natural Gas in its composition, but also promotes renewable over other thermal sources.

Our most unreliable portfolio in 2025 is the *Zero Coal, Constrained Oil and Gas* portfolio, where coal is altogether eliminated, Oil & Gas capacities are constrained to the 2018 levels, and other technologies are set to their levels in *BAU 2025*. This highlights the dependency of the *BAU* portfolio on thermal sources and Coal, and renders this portfolio unrealistic as a future energy mix. It does however, present a comparison against the *Zero Oil and Gas* portfolio for sustainability purposes.

Table 3 also displays the maximum amount of ENS observed in an hour for an unreliable portfolio and the number of hours in 2025 for which that portfolio fails to meet demand. This provides intuition into the magnitude of investment in new generation capacities required to make these portfolios reliable. For example, this implies that for the *13 GW RE* portfolio to be reliable, a generation addition of 3 GW is required to meet all demand; if this generation were available at all the high demand hours, it would ensure total ENS is brought down to zero. The *60% RE* portfolio had a max. hourly ENS of 10 GW, but required 13 GW addition to be made reliable. This can be explained by the intermittent nature of some of the technologies promoted in the development of the *Reliable 60% RE* portfolio, such as wind and solar. A reliable portfolio not only has to satisfy demand for all the hours, but also have enough generation capability to meet the maximum demand in an hour across the whole year. In our unreliable portfolios, it is observed that these two metrics go hand in hand, where more unreliable portfolios not only fail to meet demand in a higher no. of hours but also have a higher demand and supply mismatch per hour.

Both the *13 GW Renewable* portfolio and the *60% Renewable Energy* Portfolio have a total generation capacity less than the *BAU 2025*, while failing to meet demand for just a few calendar hours throughout the year. Peak shaving and demand-side load management may present a viable solution to reduce costs by eliminating the need for peaking power plants, and is a possible avenue that can be explored further by the relevant decision makers for superior benefits.

4.2 Sustainability Model Results

The sustainability model utilizes the results from the energy model to rank the portfolios under various stakeholder preferences, so as to better layout the trade-offs in any energy future for Pakistan.

Before we present and analyse the results of the different portfolios under stakeholder preferences, it provides good intuition to look into how each portfolio ranks for different sustainability metrics. Figure 5 shows that our *Reliable 60% RE* portfolio scores the best for four categories, while ranks second to worst in LCOE and Land Use. The low Land Use score can be attributed to the highest amount of Hydro capacity in this portfolio. The low LCOE score can be attributed to the high Nuclear and Wind energy in the portfolio with costs still high in Pakistan for these relatively novel technologies. The *Zero Coal* portfolio, not surprisingly, ranks the best in Air Pollution, but suffers in the Jobs created ranking since it has constrained its thermal sources and does not promote much Renewable. It also is the most unreliable portfolio and therefore may not be a viable option for portfolio development.

The *Indigenous* portfolio ranks no worse than 5th in any criteria; it may prove to be a popular choice under a combination of stakeholder preferences. On the other hand, the *BAU* ranks in the bottom 2 for 5 of the 7 criteria, so might not be a popular choice. None of our portfolios are entirely dominated across the range of sustainability metric; meaning that any of them could be preferred by a specific stakeholder.

	Fatalities	Jobs	Energy Not Supplied	GHG	Air Pollution	LCOE	Land Use
60% RE – meets demand	**1**	**1**	**1**	**1**	2	7	7
Zero Coal, Constrained Oil and Gas	2	8	8	4	**1**	3	**1**
50% reduction in Thermal by 2025	8	6	7	7	8	**1**	4
Indigenous	3	4	**1**	3	3	5	5
Zero Oil & Gas – meet demand	4	2	**1**	2	4	6	8
BAU 2025	7	7	**1**	8	7	8	3
13 GW Renewable by 2025	6	5	5	6	6	4	2
60% Renewable Energy Policy	5	3	6	5	5	2	6

Figure 5:Portfolio Ranking for Different Sustainability Metrics

A ranking of 1 indicates the best performance while 8 indicates the worst performance for a portfolio. This figure utilizes a green-white-red color scale where greener cells indicate good performance and degrees of red indicate poor performance. For ranking where same values are obtained, the highest of the ranking is assigned to all such portfolios.

