Techno-Economic Analysis of Wind Potential of Pakistan as Distributed Generation Source

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THESIS ACCEPTANCE CERTIFICATE

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DEDICATION

Firstly, I'll like to thank and dedicate this dissertation to Allah Almighty, for giving me strength, power, skill, wisdom and health, and perhaps I cannot deny his blessings. This dissertation is whole heartedly dedicated to my late beloved uncle Dr. Zahid Ishaq Khan. He has been a very loving and kind personality to me and his love is always being missed. May Allah Almighty have his blessing on him in his afterlife.

I also dedicate this dissertation to my parents, my brothers, my beloved sisters and my professors, who have been a source of continuous inspiration to me and provided me with the strength and vision to achieve my goals.

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ABSTRACT

Pakistan is a developing country with an ever-increasing energy demand. In the recent years Pakistan has been going through regional impact scale project like CPEC, which is bringing industrial and economic development in the country. Therefore, there is a large forecasted demand for energy in the country. However, Pakistan is still facing energy crisis mainly due to the inadequate electricity infrastructure in the country. The national transmission and distribution system efficiency has greatly reduced causing the shortfall in the country. Use of renewable based distributed generation is a promising option for Pakistan. Pakistan has a large wind resource available almost all around the country. This research study analyzed three different site locations in Gwadar, Quetta and Bahawalpur for 100 MW wind farms, in order to address the increasing demand by alternative source in these regions of the country as well as to reduce the load from the national transmission and distribution infrastructure. The study utilized system advisory model (SAM) for analysis and accommodated the latest financial parameter and real economic condition of the country for evaluating the feasibility of the wind farm. Additionally, the study provides the impact of various technical and economic variables, on the farm feasibility as well as provide an approach for optimum designing of wind farm in the country. A levelized cost of energy (LCOE) of 9.08 ¢/kWh, 11.0 ¢/kWh and 15.30 ¢/kWh were evaluated for Gwadar, Quetta and Baluchistan with a Payback time period of 4.2 years, 4.6 years and 6.5 years respectively. All three-site location provided a positive net present value (NPV), indicating the financial viability of the proposed sites. Additionally, energy production of 29,7859 MWh, 20,2515 MWh and 17,6848 MWh was calculated from Gwadar, Quetta and Bahawalpur site location with a net GHG reduction of 12,648 tCO_2, 85,993 tCO_2 and 75,145 tCO_2 from the respective sites. The LCOE are highly comparable with other generation sources as well as they pave the path from clean development in the country and are forecasted to provide energy security and reliability in the country for future developments.

Keywords:

Renewable energy production, Wind energy, Techno-economic assessment, clean energy, green development, System advisory model (SAM), Energy system modelling

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List of Abbreviations

DG-	Distributed Generation
RE-	Renewable Energy
GHG-	Green House Gas
EV-	Electric Vehicle
MTOE-	Metric Tons of Oil Equivalent
CPEC-	China Pakistan Economic Corridor
SAM-	System Advisory Model
LCOE-	Levelized cost of energy
NPV-	Net Present Value
IPP-	Independent Power Producer
ANN-	Artificial Neural Network

List of Publications

Title	List of Authors	Research Journal/ Category/Impact Factor	Status
Techno Economic Feasibility Analysis of 100MW Wind Farm in the Northern Coastal Region of Arabian Sea	M. Zaid Masood Khan Sehar Shakir Abdul Kashif Janjua H.M. Abd ur Rehman Adeel Waqas Majid Ali	Energy Conversion and Management / Q_1-W / 9.7	Under Review 1^{st} Revision in process

Chapter 1

Introduction

Energy, mainly in the form of electricity has become an essential component for the prosperity and development of a country. Since the industrial revolution globally, energy resource utilization has been a principal variable in re-defining the socio-economic development, prosperity & wellbeing of a country. An effective, strong and reliable energy resource profile of a country depicts how well prepared they are in order to coupe up with the future energy need [1].

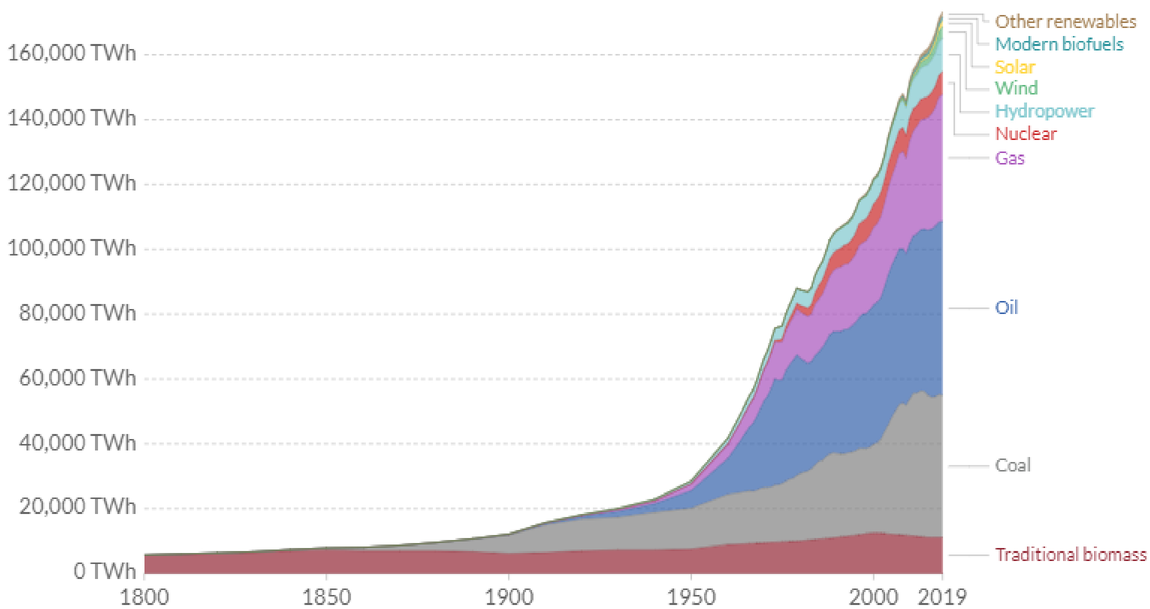

Figure 1.1: Global energy consumption by source [2] , [3]

The global human population continues to grow, and countries are continuing to develop, causing steep increases in the demand for energy. At the current rate of increasing energy use, energy demand is expected to increase 65% from 2004 levels by 2030 [4]. Up till now, the energy demand is met up majorly by the use of fossil fuel-based power generation as they provide instant energy at a much lower capital cost for initiating such power generation stations. However, traditional power plants have been the major contributor in the increased greenhouse gas emission, causing a chain reaction of global warming and acid rains around the globe [4].

Energy consumption has increased exponentially, especially in form of electricity from the beginning of this century. Greenhouse gas (GHG) emission from conventional fossil fuel usage is one of the biggest motivating factors in shifting of energy usage in form of direct combustion to electricity-based usage. Transportation sector is a major contributor in the global GHG emission and consumer of fossil fuels [5]. In 2015, the global transport sector consumed approximately 31,310TWh of final energy and contributing 14% in the global greenhouse gas emissions. However, the transportation sector is swiftly converting from fossil fuel usage to alternate form of energies such as electricity. Electrical vehicles (EV) market has been growing exponentially in the past decade with only a few thousand in the beginning to 7million EV by the end of the decade [6]. This conversion of transportation sector from fossil fuel to electricity is one of the key indicators of rise in demand of energy specially in the form of electricity.

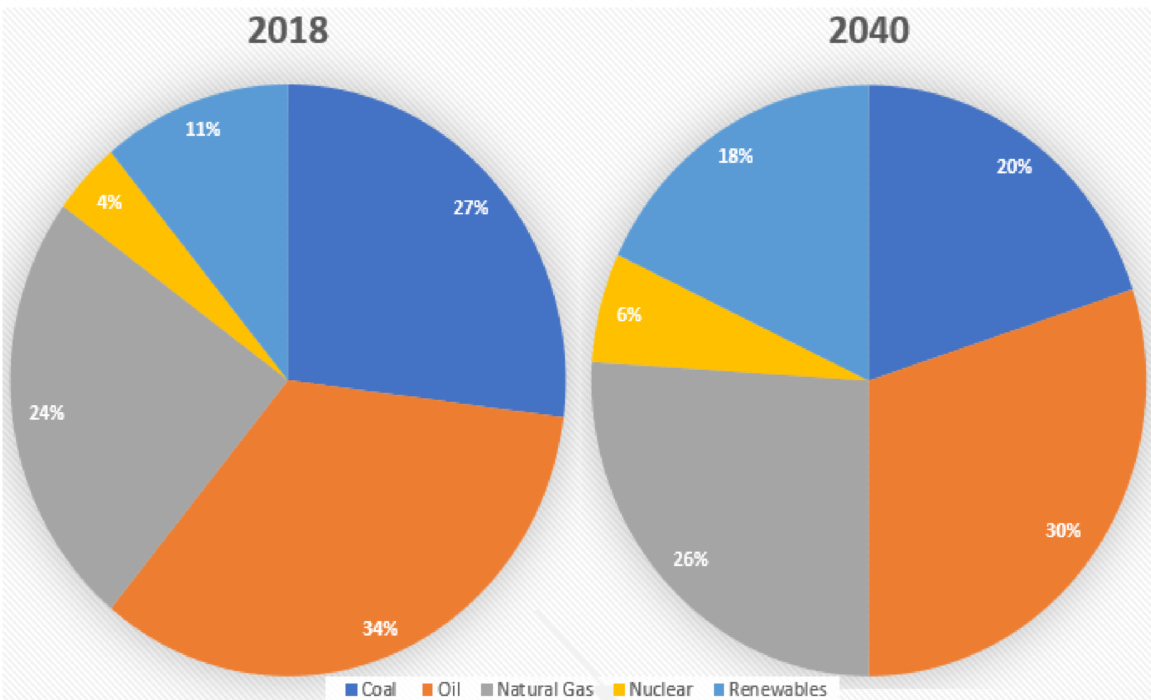

Figure 1.2 : Global energy mix 2018 & 2040 [7]

1.1 Pakistan Energy Scenario

Pakistan is a developing country, with a continuous need for energy demand due to modern development. Pakistan's energy demand in the beginning of the past decade was around 14,375 MW which by the end of decade has reached to around 28000 MW. This increase of demand is due to both in increase in the domestic sector as well as the commercial and industrial sector [8]. The share of household consumption has increased significantly as compared to the pervious years at around 44.20% share of total consumption of electricity followed by industrial sector at 29.45% in fiscal year 2019-2020 [9].