To further understand the tradeoffs, correlation between any two metrics is presented in a scatterplot matrix in Figure 6. All reliable portfolios are indicated by colored dots, whereas non-reliable portfolios are indicated with blue dots. The correlation values between sustainability metrics are also presented in Appendix C for further intuition. It is observed that some criteria can be grouped together as they tend to be highly correlated. In general, any stakeholder would have to assess the tradeoffs between the following groups in our metrics: (i) Air pollution, Fatalities and GHG emissions, (ii) Land Use and LCOE and (iii) Jobs. The tradeoffs between these groups is driven by the energy composition of the portfolios and the technologies considered in each portfolio. Positive correlations are observed between Air Pollution, Greenhouse Gas Emissions and Fatalities, since renewable energy sources generally have lower emissions for both air pollution and Greenhouse gases. On the other hand, thermal sources are more prone to fatalities due to their hazardous labor-intensive operations and installation. All portfolios promoting RE technologies therefore score well for all three metrics. This implies that if a stakeholder is only interested in one of these three metrics, he will still end up with higher scores on the other two metrics as well.

Land Use is also positively correlated to LCOE as upfront capital costs are a major factor in capital investment required for new energy projects. Land intensive technologies, especially Solar and Wind, have higher capital costs. A comparison between the *Indigenous* and the *Reliable 60% RE* portfolio also highlights the opposition of Hydro to this norm. A portfolio promoting Hydro more than Wind and Solar uses more land but lower LCOE. Across all our portfolios however, LCOE and land use are generally positively correlated.

Group (i) is generally positively correlated with Group (iii) due to the high number of jobs associated with Solar and Hydro power. On the other hand, it negatively correlates to Group (ii) as land intensive technologies such as Hydro, solar and wind powers have lesser GHG emissions. This displays a tradeoff between our groups where a stakeholder might have to compromise on emissions and jobs to positively impact on land use.