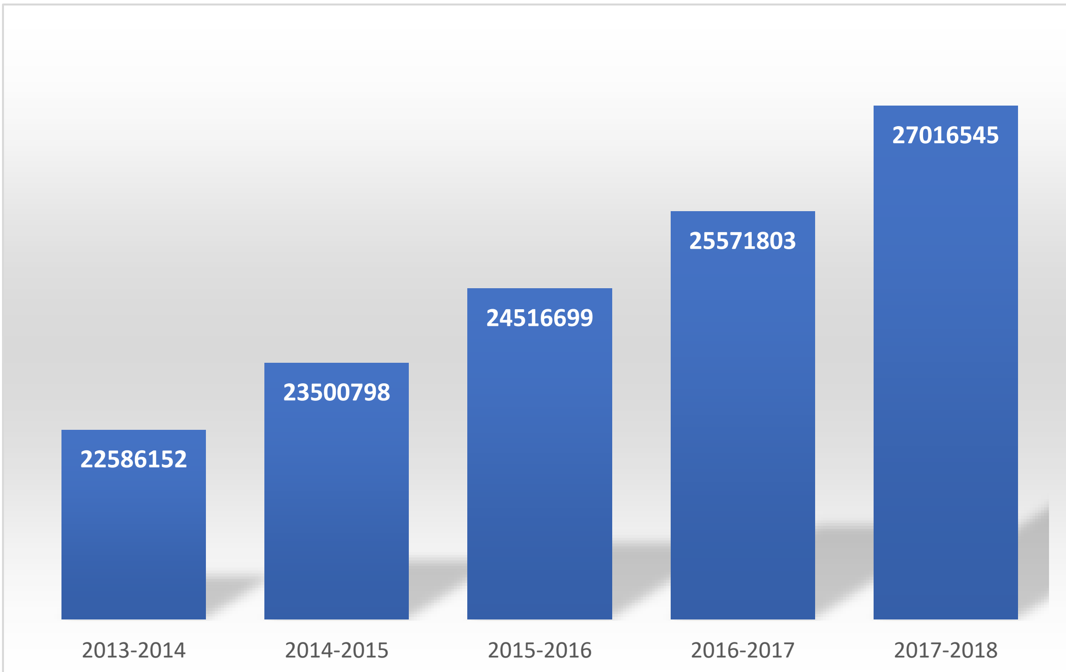

Figure 1.3 : Trend of number of electricity consumers in Pakistan [11]

Conventionally, the increased electricity demand globally is met by the use of fossil fuels-based power plant. However, this extensive use of fossil fuels has caused a chain of catastrophic events such as global warming due to the GHG emission produced by the fossil fuel-based power generations. Pakistan like other countries also relies heavily on the fossil fuel-based generation to meet its energy demand which has caused a significant damage to its environment [4]. Pakistan depends heavily on crude oil for producing electricity as well as in the industrial and transportation sector. The oil makes around 40% of the Pakistan's energy mix followed by the use of natural gas for both the domestic and commercial use as well as in Industries. The use of coal makes about 15% of the Pakistan energy mix and is used majorly in the power sector for coal-based power generation. Pakistan produced around 194.09 MTOE of CO_2 in 2018 across all sector of the society

[10]. Figure 1.4 represents the Pakistan energy mix which is clearly dominated by the fossil fuels.

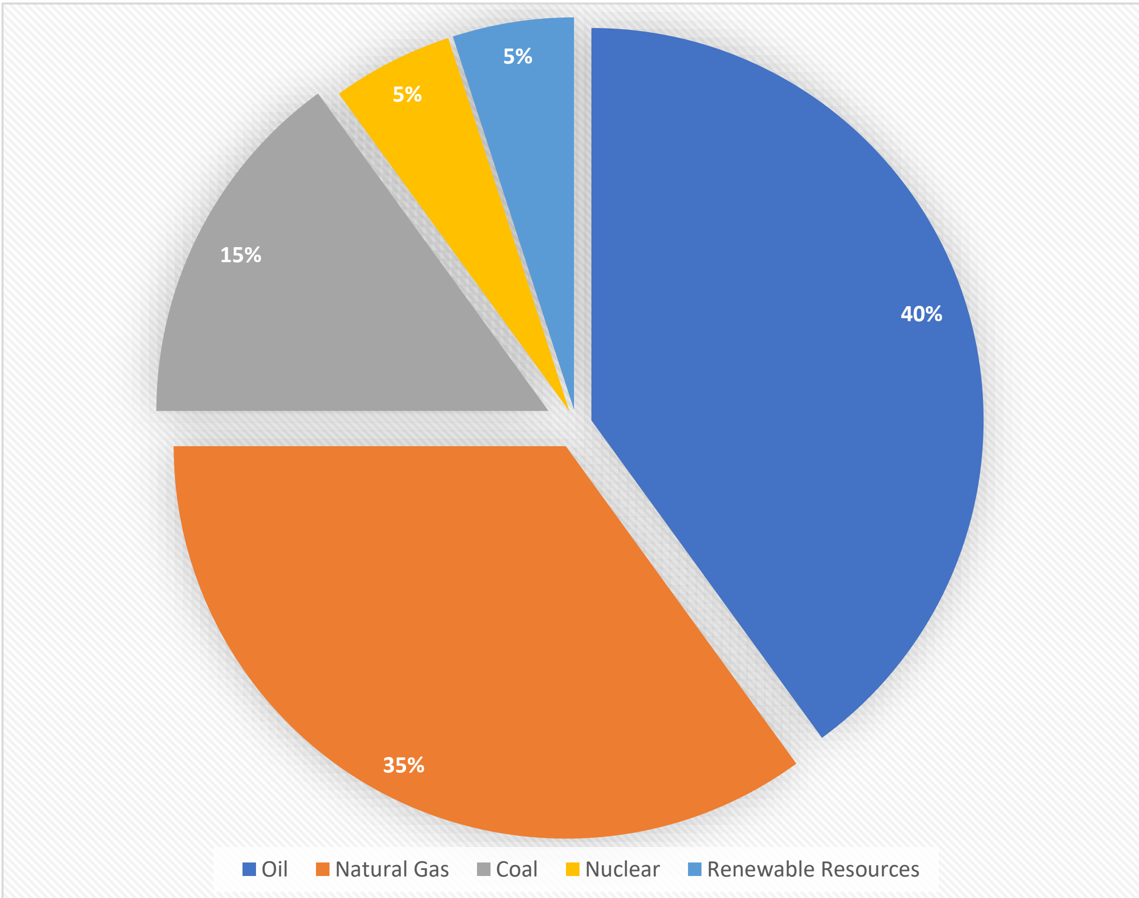

Figure 1.4: Energy Mix of Pakistan [11]

1.2 Problem Statement

Pakistan has a current installed generation capacity of electricity at around 37,402 MW with a current demand of around 25,000 MW. However, Pakistan is still facing energy crisis in the current century [12]. One of the key reasons of these energy crisis is not the generation capacity, but the inadequate electricity transmission system capacity[13], [14]. Pakistan transmission and distributed system is badly affected causing extreme energy losses and is stalled at around 22,000 MW capacity. This difference is the major reason of the energy crisis in Pakistan badly effecting not the only the economy as well as the power system reliability and quality.

Replacing or upgrading this transmission system is one possible solution to this energy crisis, However, the upgradation and replacement not only requires large amount of capital and but also extensive amount of time. Another, promising solution to addressing this energy crisis issue in Pakistan is the use of distributed generation (DG) in the power system which will not only reduce the number of losses caused due to aging infrastructure but also help in increasing the power system quality and reliability. Various researches have presented along with different approaches for the solution of these energy crisis through distributed generation. Use of renewables as distributed generation near the load centers is seen as one of the green solution to address this problem of energy crisis and GHG emissions in these countries [14], [15].

Pakistan has a large potential of renewable resource available, spread across the country which can be used as distributed generation stations. Pakistan has a theoretical potential of 340 GW of wind energy available which is majorly available in the down south region along the coastal line as well as in the central and western region of the country [16]. The use of wind energy will not only provide the necessary energy security in the country but can also significantly reduce the emission while coping up with the electricity demand. A large number of annual emissions can be reduced by producing electricity with wind turbines instead of fossil fuels. A rough approximation shows that 1 MW wind turbine can reduce about 1.36×10^6 Kg of CO_2, annually [17].

The research study focuses on the techno-economic analysis of different wind energy potential location in the country, in order to provide a detailed feasibility analysis of addressing the energy crisis of Pakistan through wind potential.

1.3 Objectives

The objective of this research is:

- To analyze the potential of wind energy in Pakistan as a source of distributed generation
- To provide a detailed techno-economic feasibility analysis for electricity generation from wind energy.

- To provide a detailed analysis of different aspects of economic and technical feasibility, acting as a guideline document for future policy making.

1.4 Scope

The research study focuses on the potential assessment of wind in the regions with a forecasted increasing demand of energy in Pakistan. The study looks into the possibilities of how they can be efficiently used in making a considerable difference in increasing the power system efficiency and reliability trough the utilization of wind potential as a source of DG.

1.5 Limitations

A major limitation for this study is the data used for the analysis will be used from the nearby weather station or collections point. We cannot make our own primary data as it is a long and extensive process and will highly affect the research time period. The use of secondary data for analysis will provide an approximation of the potential assessment of the region. However, for the true site location estimation a physical anemometer needs to be deployed and the proposed site location for the exact estimation and analysis of potential assessment.

1.6 Thesis Structure

Chapter #1 provides an overview to the global energy scenario, followed by a brief introduction of the current energy scenario of Pakistan. The chapter presents in detail the problem to be addressed in the research study. The chapter enlists the objectives, scope and limitation of the research study.