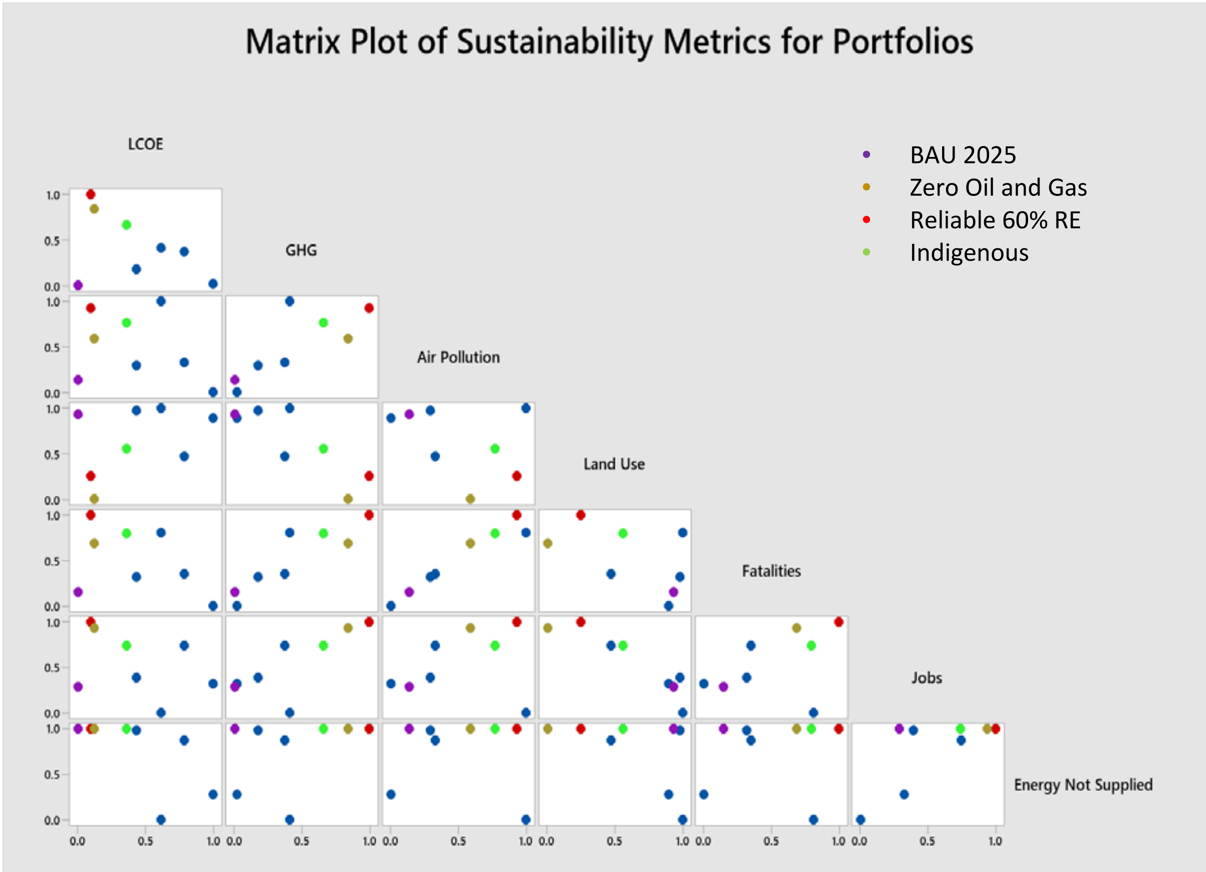

Figure 6: Scatterplot Matrix of different Sustainability Metrics for Portfolios
Each dot represents a single portfolio value with 1 indicating the highest score for a metric and 0 indicating the lowest score for the metric. Each box represents the sustainability scores for all the considered portfolios for a single metric. The four reliable portfolios are highlighted with specific colors; the blue dots represent the unreliable portfolios.

4.2.1 Equal Preference Scenario

In this section, we use equal scaling coefficients to calculate the sustainability score for the portfolios. All metrics are given the same scaling coefficient, which implies that a stakeholder is indifferent between moving from the worst to best for any criteria. To better interpret the meaning of scaling coefficients for our metrics, the maximum and minimum portfolio metric values are presented in Appendix D. The *2018 Capacity Mix* portfolio is not included in this analysis as it greatly skews the normalized values, particularly in Reliability and Costs. Figure 7 displays the results, ranking the portfolios from highest to lowest sustainability scores.

Of note is the *BAU 2025* portfolio. In fact, in terms of sustainability, the portfolio, while being reliable, performs worse under equal preferences than even the *Current (2018)* portfolio. Three of our four fully reliable portfolios rank amongst the best in terms of sustainability score whereas the fourth, *BAU* ranks the last amongst all portfolios. This brings up questions about the sustainability focus in portfolio development by the existing decision makers and points towards the requirement of an urgent rethink in this regard.

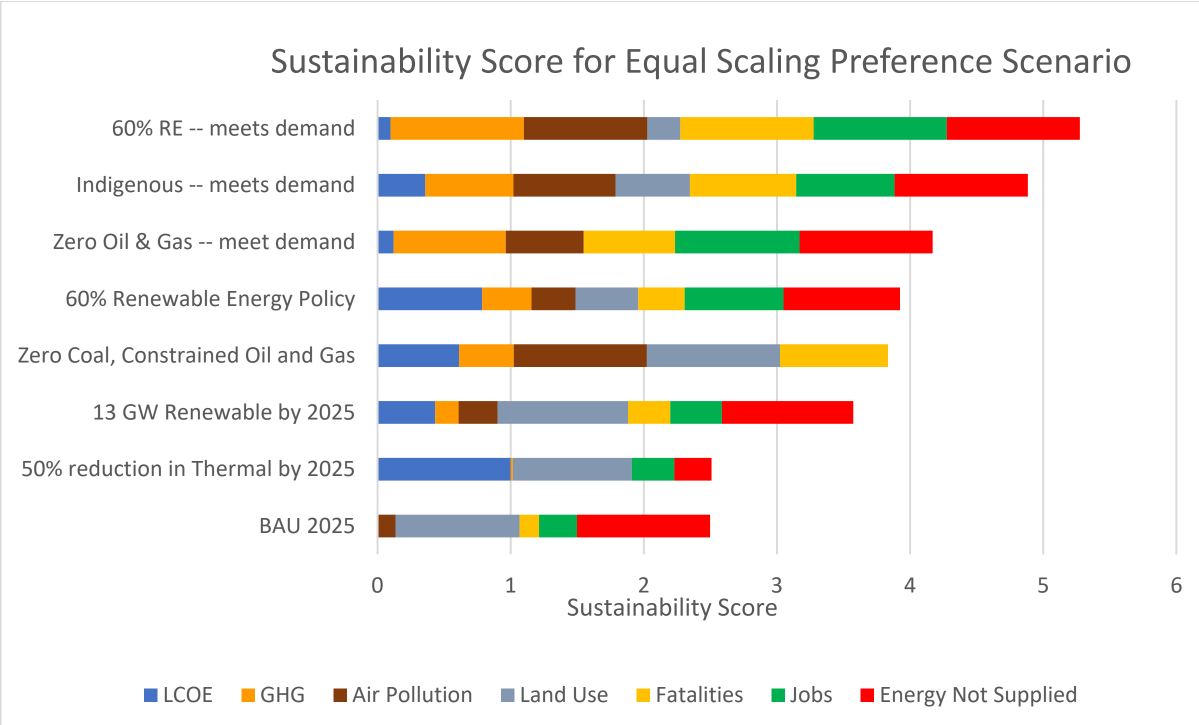

Figure 7: Sustainability Score under equal scaling coefficients

The stacked bars display the sustainability score for each portfolio, with different colors indicating the contribution to the score by different sustainability metrics. The portfolios are ranked from highest at the top to lowest at the bottom. Each sustainability metric has a maximum score of 1 and a minimum score of 0 for each portfolio.

Our top two portfolios differ in terms of the amount of Renewable Energy technologies. The *Indigenous* portfolio includes high amounts of local coal and natural gas, along with 16 GW of Solar and Wind generation capacity. The *Reliable 60% RE portfolio* has greater capacities of Wind, Solar and Hydro, almost double the amount of Nuclear, and lesser capacities of thermal sources compared to the *Indigenous* Portfolio. Both of these options present decision makers with fairly good choices: those prioritizing LCOE and land use would prefer the *Indigenous* portfolio; the *Reliable 60 % RE* portfolio would be the popular choice for decision makers prioritizing lesser GHG emissions and Air Pollution.

A comparison between *Zero Oil and Gas* and *Zero Coal* portfolios is also of interest. The reliable *Zero Oil & Gas* portfolio, which established a coal-renewable nexus, generally scores better overall. It might be an improvement on *BAU 2025*, but still suffers greatly in terms of sustainability compared to other available alternatives. The *Zero Coal* portfolio on the other hand, while scoring worst for reliability, excels in other sustainability metrics and scores better than the *60% RE* and *Zero Oil & Gas* portfolios in the absence of the reliability metric. This is due to the fact that this portfolio highly minimizes brown energy sources leading to low levels of Air Pollution, Greenhouse Gas emissions & Fatalities. While an unreliable portfolio may not be a viable solution for a stakeholder, it does provide an insight on the detrimental effect of coal to any portfolio, due to its high lifecycle air pollution emission as well as higher fatality rate.

The *60% RE* portfolio as well as *Zero Oil & Gas* portfolio also suffer due to lower scores in land use due to the higher amounts of Hydro Power in the portfolios. Land Use is an important metric for Pakistani stakeholders due to Pakistan's high population density and ever-increasing population. Nuclear Energy features heavily in the top scoring portfolios as it provides a sustainable alternative for base loads, compared to other thermal sources. The almost reliable *13 GW RE* portfolio offers a more sustainable alternative to the *BAU 2025* for a stakeholder who wants to ensure lower LCOE as well as lesser land use.

Our sensitivity analysis on the Discount Rate used in the LCOE calculation affected the total scores for some of our portfolios. Figure 8 shows the portfolio ranking for LCOE across 5% and 15% Discount Rates and how that affects the overall ranking for the portfolios under an equal preference stakeholder scenario. At a 15% discount rate, *BAU 2025* performed much better for LCOE than it did under a 5% rate, ranking best amongst the reliable portfolios. However, across all sustainability metrics in the equal scaling coefficients scenario, it still only outperforms the *50% Reduction in Thermal* portfolio. To provide further intuition towards the normalization of our scores for the LCOE metric, the minimum and maximum values of LCOE obtained for a portfolio for each of these Discount rates are displayed in Appendix D.

	LCOE - 5% DR	Overall Ranking using Equal Scaling Coefficients – 5% DR	LCOE - 15% DR	Overall Ranking using Equal Scaling Coefficients – 15% DR
60% RE -- meets demand	7	**1**	7	**1**
Indigenous -- meets demand	5	2	6	2
Zero Oil & Gas -- meets demand	6	3	8	4
60% Renewable Energy Policy	2	4	3	5
Zero Coal, Constrained Oil and Gas	3	5	**1**	3
13 GW Renewable by 2025	4	6	4	6
50% reduction in Thermal by 2025	**1**	7	2	8
BAU 2025	8	8	5	7

Figure 8: Sensitivity Analysis of the Portfolios for different Discount Rates
A ranking of 1 indicates the best performance while 8 indicates the worst performance for a portfolio. This figure utilizes a green-white-red color scale where greener cells indicate good performance and degrees of red indicate poor performance.