Chapter # 2 explain in details the Pakistan energy sector and the challenges being faced, followed by the Pakistan wind energy scenario. The chapter discusses the possible solution to the problems faced and presents similar works and methodologies used to analyze the wind potential and their feasibilities.

Chapter # 3 defines the methodology and approach used for analysis of various location. It also compares different methodologies and defines the flow of study

Chapter # 4 consist of the results and their discussion based on the objectives of the research study. It discusses in details the results and compare them with already published literature and studies.

Chapter# 5 concludes the documents and highlights the major finding of the study with policy recommendations.

Summary

Energy demand is directly linked with the human development. Pakistan is a developing country with a forecasted very high energy demand in the coming years. However, Pakistan is still facing severe energy crisis due to its aging infra structure of transmission and distribution. The use of wind potential as DG is a promising solution to address this energy crisis while achieving a clean and green development process.

The study focuses on the potential assessment of wind potential along with the detailed techno-economic feasibility analysis in areas where there is a forecasted increasing energy demand in the future.

References

[1] U. Zafar, T. Ur Rashid, A. A. Khosa, M. S. Khalil, and M. Rahid, "An overview of implemented renewable energy policy of Pakistan," Renewable and Sustainable Energy Reviews, vol. 82. Elsevier Ltd, pp. 654–665, Feb. 01, 2018, doi: 10.1016/j.rser.2017.09.034.

[2] "Statistical Review of World Energy | Energy economics | Home." https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed May 11, 2021).

[3] "Energy Production and Consumption - Our World in Data." https://ourworldindata.org/energy-production-consumption (accessed May 11, 2021).

[4] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," Renew. Sustain. Energy Rev., vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[5] S. Khalili, E. Rantanen, D. Bogdanov, and C. Breyer, "Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world," Energies, vol. 12, no. 20, p. 3870, Oct. 2019, doi: 10.3390/en12203870.

[6] R. G. Newell, D. Raimi, and G. Aldana, "Global Energy Outlook 2019: The Next Generation of Energy," Resour. Futur., no. July, p. 46, 2019.

[7] R. Rasheed et al., "An analytical study to predict the future of Pakistan's energy sustainability versus rest of South Asia," Sustain. Energy Technol. Assessments, vol. 39, p. 100707, Jun. 2020, doi: 10.1016/j.seta.2020.100707.

[8] Ministry of Finance, "Chapter 14 - Pakistan Economic Survey 2015-2016," pp. 98–105, 2016.

[9] M. of Finance, "Pakistan Economic Survey 2019-20," pp. 1–27, 2020, [Online]. Available: http://www.finance.gov.pk/survey/chapter_20/PES_2019_20.pdf.

[10] "Pakistan - Countries & Regions - IEA." https://www.iea.org/countries/pakistan (accessed Feb. 04, 2021).

[11] Ministry of Finance, "Pakistan Economic Survey," 2019, [Online]. Available: http://www.finance.gov.pk/survey/chapters_19/Economic_Survey_2018_19.pdf.

[12] S. Z. Abbas, A. Kousar, S. Razzaq, A. Saeed, M. Alam, and A. Mahmood, "Energy management in South Asia," Energy Strategy Reviews, vol. 21. Elsevier Ltd, pp. 25–34, Aug. 01, 2018, doi: 10.1016/j.esr.2018.04.004.

[13] S. Shah, A. Rashid, M. K. L. Bhatti, S. Khattak, and L. Khan, "Crisis of Electrical Energy in Pakistan and Future guide line for policy makers," 2010.

[14] C. Vidya, P. M. Anbarasan, and K. M. Prabu, "Energy Crisis and Recent Technological Development in India," vol. 7, no. 1, 2017, Accessed: May 11, 2021. [Online]. Available: www.iiste.org.

[15] K. Latif, M. Y. Raza, Shahid Adil, and Rehana Kouser, "Nexus between Economy, Agriculture, Population, Renewable Energy and CO2 Emissions: Evidence from Asia-Pacific Countries," J. Bus. Soc. Rev. Emerg. Econ., vol. 6, no. 1, pp. 261–276, 2020, doi: 10.26710/jbsee.v6i1.1072.

[16] S. H. Shami, J. Ahmad, R. Zafar, M. Haris, and S. Bashir, "Evaluating wind energy potential in Pakistan's three provinces, with proposal for integration into national power grid," Renewable and Sustainable Energy Reviews, vol. 53. Elsevier Ltd, pp. 408–421, Jan. 01, 2016, doi: 10.1016/j.rser.2015.08.052.

[17] M. Memon, K. Harijan, and M. A. Uqaili, "Assessment of wind home system's potential in coastal areas of Pakistan," in AIP Conference Proceedings, 2007, vol. 941, pp. 80–89, doi: 10.1063/1.2806075.

Chapter 2

Literature Review

There is a never-ending increasing demand for energy as humankind is developing. Energy demand trends are a key indicator of development in a country [1]. Energy demand per capita has exponentially increased in the past decades mainly caused due to the modern development and increased per capita consumption around the globe [2]. So far, the rising demand is fulfilled by the use of fossil fuels for energy production. However, fossil fuels are not only finite, as well as a major source of GHG emissions. These extensive use of fossil fuels for energy production has led to a chain reaction of global Warming and acid rains around the globe [3].

Fossil fuels has been dominating the global energy mix for a very long time. The major motivating factor for the use of fossil fuels are, easy availability of resource as well as the ability to provide instant energy along with low cost. However, this resource is not only finite but also comes with short-comings like GHG emissions [3]. Figure 2.1 depicts the per capita use of energy around the globe.

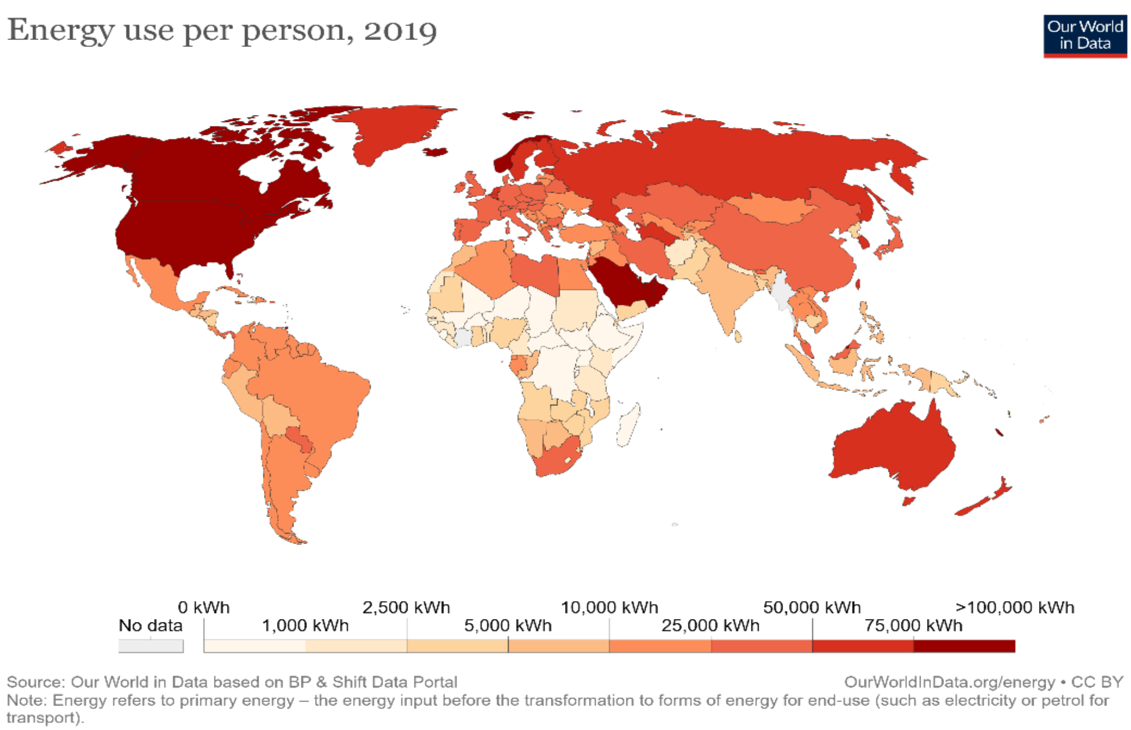

Figure 2.1: Energy consumption per capita map of the world [4]

Pakistan like other developing country has a continuous increasing demand of energy. Pakistan has a per capita consumption of 460.23 kg of oil equivalent in 2014. In Pakistan, primary energy sources are mainly thermal (62.1%), hydropower (25.8%) and nuclear power (8.2%) [5]. The total energy supply in 2018 was 111.28 million tons of oil equivalents (MTOE). The primary energy sources were Oil (28.894 MTOE), Gas (28.307 MTOE), Coal (11.376 MTOE), Hydroelectricity (3.2 MTOE), Nuclear electricity (2.7 MTOE). The energy mix of Pakistan is dominated by the Oil at 40% followed by natural gas at 35% with 15% share of Coal as well as 5% from Nuclear as well as from different renewable resources [6]. This domination of fossil fuel resource is the energy mix of Pakistan is causing the energy security and environmental issues in Pakistan as the fossil fuels are not only expensive as well as cause emissions. Pakistan has a total CO_2 emission in 2018 of around 194.09 metric tons which is causing serious environmental damages in the country [7].

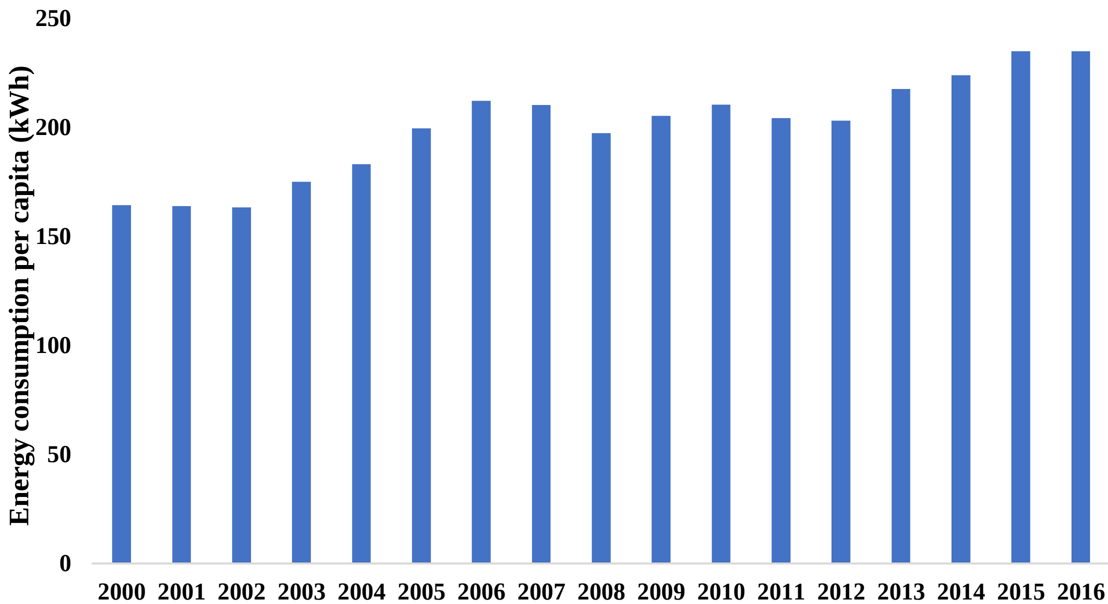

Figure 2.2: Pakistan energy consumption per capita trend [8]

However, Pakistan still faces extreme energy crisis in meeting its energy demand [9]. One of the key reasons of the energy crisis in the country is the aging electricity transmission and distribution infrastructure. The transmission system efficiency has declined badly causing immense amount of losses causing these energy crisis in Pakistan [10], [11].

2.1 Pakistan Energy Demand

Pakistan has an ever-increasing energy demand, due to increasing industrial development and consumption due to human development across every sector of the society. Domestic sector accounted for the largest avg. growth in the energy consumption at a growth rate of 4.66% in between 2014-18. Commercial sector showed an avg. growth rate of 3.47% followed by industrial sector at 2.58% and 1.98%. Similarly, agriculture sector has also shown a growth rate of 0.82% in between 2014-18 [12].

The increased growth rate in the domestic sector is mainly due to the increasing population and the infra structure development across the country. Moreover, industrial sector has been developing in the past decade, specially under the CPEC causing escalated demand from the industrial sector. It is calculated that by 2027-28 the domestic sector energy demand will reach up to 93,753 GWh followed by the industrial sector at 44,416 GWh [12]. This escalated increase in demand needs to be met by the country in order to continue its development. A reliable and optimal energy resource utilization is important in this prospect in order to achieve a smooth sustainable development.

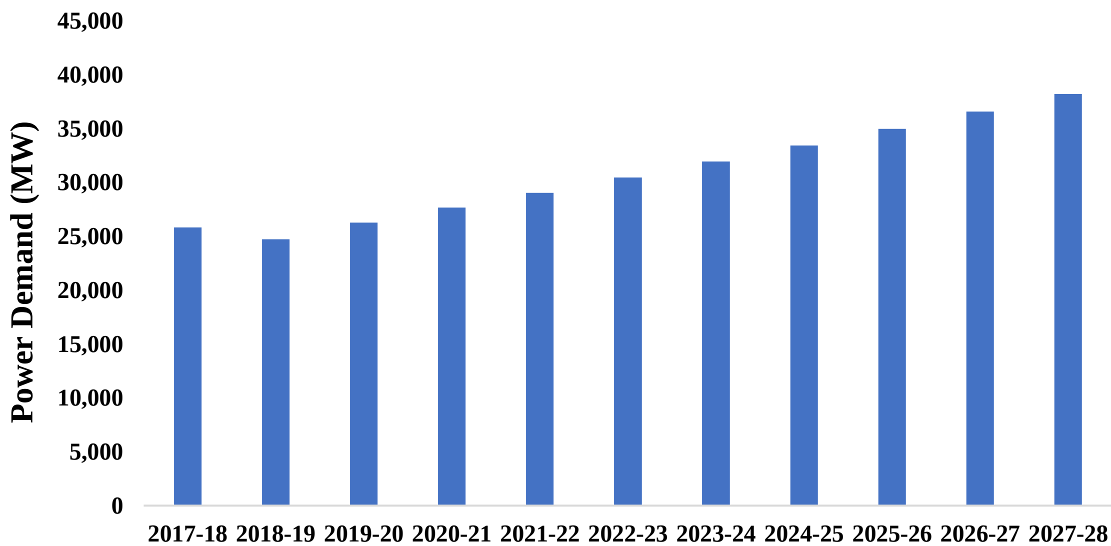

Figure 2.3: Pakistan peak demand forecast [12]

2.2 Pakistan Energy Crisis

Pakistan's energy generation sector consists of vertically integrated system and is categorized into 3 main parts. The central generation stations, The transmission and distribution system and the energy consumption/end user. Losses at any stage of power system cause the disruption in the system causing energy crisis across the country [10]. There is a very high demand in the energy consumption caused due to the development almost across every sector of the country. National transmission and dispatch company (NTDC) reports a forecasted growth rate of 4% in energy demand from 2017-2028 [12].

Pakistan has been suffering severely with the energy crisis from the beginning of this century due to decaying transmission and distribution system leaving millions behind with no or very poor power supply. Urban areas of Pakistan have been facing load shedding of up to 8hrs in summer while the rural areas are facing a load shedding of up to 12 hrs or more [13].

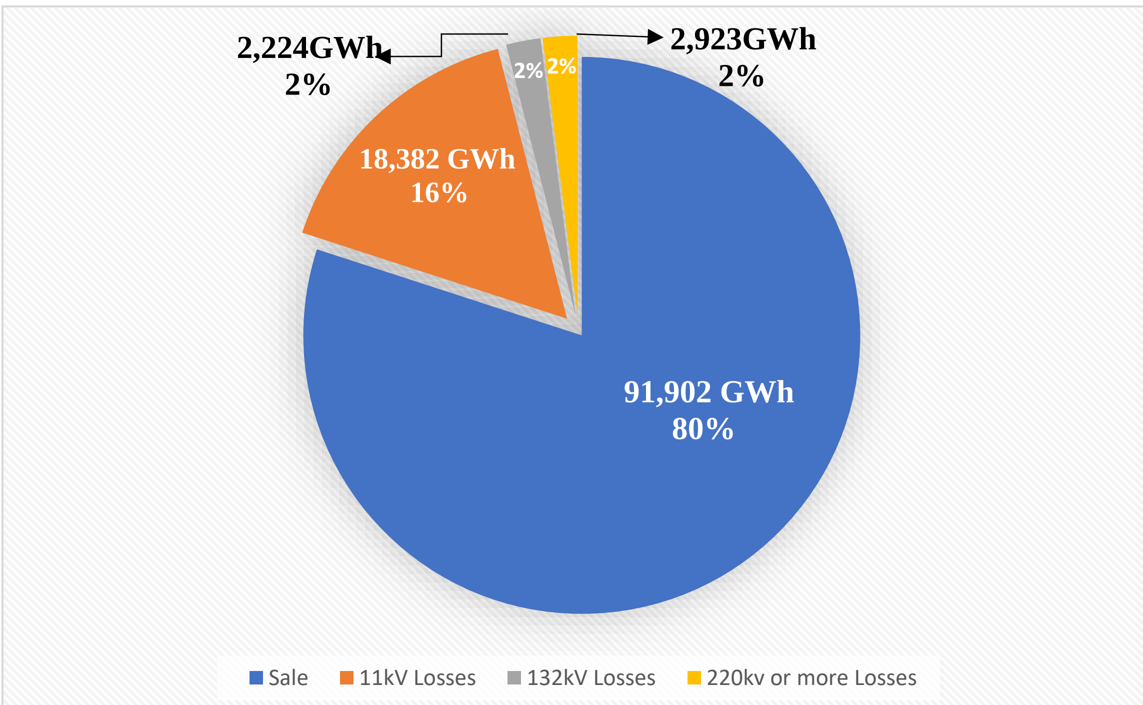

Figure 2.4: Trend of energy losses and power sale in 2017-18 [12]

Pakistan has an adequate generation capacity of 37,402 MWh with a peak demand of 25,000 MWh. However, all the generation systems are attached to a central transmission and distribution network that provides energy from generation source to the consumer. Pakistan transmission and distribution efficiency has decade over the years and is stalled at a capacity of 22,000 MWh, due to large amount of line losses. These losses account for around 20% of the total energy production. Additionally, these losses not only cause financial losses but also cause the performance of the lines to decay causing the trappings of major transmission lines leaving behind large population with load shedding and energy crisis.

The losses are divided into 2 main types:

1. **Transmission Losses (220kV and above)**
2. **Distribution Losses (132kV and below)**

These losses can be mitigated by replacing the lines with properly sized conductors in both the high- and low-tension wires. Another, possible solution is to install reactive power sources for power factor management to reduce these losses [12], [14]. However, the solution proposed are not only expensive but also requires a large amount of time for upgradation and replacement.

2.3 Addressing the Energy Crisis

Various research studies have been conducted in order to address the energy crisis and presented different remedies and solutions to coupe up with the energy crisis around the globe. Replacement of electricity transmission infrastructure is not only expensive but also requires a large amount of time effecting even greater population throughout the country. An optimal solution to reduce the energy crisis in the current infrastructure and increase energy security the DG systems is a promising solution.

Sahito et al. presented the importance of DG's and how they can help improve the system reliability and security. They analyzed the impacts of DG on the system and found that, the integration of DG in the system improves the voltage quality, stability and security of the power system. One of the key points highlighted with the DG, is that as close the DG are to the load center the system will observe more stability and reliability [15]. M K L Bhatti et al. analyzed the energy crisis in Pakistan and presented those non-conventional resources like wind and solar plays an important role in overcoming the energy crisis in Pakistan. Moreover, in his discussion he highlighted that it's not only the problem with the generation capacity in Pakistan but as well as the transmission system. The generation capacity of Pakistan is quite enough to meet the demand but the transmission and distribution system doesn't support such high load causing problem in energy security and reliability [16].