These results shed some light on the role of Overnight Capital Cost and Interest rates on loans for Pakistan in energy project development. Our top two portfolios for total sustainability score remained unchanged across all Discount Rates. A notable change was the *Zero Coal* portfolio, which performs better under an equal preference scenario at a 15% discount rate than the *Zero Oil & Gas* portfolio, moving up to third amongst all portfolios. As displayed in Figure 8, this can be attributed to both *Zero Coal* portfolio performing the best overall in LCOE and *Zero Oil & Gas* performing the worst at higher discount rates. The performance for *Zero Oil & Gas* portfolio can be explained by the very high amounts of Hydro Power and Renewable capacities in the portfolio, which are more effected by increasing the Discount Rates.

4.2.2 Sustainability Ranking under Alternate Preference Scenarios

Here, we investigate how the portfolios perform under different stakeholder preferences. The scaling weights are illustrated in Table 4, where the preferred metrics are given more weightage. The highest rated metrics in a preference scenario are indicated in Bold and add up to 0.9 while the non-preferred metrics constitute the remaining 0.1. All coefficients for a single preference scenario add up to 1. The preferred metrics for each scenario are indicated in Bold.

	LCOE	GHG	Air Pollution	Land	Fatalities	Jobs	ENS
Equal	**0.143**	**0.143**	**0.143**	**0.143**	**0.143**	**0.143**	**0.143**
Climate Change	0.017	**0.900**	0.017	0.017	0.017	0.017	0.017
Climate Change-economy	**0.300**	**0.300**	0.025	0.025	0.025	0.025	**0.300**
Economic	**0.450**	0.020	0.020	0.020	0.020	0.020	**0.450**
Environmental	0.025	**0.300**	**0.300**	**0.300**	0.025	0.025	0.025
Jobs	0.017	0.017	0.017	0.017	0.017	**0.900**	0.017
Jobs-climate change-economy	**0.225**	**0.225**	0.033	0.033	0.033	**0.225**	**0.225**
Jobs-economy	**0.300**	0.025	0.025	0.025	0.025	**0.300**	**0.300**
Socio-economic	**0.180**	0.050	**0.180**	0.050	**0.180**	**0.180**	**0.180**
Reliability	0.017	0.017	0.017	0.017	0.017	0.017	**0.900**

Table 4: Scaling Coefficients for Different Stakeholder Preferences

The results under alternate preference scenarios are displayed in Figure 9 below. The first thing we notice is how *BAU* performs poorly for all stakeholder preferences, despite being a reliable portfolio. Even for the reliability-heavy preference, it does worse than the *13 GW RE* portfolio, which failed to meet demand and had an ENS for 5 hours. This indicates that a rethink is required moving forward to make the energy mix of Pakistan more sustainable and environment friendly. The argument that the *BAU* is a portfolio providing the best economic solution for the generation mix is also refuted with reliable portfolios such as *Indigenous* as well as almost reliable portfolio of *13 GW RE* performing much better from an economic viewpoint. The *Indigenous* portfolio is one where a good compromise is observed between all stakeholder scenarios, as the portfolio scores well in all preference scenarios and is amongst the top ranked for all preferences, ranking 2nd or 3rd across the board.

Under an environmental preference, the *Zero Coal* portfolio scores the best but remains unreliable. It provides a valid comparison with the *Zero Oil & Gas* portfolio, where getting rid of coal scores better from an environmentalist's perspective but getting rid of oil and gas can be better when climate change and economy or a combination of it is preferred. Coal ranks very highly on lifetime air pollution emissions, whereas collective Greenhouse gas emissions from thermal sources such as Oil and Gas, overtakes the emissions through coal in Pakistan. Oil and gas industry in Pakistan is a well developed industry with highest contributions in the current energy mix. Coal however, is still a recent entrant to the energy mix and if further investments in coal continue over the coming years, the potential of coal overtaking the oil and gas sector in GHG emissions remain highly likely.

	Equal	Socio-economic	Climate Change	Climate Change-economy	Economic	Environmental	Jobs	Jobs-climate change-economy	Jobs-economy	Reliability
60% RE -- meets demand	**1**	**1**	**1**	**1**	5	2	**1**	**1**	2	**1**
Indigenous	2	2	3	2	2	3	3	3	3	2
Zero Oil & Gas -- meet demand	3	3	2	4	6	4	2	2	4	3
60% Renewable Energy Policy	4	4	5	3	**1**	6	4	4	**1**	6
Zero Coal, Constrained Oil and Gas	5	5	4	7	8	**1**	8	8	8	8
13 GW Renewable by 2025	6	6	6	5	3	5	5	5	5	4
50% reduction in Thermal by 2025	7	7	7	6	4	8	6	6	6	7
BAU 2025	8	8	8	8	7	7	7	7	7	5

Figure 9: Sustainability Ranking under Alternate Preference Scenarios
This table utilizes a Green-Yellow-Red scale where green indicates highest ranking while red indicates lowest ranking.
A bold value indicates the highest ranked portfolio.