Wajid et al. presented a steeple analysis of prolonged energy crisis in the country. The work presented a case study of prolonged energy crisis in Pakistan highlighted various issues causing these crises using the STEEPLE analysis. He looked into various policy, infrastructure, technical and environmental issues. He found in his analysis that in order to improve the energy security in the country, there needs to be an improvement in the transmission system, but this is a pro-longed and financially intensive process. Another, recommendation in his analysis was to increase the DG near the load centers so as to improve the energy security in the system [17]. Khalid Latif et al. presented a Nexus between the economy, agriculture, population. renewable energy and CO_2 emission, their work analyzed the energy crisis of Pakistan and potential of renewable energy. In his finding he emphasized on the use of renewable and discussed the polices which can help increasing the energy security in the country. He highlighted the importance of renewables and identified the areas for implementation. In his finding, he reported that Pakistan can overcome its energy crisis with implementing renewable energy technologies like wind and solar with providing the energy security for many years to come [18].

2.4 Pakistan Wind Energy Potential

Pakistan has a large potential of renewable resource available, spread across the country. Pakistan has a theoretical potential of 340 GW of wind energy available which is majorly available in the down south region along the coastal line as well as in the central and western region of the country [19]. The use of wind energy will not only provide the necessary energy security in the country but can also significantly reduce the emission while coping up with the electricity demand. A large number of annual emissions can be reduced by producing electricity with wind turbines instead of fossil fuels. A rough approximation shows that 1 MW wind turbine can reduce about 1.36×10^6 Kg of CO_2, annually [20].

2.5 Pakistan Wind Energy Scenario

Globally, the wind installed capacity is on a rise due to the technology advancement, more efficient designs and system as well as market acceptability. Wind turbine installation globally increased from 7.7 GW in 1997 to 564 GW in 2018 [22]. In Pakistan, the 1st Wind Farm was installed in 2002 with capacity of 50 MW. The world bank in 2015 initiated a project of mapping global wind energy potential. This project highlighted the potential sites where wind potential is available for larger and small-scale implementation globally. In Pakistan, the largest corridor assessed is the Jhampir corridor of Sindh were already a lot of wind energy harvesting is ongoing and contributing a significant share in the Pakistan's total energy mix [23].

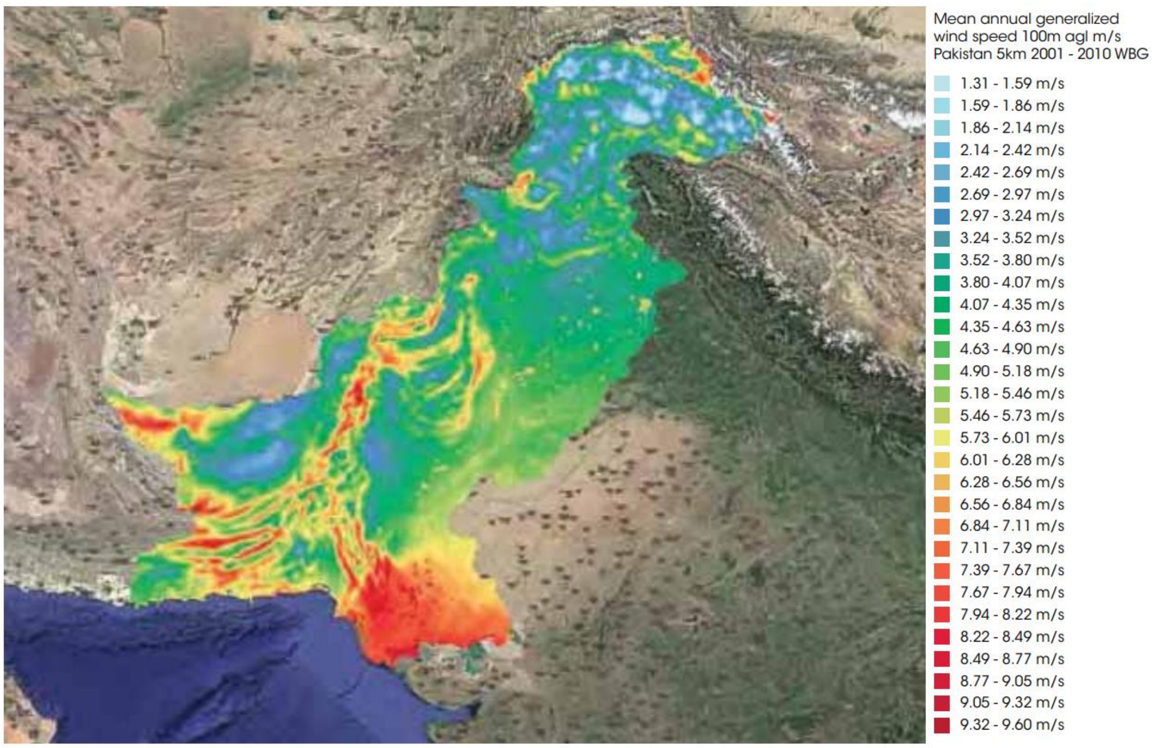

Figure 2.5: Wind Energy Resource Map of Pakistan [21]

Pakistan has about 1000 km long coastal line of which 270 km is in Sindh and rest of the coastal line is in Baluchistan, both provinces have great potential to utilize this wind energy to meet their energy demands. However, energy from renewable resources has very little contribution to the national energy mix of Pakistan despite having immense wind and solar potential [24].

In Pakistan, currently 12 projects with a combined capacity of 590.5 MW are providing electricity in the national grid as well as 5 more projects with a combined capacity of 297.6 MW are being completed currently and will be providing the electricity to the national grid in coming future [21]. Table 2.1 and 2.2 enlist some of the installed and under construction wind energy projects in Pakistan.

Table 2.1: Major installed wind farm in Pakistan [25]

Project Name	**Installed Capacity (MW)**
Zorlu Energy Pakistan Ltd.	56.4
FFC Energy Ltd.	49.5
Foundation Wind Energy I	50
Foundation Wind Energy II	50
Three Gorgeous Wind Farm Pakistan (PVT) Ltd.	49.5

Table 2.2: Under construction wind energy projects in Pakistan [25]

Project Name	**Installed Capacity (MW)**
Sapphire Wind Power Company Ltd.	50
Metro Power Company Ltd.	50
Master Wind Energy (Pvt) Ltd.	50
United Energy Pakistan (Pvt) Ltd.	50
Tapal Wind Energy Ltd.	50
Yunus Wind Energy Ltd.	50
Tenaga Generasi Ltd.	50
Hydro China Dawood Power (Pvt) Ltd.	50
Gul Ahmed Wind Power Ltd.	50

2.6 Distributed Generation

Vertical-Integrated system are a common standard of power system around the globe. In vertical integrated power system, the power is generated in large plants and then transferred to the load center/consumers through a transmission and distribution system working at high and low voltage levels. A major motivating factor of the vertical integrated power system was the economics of scale, as large amount of generation in a central location produces energy at fairly low cost than multiple power station on each load center. However, the vertical integrated system has some drop back such as the power losses in the transmission and distribution of electricity. Over the time the conductor's decay, causing the losses to multiply thus dropping down the transmission capacity and the efficiency of the system [26].

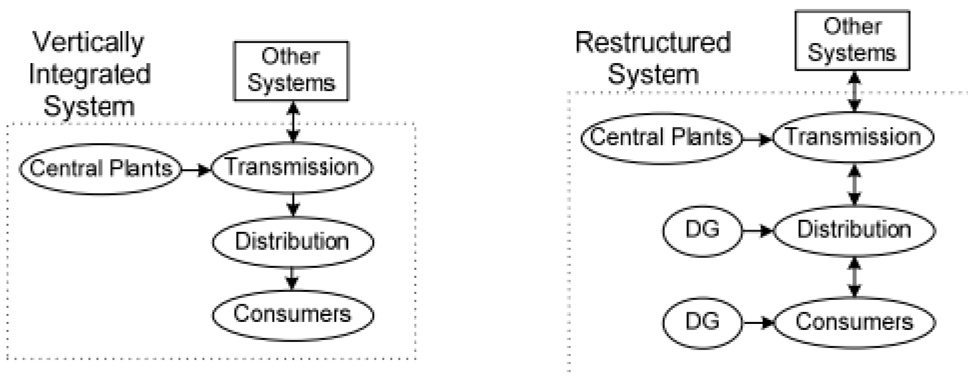

Figure 2.6: Vertical integrated system vs restructured system [27]

One of the major ways of dealing with the up stated concerns of power losses is mitigated by re-structuring the system by adding DG at each part of the system. This will provide not only better performance but also help in ensuring the energy security and blackout avoidance.

2.6.1 Defining Distributed Generation

Distributed generation (DG) can be simply defined as a small-scale generation near the load center. However, the literature presents multiple definitions to DG. CIRED (The International Conference on Electricity Distribution) defines the distributed generation to be generation source of maximum capacity of 100 MW, connected to a distribution network [28]. IEA however, presents a comprehensive definition of distributed generation as power generation on consumer site or within local distribution system and provide power to the local distribution network [27]. IEEE also defines DG as generation facilities, connected to a local region power system through a point of common coupling [29].

2.6.2 Technologies for Distributed Generation

Distributed generation can be majorly divided into 2 categories: 1. Renewable based 2. Fuel-based. The fuel-based technologies utilize mostly the fossil fuels as primary source of energy to produce electricity. Fuel based technologies include steam turbines, diesel generators and micro-turbines. The fuel-based technologies have however an associated disadvantage of the fuel cost as well as GHG emissions.

Renewable based DG have a distinct advantage over the fuel-based system as they produce no or comparatively very small-scale emission. PV technologies, wind turbines and micro-hydel system are considered in the renewable based DG sources.