Any portfolio promoting Renewable energy not only scores well for GHG emission and Environment, but also for job creation. Economically, a coal-RE nexus ranks badly for Pakistan, due to the higher costs associated with wind and imported coal. There is also a visible tradeoff between our top two portfolios, where adding some amount of thermal capacities, instead of the expensive RE technologies favors the economical perspective. However, given the learning curve trends observed globally as well as the trends observed in Solar energy within Pakistan for Solar tariffs, there are some positive indicators for decreasing RE costs going forward. Hence as such, the *60% RE portfolio* meeting demand, which currently suffers under economic preference scenarios might improve its ranking and present a uniformly viable alternative for all stakeholder preferences.

Just adding Renewable energy to the generation mix as observed in *13 GW RE* portfolio or reducing thermal energy sources by 50% are not the best solutions under any stakeholder preference, unless they are combined together for better performance.

We observe some dominated portfolios. The *BAU 2025* and the *Zero Oil and Gas* portfolios are dominated by the *Reliable 60% RE* portfolio; and the *50% Reduction in Thermal* and the *13 GW RE* portfolios are dominated by the *Indigenous* portfolio. Hence, our three bottom portfolios as well as the reliable *Zero Oil & Gas* portfolio are dominated by other options, and are not the best option for any of the stakeholder preferences we model.

Of the portfolios completely meeting demand, the *Reliable 60% RE* portfolio dominates across all stakeholder preferences except for economics, where it is outscored by the *Indigenous* portfolio.

In terms of energy diversity, *BAU* portfolio is the most energy diverse, whereas *Zero Oil & Gas* is the least diverse; getting rid of Oil, Natural Gas, RLNG and HSD. No generalizable relationship is observed between sustainability ranking for different stakeholder preferences and energy diversity.

CHAPTER 5
CONCLUSION

In this research we modelled the electrical grid system of Pakistan to evaluate the sustainability of electricity generation, considering a set of different energy portfolios. We defined a set of energy futures for Pakistan by combining different generation technologies and capacities. These portfolios were fed into our electricity generation model which evaluated the different portfolios by calculating the energy generated by each technology in that portfolio and whether the portfolio met demand or not. We then evaluated the results of the energy model against a set of sustainability metrics, so as to evaluate the portfolios considering the broad sustainability impact of both energy and capacity. An MCDA analysis was performed and the portfolios were evaluated in terms of various stakeholder preferences and policy scenarios.

Our research was based on the underlying principle that for portfolio development, each energy generating technology is evaluated as part of an energy portfolio. The aim of any stakeholder is to maximise utility of a portfolio as opposed to a single generating technology. We also understand that sustainability is multi-faceted and stakeholders can assign different weightages to multiple metrics. Our research was aimed at not providing a 'winner' portfolio but to understand the various correlated groups of sustainability metrics and the trade-offs involved in ensuring the preference of a stakeholder. Through this research we provided multiple paths towards a sustainable future, where determining the best path is left to the discretion of the decision makers and their preferences.

Our two most broadly sustainable portfolios offer the trade-off between Cost and Emissions. A *Reliable 60% RE* portfolio performs better in terms of environmental sustainability metrics, however an *Indigenous* Portfolio offers the least costly, but still reliable form of electricity for the nation. Generally, both perform well across our range of sustainability metrics, ranking amongst the top five across all stakeholder preferences.

The *Reliable 60% RE* portfolio offers a route for stakeholders to negate the current over-reliance on Thermal Independent Power Producers by an influx of wind and solar projects.

Meanwhile, the *Indigenous* portfolio provide a way to combat the high dependence on foreign oil for electricity generation by the utilization of indigenous sources of power.

Another important takeaway is the analysis observed in the sensitivity of the Discount Rate for LCOE. It was presented that with a discount rate of 5%, the *BAU* alternative is weak across all sustainability metrics. However, if we utilize a discount rate of 15%, which might reflect a more realistic option for Pakistan under the CPEC scenario, the *BAU* stands out as the least costly amongst the reliable portfolios. The Pakistan electricity market is currently facing issues of circular debt, crushing foreign loans and overreliance on subsidies for electricity generation. Hence as such, it is pivotal that the stakeholders understand the trade-offs involved in ensuring an economical and sustainable energy mix. To ensure economic sustainability, any stakeholder would have to be mindful of not only the LCOE but also the upfront capital cost associated with an energy project.