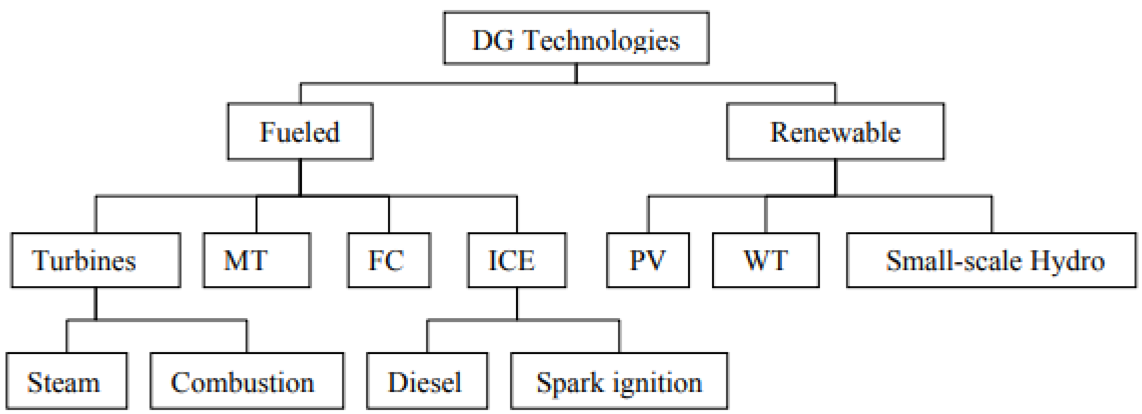

Figure 2.7: Classification of distributed generation technologies

2.6.3 Potential Benefits of Distributed Generation

The use of DG provides a wide range of advantages in the power system. Some of the major advantages are enlisted below:

- Deferred and avoided T&D expansion
- Reduced system losses
- Improved reliability and power quality
- Improved grid security
- Reduced emissions

2.6.3.1 Deferred and Avoided T&D Expansion

The use of DG system in the integrated power system can help avoiding the expensive cost of replacement or expansion of decaying transmission and distribution infrastructure by implementing DG in optimal locations. Utilizing DG in the power system helps in reducing the power losses in both the transmission and distribution infrastructure. Moreover, utilizing DG also reduces the cost of electricity as the consumer tariff includes a significant share of transmission and distribution. It is calculated that localized DG can reduce the cost of electricity by 30%. Additionally, utilizing DG reduces the power loss in the transmission and distribution, which reduces the financial losses, caused by the power disputation during transmission and distribution [30].

2.6.3.2 Reduced System Losses

The power losses are given by the formula I^2R. Resistance has a direct proportion to the power loss. The resistance increases in conductor as the length increases. In case of DG, the generation is done near to the load center, which requires less transmission or distribution thus reducing the power losses as compared to conventional central power generation system. Moreover, the utilization of DG will also provide relief for the over loaded lines thus decreasing their power losses in the whole system [30].

2.6.3.3 Improved Reliability and Power Quality

Utilizing DG also aids in increasing the reliability and power quality of the grid. Reliability in this context can be expressed as the expected duration of an outage over a period of time, while the power quality is expressed by the frequency of occurrence and duration of voltage sags. This is achieved by DG as they act as alternate or back up source on the grid and in case of power outage from central generation station, they can keep the local grid energized [31].

2.6.3.4 Reduced Emission

Renewable based DG significantly contribute in reducing the emissions. GHG emission is a byproduct of fossil fuel-based electricity generation. Utilizing renewable based DG in the system will reduce the dependance and demand of power from the conventional fossil fuel powered central power station, thus reducing the emission. Moreover, high voltage transmission faces a phenomenon named as corona effect. This corona effect causes the ionization of the air around it thus producing ozone which is harmful for the local environment. Utilizing DG will also reduce the net effect of the ozone production due to high voltage lines [32].

2.7 Wind Energy as a Potential Source of DG in Pakistan

Pakistan has a large resource of wind potential available all across the country. The potential ranges from low head winds to high end winds, with many small and large wind corridors in almost all the regions of the country. Various research studies have evaluated the wind resource across the country with multiple approaches for their utilization in various application specially in from of DG.

Pakistan follows the conventional vertical integrated grid infrastructure in its electricity sector. The power is majorly produced in the major central power station either thermal or hydro power plants. This generation at 11kV is then step-up using power transformer to 220kV and 500kV for transmission to load centers and then step down to 132kV and 11kV for supplying in the distribution system [13]. This step-up and down incorporate losses in the system, causing both financial losses and energy crisis. Moreover, the transmission system is being heavily loaded increasing the I^2R losses of the line causing energy crisis. Use of DG near major load center will help in reducing these losses and better accommodate the rising energy demands from load centers for future development. Various evaluation of use of wind as source of DG have been conducted. Some of them are discussed below.

Zahid et al. Evaluated the wind potential along the motorways of Pakistan. His evaluated different areas along motorways for wind production. He highlighted that moving traffic on motorway has positive effect on the surrounding wind speed as well as the flow of wind is more linear than anywhere else. According to his findings the Chakri area is the windiest, where around wind speed is 7.5m/s and a potential of 1982 W or 792.800 kW of wind potential is available which can be extracted by placing low head wind turbines [33]. Similarly, Mazhar et al. analyzed the potential of electricity generation from wind corridor in Pakistan. His area of study were mainly the remote zones in the province of Baluchistan and Sindh. In his finding he discussed that not only such remote zones application will help improving the system efficiency and energy system stability but as well as help in clean and sustainable development. The energy from such projects will be cheap as compared to the other conventional energy project as well as will serve the purpose of rural electrification. He also did a policy review for the implementation of wind projects and highlighted the issues and advantages associated with it. He also reported that the two sites in the Baluchistan & Sindh let alone will help solving the energy crisis situation of Pakistan immediately. The estimated power generation from those sites is reported at around 6 GW [34].

Ali et al., Jianna et al., and Sulimen et al. in their studies evaluated the impact of wind resource utilization in their respective studies. They evaluated the impact of wind power generation as a DG on the power system. They concluded in their study that, if the DG though wind is added in the system at the optimal point in a power system it helps increasing the power quality of the system and reduces the losses occurring due to the overloading of transmission system[35]-[36]-[37].

2.8 Wind Turbine Technology

Modern wind turbine technologies are still based on the ancient concept of wind driven rotor. Vertical axis wind mills are dated back to 644 AD in Siestan Region of Iran [38]. They were primarily used for grinding grain and water pumping purposes. However, modern wind turbines though follow the same phenomena of working, but they are required to generate electricity in the current form of application. Wind turbines are now a mature technology and being used around the globe by utilities, independent power producers and the costumers.

2.8.1 Turbine Classification

Wind turbines are majorly classified into two types: 1. The Horizontal axis wind turbine 2. The vertical axis wind turbine. Each of the turbine types holds its distant advantages and dis-advantages over each other. The vertical axis turbines have a design advantage over horizontal axis as they are omni directional and the Nacelle if located on ground which provide greater ease in the troubleshooting of the components. However, due to its lower efficiency and weight consideration it is not being commercially used for feasible operations.

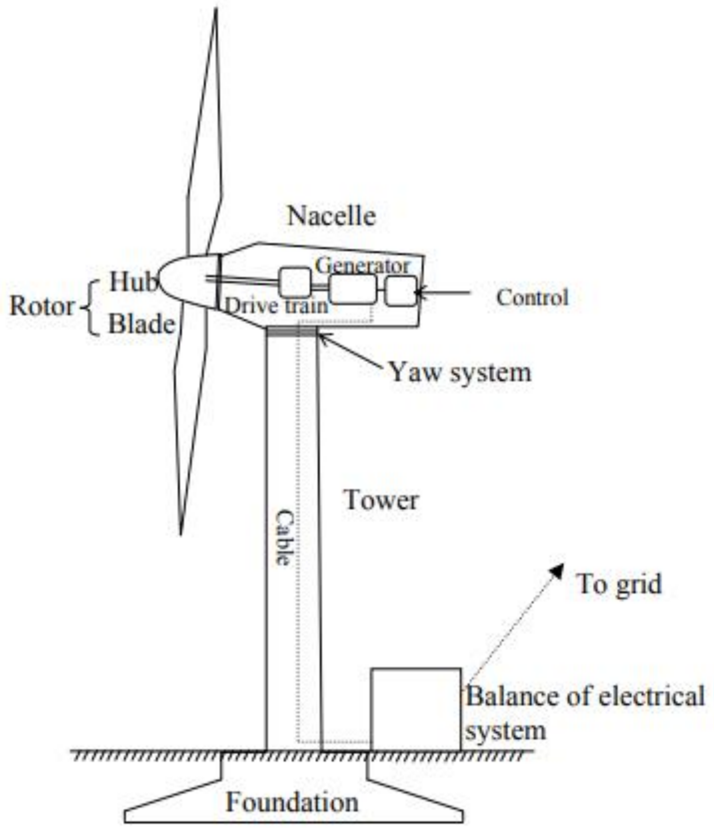

Figure 2.8: Main Components of a Horizontal Axis Wind Turbine [41]

Horizontal axis turbines however, are being commercially used due to their higher efficiency and maximum wind speed utilization. Additionally, up till now the 3-blade design is being utilized in the horizontal axis wind turbine, mainly due to the reason of stability as well as due to visual impacts of more multi-blade design.

Horizontal axis wind turbine consists of the following major components:

- The Rotor (consists of Blades and Hub)
- The Nacelle (consist of drive train components, generator and control system)
- The Yaw controls (used for aligning the rotor with the wind direction)
- The Tower (used for adjusting height and utilizing higher wind speed)
- The Foundation (to withhold the turbine on ground)

- Balance of Electrical System (consists of electrical system such as cables and transformer)

2.8.2 Power Control

The output power of a turbine is directly proportional to the wind speed. However, when a specific wind speed is reached called nominal or rated wind speed, the turbine reaches its maximum generation capacity. Any increase in the wind speed then needs to be addressed or it might cause damage to the turbine component.

This power control is achieved mainly by three different approaches: Changing pitch angle of blades, stall and active stall control. The stall control utilizes the complex wind blade design which create a specific turbulence behind the blades after a specific wind speed limiting the output. However, this approach has certain limitation such as complex design and stress on the blades as well as reduction in output power at higher wind speed.