On the environmental front, given Pakistan's vulnerability to climate change, an urgent rethink is required particularly towards the coal heavy investment coming in through the Belt Road Initiative of China. Even local coal projects may well prove to be a detriment in the climate change struggle due to their high GHG emissions and pollution indices. Issues such as seasonal smog and air pollution will only be exacerbated by adding coal projects to the energy mix. For Pakistan to reach its NDC commitments and champion itself as a country at the forefront of the South Asian war against Climate change, energy dependency on coal would not be the best policy going forward. Stringent measures and policies need to be introduced for the approval of new energy projects and a consistent strategy is required to combat the inevitable climate change battle. A *Zero Coal* portfolio remains the best option from the perspective of a stakeholder promoting the environment. Our research provides alternative portfolios such as the *Indigenous* and 60% *RE* portfolios that can effectively meet demand, perform better from an economic perspective and score high across other sustainability metrics while limiting the amount of coal in the generation mix.

Another possible alternative to look at, if Pakistan is adamant on using its coal resources, is the Carbon Capture and Storage (CCS) technology. It presents a viable option for utilizing coal while remaining environment friendly. On the flip side it might be a land-use heavy alternative and is still a nascent technology, particularly for Pakistan. Further research is recommended on analysing how such a scenario might perform in comparison to the available alternatives to Pakistan and parallels can be drawn from the learning curves of solar and wind to suggest earliest adoption for CCS as a possible policy choice.

Both Hydro power and Nuclear energy currently offer good low emission energy alternatives for the country. However, geopolitics have to be taken into account for any such decision where these technologies are promoted, with Pakistan battling for an NSG membership since 2016 [28] and also battling multiple conflicts and disputes with India for water flow issues under the Indus Water treaty of 1960.[29]

From a Renewable energy perspective, both Wind and Solar offer good capacity factors for Pakistan and high Renewable portfolios generally score well under different sustainability metrics and rank well for various stakeholder preferences. Global trends of decreasing costs associated with these technologies present a good omen for Pakistan and can be a defining factor for current investments planned in the energy sector. Solar technology is comparable to some of the cheapest forms of energy in Pakistan right now and application of storage technologies might present one possible avenue to further expand and promote this technology.

Through this research we aimed at helping the stakeholders work towards achieving the following UN Sustainability goals from an energy perspective

- Goal 7: Production of affordable and clean energy
- Goal 8: Decent work and economic growth
- Goal 11: Sustainable Cities & Communities
- Goal 13: Climate Action

It is hoped that this research provides a viable middle ground for stakeholders and decision makers for an energy portfolio which not only combats the effects of climate change and incorporates greener sources of energy but also is economically viable for the Pakistani market and eases the dependence on foreign oil and gas for a more sustainable future.

APPENDICES

APPENDIX A
ELECTRICITY MODEL DATA

Electricity demand data was sourced by NTDC. Hourly demand data of the years 2015-16 up to 2019-20 was utilized in calculating the hourly growth rate for demand and projected up to 2025.

For calculation of hourly generation through wind technology, three sites were selected, and their results averaged out. The selected sites were Sujawal, Tando Ghulam Ali and Sanghar. Hourly wind energy speeds at 80m were sourced for the year 2016-17 for all three sites by data available through World Bank [30]. Wind turbines were assumed to be 5 MW in Power and with a hub height of 90 metres. An operational speed between 3 m/s and 25 m/s was assumed.

For calculation of hourly generation through Solar technology, solar irradiation data from three sites was utilized for the time period 2016-17. The selected sites were Quetta, Khuzdar and Hyderabad. Hourly global horizontal irradiance was sourced by the data available through world bank [31]. A solar farm of 1 MW was assumed with a Performance ratio of 0.75 and percentage yield of 0.15.

Monthly availability of hydro power resource was sourced through the NTDC State of Industry report [16]. Nuclear outages were assumed by a method similar to one utilized by the IGCEP report [19] where each nuclear plant was assumed to have 60 days of scheduled outage and 5% of unscheduled outages per year.

APPENDIX B

SUSTAINABILITY MODEL DATA

Table 5 and Table 6 below summarize the values utilized by the sustainability model in its calculations.

	Life Cycle GHG (gCO2eq/kW)	Life Cycle GHG (gCO2eq/kWh)	Air pollution emissions (mg/kW)	Air pollution emissions (mg/kWh)	Land use (m^2/MW) - max life cycle	Fatalities/GWh	Jobs (FTE/GW)
Coal	0	1140	0	19260	49412	28.00	1.01
HSD	0	778	0	1500	50586	10.00	0.48
BioMass	0	69	0	2971	14164	4.63	1.80
RLNG	0	520	0	1200	50586	3.00	0.94
Onshore Wind	20	0	345	0	285870	0.15	1.58
Solar	74	0	1528	0	176038	0.44	5.00
Natural Gas	0	487	0	988	50221	2.82	0.94
Nuclear	45	0	1671	0	51436	0.07	1.20
Hydro	15	0	419	0	1274761	1.40	2.33
Oil	0	875	0	3725	72843	18.43	0.94

Table 5: Sustainability Metrics Input Data

The Lifecycle Greenhouse Gas emissions data was sourced from NREL's Lifecycle Assessment Harmonization Data [32] and IPCC [33]. For greater accuracy and consistency in inferring this data for Pakistan, we assumed the third quartile value for each technology from the available datasets. [34]

Air Pollution emission values were sourced from Nock & Baker [21] and Klein & Whalley [35]. Air Pollution emission for Oil, Natural gas and Bio Mass was calculated through the US annual generation and United States Annual emission database (EIA) [36]

Life cycle Land Use by technology statistics were sourced by Fthenakis & Kim [25]. Data on fatalities was sourced from Markandaya & Wilkinson[37], [38]. Statistics about total jobs per unit capacity were secured from Wei et al [39].

Technology	C_Cap ($/kW)	C_o&m,f ($/kW)	C_o&m,v ($/kWh)	C_fuel ($/kW)
Coal	1300	25	0.0012	0.0521
HSD	900	17	0.0042	0.1384
BioMass	800	11	0.0025	0.0608
RLNG	900	17	0.0029	0.0789
Onshore Wind	2600	18	0.0038	0
Solar	1300	50	0.0040	0
Natural Gas	850	26	0.0062	0.0700
Nuclear	4000	80	0.0015	0.0100
Hydro	2300	33	0.0040	0
Oil	1160	22	0.0080	0.1028

Table 6: LCOE Metric Input Data

For Capital costs as well as Fixed and Variable maintenance costs, NEPRA Tariff documents for different technologies were utilized to source our values [40]. Fuel costs were sourced by NTDC State of Industry Report 2018 [17].

APPENDIX C

SUSTAINABILITY METRICS CORRELATION VALUES

Figure 10 below highlights the correlation values between any two sustainability metrics considered in our research. It takes into account all the different portfolios examined and gives a combined correlation value.

LCOE	-0.44	-0.31	0.38	-0.42	-0.38	-0.66
-0.44	**GHG**	0.78	-0.83	0.90	0.77	0.33
-0.31	0.78	**A.Pollution**	-0.35	0.97	0.23	-0.10
0.38	-0.83	-0.35	**Land Use**	-0.52	-0.92	-0.51
-0.42	0.90	0.97	-0.52	**Fatalities**	0.44	0.10
-0.38	0.77	0.23	-0.92	0.44	**Jobs**	0.71
-0.66	0.33	-0.10	-0.51	0.10	0.71	**ENS**

Figure 10: Correlation values between different sustainability metrics

A red bar indicates a negative correlation, whereas a green bar indicates a positive correlation. The length of the bar indicates the degree of correlation, while the number in each cell is the correlation value between two metrics.

APPENDIX D

HIGHEST AND LOWEST METRIC VALUES

To provide interpretation to the meaning of the scaling coefficients utilized in our sustainability analyses, the highest and lowest values for all metrics across our portfolios is presented in Table 7 below.

	Minimum Value	**Maximum Value**
LCOE ($/kWh) – 5% DR	0.086	0.100
LCOE ($/kWh) – 10% DR	0.111	0.142
LCOE ($/kWh) – 15% DR	0.155	0.223
GHG (gCO2eq/kWh)	104	408
Air Pollution (mg/kWh)	911	4970
Land Use (m^2/MW)	334000	491000
Fatalities /PWh	2.28	8.34
Jobs (FTE/MW)	1.45	2.11
ENS (GWh/portfolio)	0	743

Table 7: Minimum and Maximum Portfolio Metric Values

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