Pitch angle control for controlling the power is a more efficient way than the stall. Pitch control, changes the blade pitch angle by rotating the blade along its axis when the rated wind speed in exceeded. When the excessive wind speed is reduced to the rated limit the pitch angle is again re adjusted to its optimum position by movement of the blades. This approach smoothly controls torque over then generator and provide active control.

The active stall on the other hand work similar to the pitch control. However, this active stall moves the blades into the wind direction when excessive wind speed is achieved causing the blades to stall and limiting the power output.

2.8.3 Wind Power Content

Energy is available in two forms in nature: kinetic and potential energy. Moving objects such as air contain kinetic energy in them. This energy content is quantified in form of Joules, which depends on the object mass and velocity. It is stated mathematically as in (1)

$$P_{wind} = \frac{1}{2} m v^2 \qquad (1)$$

The power contained in the wind air mass, which flow at speed v through an Area A_s is given by equation (2):

$$P_{wind} = \frac{1}{2}\rho A_s v^3 \qquad (2)$$

Where,

P_{WIND} = power content of wind

ρ = air density

A_s = swept area of rotor

V = wind speed

The power extracted from wind turbine is much lower than calculated through equation 2. This is due to the fact that the equation assumes the complete air mass would be intercepted in the swept area; However, in actual the turbine blades cover only a proportion of that area in one instance. Theoretically, maximum power extracted from wind turbine is 59.3% called the Betz Limit. In practice however, this value is around 45% for large wind turbines. The power output of wind turbine is given by the equation 3 stated below:

$$P_e = \frac{1}{2} C_p \rho A_s v^3 \qquad (3)$$

Where, P_e is the output power of turbine, C_p is the turbine coefficient of performance.

2.8.4 Turbine Power Curve

Turbine Power curve is characterized by 3 speeds; cut-in speed, cut-out speed and nominal/rated speed. When the wind speed is below the cut-in speed no power is produced. As soon as the wind speed rise up above the cut-in speed, the power output proportionally increase until it reasons it rated speed. In case of speeds above the Rated Speed, the turbine power cuts out at cut out speed and no power are generated. Variable-speed wind turbines have the capability of tracking the locus of maximum power, corresponding to the locus of maximum C_p, as wind speed varies by adjusting the speed of the turbine.

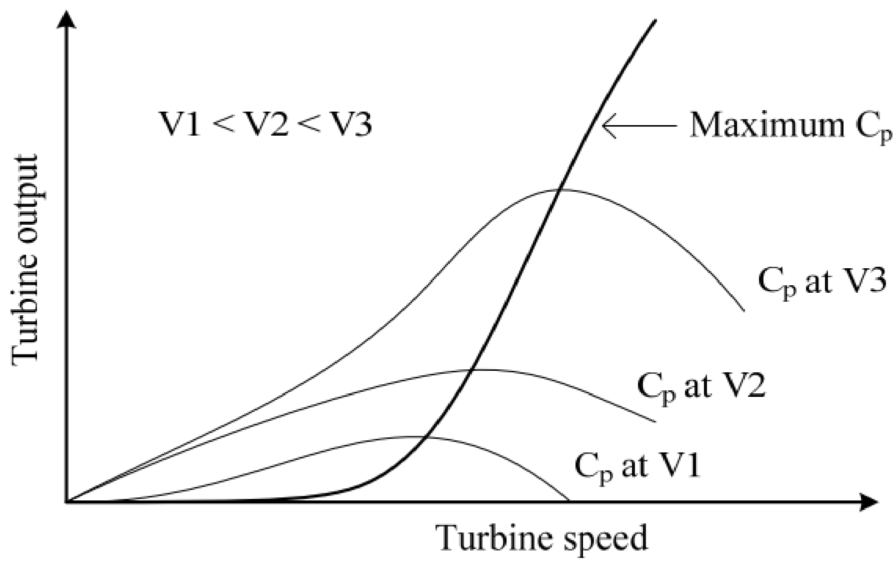

Figure 2.9: Maximum power tracking b/w cut in and cut out speeds [41]

A nominal speed, the power output is at rated value. The output power of the turbine remains constant as the wind speed increases until it reaches the cut-off speed at which the turbine is turned off in order to prevent it from any sort of damages. Figure 2.10 represents a typical turbine power curve of Vestas V90 Turbine.

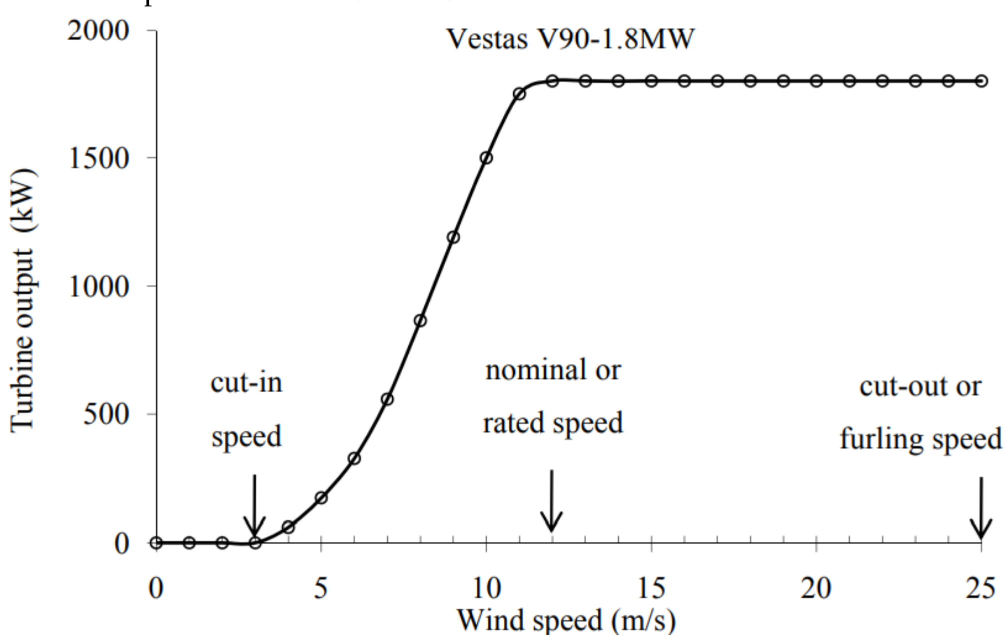

Figure 2.10: Turbine Power Curve Vestas V90 Turbine [41]

2.8.5 Wake Effect and Losses

Wind turbine extract energy from flowing wind to produce electricity. Therefore, the wind leaving the turbine will have reduced wind speed as well as turbulence caused due to the interaction with the turbine blades. This effect is called wake effect. This effect is recovered after a small instance and distance, and the wind gain backs to the wind speed and gradually returns to free stream wind speed [39].

In wind farms, the wind turbines are arranged one after another. If the swept area of a wind turbine is coming under the downstream wind from the other turbine it will reduce its power output due to the reduced wind speed and turbulence. Wake Effect have majorly 2 main effects in a wind farm: 1. It reduces the wind speed, in the downstream which reduces the wind farm output, 2. Increase in the turbulence of the wind in the downstream causing dynamic mechanical loading on the downwind turbine.

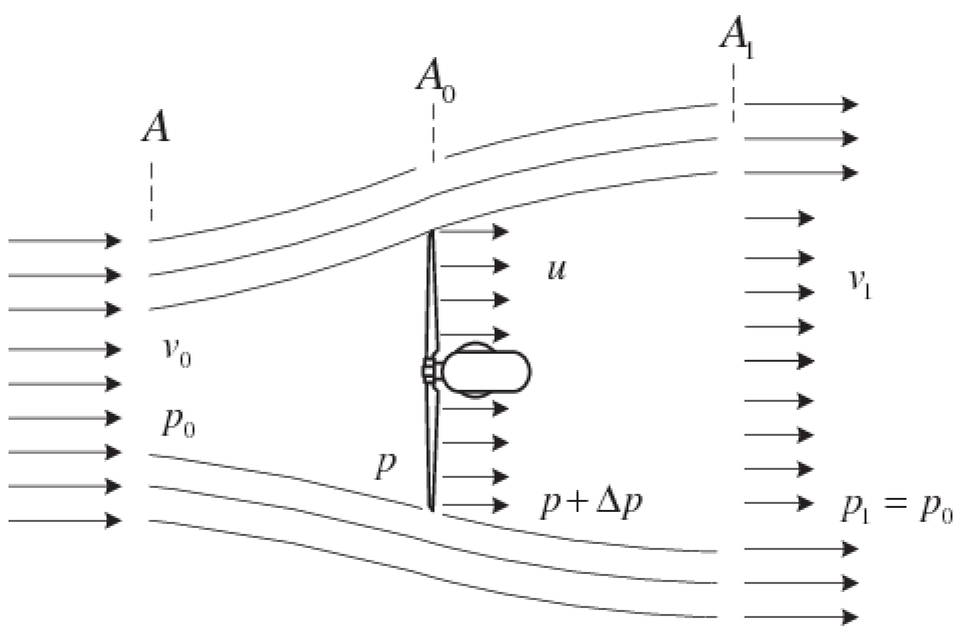

Figure 2.11: The linear expansion of wake effect behind a wind turbine downstream [39]

It is important to consider the wake effect while designing a wind farm, in order to maximize the energy output and lifetime of the wind farm. The wake effect expands linearly in the downstream of the wind turbine, so the turbine arrangement in a wind farm should be optimized to minimize this effect.

2.9 Annual Energy Output

Annual Energy Output is the total energy produced by a wind farm or turbine at the end of a year. Annual Energy output depends on the Avg. wind speed probability at a specific height, Rayleigh Distribution, the area of turbine and the total number of turbines[40]. It is given by the equation (4):

$$\textbf{Annual Energy Output} = \mathbf{K V_m^3 A_t T} \qquad (4)$$

Where;

K= Rayleigh distribution (typical value of 3.2)

V_m^3= Annual mean wind speed

A_t = Swept area of turbine

T= Total number of turbines in a wind farm.

The above stated equation provides you a gross energy yield. However, the actual energy yield comprises of other factors such as adjustment of loss factor (wake losses, electrical losses) and capacity factor. It is explained in Figure 2.12 below.

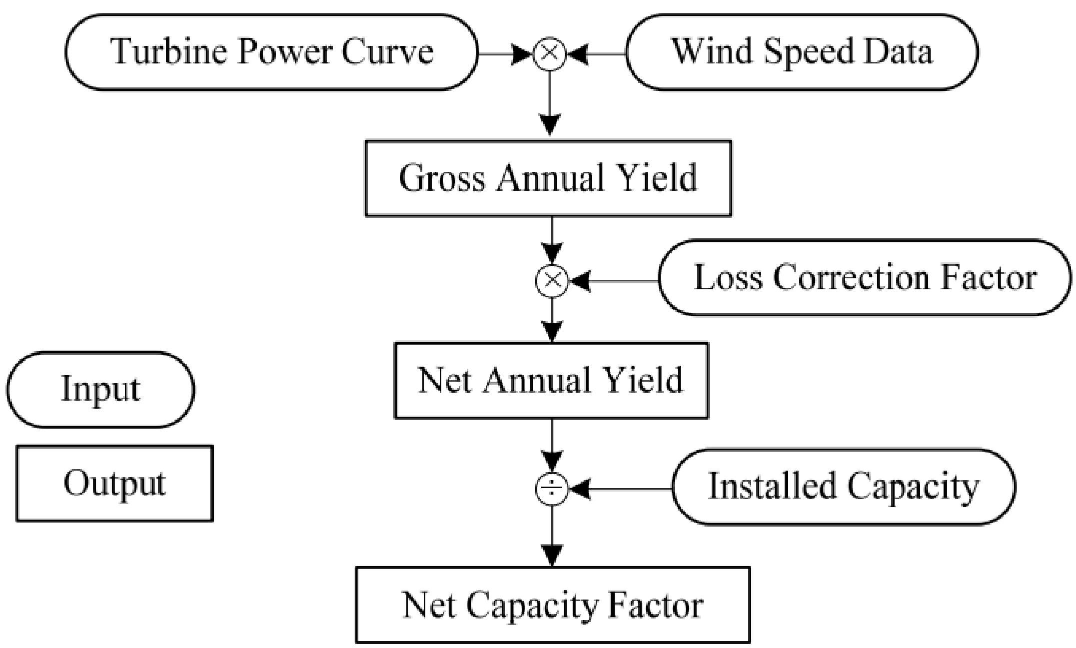

Figure 2.12: Annual net energy calculation

2.10 Capacity Factor

Capacity Factor is defined as the ratio between the avg. output power of a turbine to the rated output power of the turbine or wind farm over a period of time. The annual capacity factor is given by the equation below:

$$CF = \frac{Ea}{P_{rated} * 8760} \quad (5)$$

Where, E_a is the annual energy production and P_{rated} is the rated output power of the turbine.

2.11 Net Present Value

Net present value is defined as the difference between the inflow and outflow of sum of discounted cash flow. A positive NPV is a major indicator of feasibility of a project It is calculated by the following equation:

$$NPV = \sum_{n=0}^{N} \frac{\hat{C}_n}{(1+r)^n} \quad (6)$$

Where;

r is the discount rate for the project

$\mathbf{C_n}$ is the After-tax cash flow in the N total number of years.

2.12 Payback time

Payback time is the time is required for cashflow to be equal to the investment. It is calculated by the following equation:

$$SP = \frac{C - IG}{(C_{ener} + C_{capa} + C_{RE} + C_{GHG}) - (C_{O\&M} + C_{fuel})}$$

(7)

Where;

C: "Total initial cost of Project

IG= "Incentives and grant"

$\mathbf{C_{ener}}$= "Annual energy saving"

$\mathbf{C_{capa}}$= "Annual capacity saving"

$\mathbf{C_{RE}}$= “Annual renewable energy production credit income”

$\mathbf{C_{GHG}}$= “Greenhouse gas reduction income”

$\mathbf{C_{O\&M}}$= “Annual operation and maintenance cost”

$\mathbf{C_{fuel}}$ = “Annual cost of fuel or electricity”

References

[1] A. Armin Razmjoo, A. Sumper, and A. Davarpanah, “Development of sustainable energy indexes by the utilization of new indicators: A comparative study,” Energy Reports, vol. 5, pp. 375–383, 2019, doi: 10.1016/j.egyr.2019.03.006.

[2] M. Wakeel, B. Chen, and S. Jahangir, “Overview of energy portfolio in Pakistan,” in Energy Procedia, Jun. 2016, vol. 88, pp. 71–75, doi: 10.1016/j.egypro.2016.06.024.

[3] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” Renew. Sustain. Energy Rev., vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[4] S. Ahmed, A. Mahmood, A. Hasan, G. A. S. Sidhu, and M. F. U. Butt, “A comparative review of China, India and Pakistan renewable energy sectors and sharing opportunities,” Renewable and Sustainable Energy Reviews, vol. 57. Elsevier Ltd, pp. 216–225, May 2016, doi: 10.1016/j.rser.2015.12.191.

[5] H. Ritchie and M. Roser, “Energy,” Our World Data, Nov. 2020.

[6] Ministry of Finance, “Economic Survey of Pakistan 2018-19,” 2019. doi: 10.1038/479299e.

[7] “Pakistan - Countries & Regions - IEA.” https://www.iea.org/countries/pakistan (accessed Feb. 04, 2021).

[8] “World Development Indicators (WDI) | Data Catalog.” https://datacatalog.worldbank.org/dataset/world-development-indicators (accessed May 24, 2021).

[9] S. Z. Abbas, A. Kousar, S. Razzaq, A. Saeed, M. Alam, and A. Mahmood, “Energy management in South Asia,” Energy Strategy Reviews, vol. 21. Elsevier Ltd, pp. 25–34, Aug. 01, 2018, doi: 10.1016/j.esr.2018.04.004.

[10] S. Shah, A. Rashid, M. K. L. Bhatti, S. Khattak, and L. Khan, “Crisis of Electrical Energy in Pakistan and Future guide line for policy makers,” 2010.

[11] C. Vidya, P. M. Anbarasan, and K. M. Prabu, “Energy Crisis and Recent Technological Development in India,” vol. 7, no. 1, 2017, Accessed: May 11, 2021. [Online]. Available: www.iiste.org.

[12] NTDC, “Electricity Demand Forcast based on Power Market Survey 2019-2028,” 2019. [Online]. Available: http://ntdc.gov.pk/ntdc/public/uploads/services/planning/power market survey/PMS NTDC System.pdf.

[13] K. Ullah, “Electricity infrastructure in Pakistan : an overview Electricity Infrastructure in Pakistan : an Overview,” no. August, 2019.

[14] M. Shahid, K. Ullah, K. Imran, I. Mahmood, and A. Mahmood, “Electricity supply pathways based on renewable resources: A sustainable energy future for Pakistan,” J. Clean. Prod., vol. 263, p. 121511, 2020, doi: 10.1016/j.jclepro.2020.121511.

[15] A. A. Sahito, I. A. Halepoto, M. A. Uqaili, Z. A. Memon, A. S. Larik, and M. A. Mahar, “Analyzing the Impacts of Distributed Generation Integration on Distribution Network: A Corridor Towards Smart Grid Implementation in Pakistan,” Wirel. Pers. Commun., vol. 85, no. 2, pp. 545–563, 2015, doi: 10.1007/s11277-015-2754-y.

[16] S. Shah and M. K. L. Bhatti, “Crisis of Electrical Energy in Pakistan and Future guideline for Policy makers,” no. 09, pp. 11–15, 2009.

[17] W. Ali, “Steeple analysis of prolonged energy crisis in pakistan and way forward to energy security,” pp. 24–49, 2019.

[18] K. Latif, M. Y. Raza, Shahid Adil, and Rehana Kouser, “Nexus between Economy, Agriculture, Population, Renewable Energy and CO2 Emissions: Evidence from Asia-Pacific Countries,” J. Bus. Soc. Rev. Emerg. Econ., vol. 6, no. 1, pp. 261–276, 2020, doi: 10.26710/jbsee.v6i1.1072.

[19] S. H. Shami, J. Ahmad, R. Zafar, M. Haris, and S. Bashir, “Evaluating wind energy potential in Pakistan’s three provinces, with proposal for integration into national

power grid," Renewable and Sustainable Energy Reviews, vol. 53. Elsevier Ltd, pp. 408–421, Jan. 01, 2016, doi: 10.1016/j.rser.2015.08.052.

[20] M. Memon, K. Harijan, and M. A. Uqaili, "Assessment of wind home system's potential in coastal areas of Pakistan," in AIP Conference Proceedings, 2007, vol. 941, pp. 80–89, doi: 10.1063/1.2806075.

[21] IRENA, Renewables Readiness Assessment: Pakistan, International Renewable Energy Agency (IRENA), Abu Dhabi., no. November. 2018.

[22] "Wind energy." https://www.irena.org/wind (accessed May 15, 2021).

[23] "Mapping the World's Wind Energy Potential." https://www.worldbank.org/en/news/press-release/2017/11/28/mapping-the-worlds-wind-energy-potential (accessed Feb. 04, 2021).

[24] S. Siddique, R. Wazir, Z. A. Khan, and N. Iqbal, "Technical and financial analysis of 50MW wind farm at Gwadar, Balochistan," Oct. 2015, doi: 10.1109/PGSRET.2015.7312211.

[25] Z. Ullah, S. M. Ali, I. Khan, F. Wahab, M. Ellahi, and B. Khan, "Major Prospects of Wind Energy in Pakistan," 2020 Int. Conf. Eng. Emerg. Technol. ICEET 2020, no. February, pp. 1–6, 2020, doi: 10.1109/ICEET48479.2020.9048201.

[26] A. Kosygina, I. O. Volkova, and L. M. Gitelman, "Perspectives on Distributed Generation in the Electric Power Industry," Springer, Cham, 2018, pp. 37–44.

[27] IEA, "Distributed Generation in Liberalised Electricity Markets Distributed Generation in Liberalised Electricity Markets," Int. Energy Agency, p. 124, 2002.

[28] "Special Report-Technical Theme 4 DISPERSED GENERATION-MANAGEMENT AND UTILISATION OF ELECTRICITY."

[29] "1547-2003 - IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems | IEEE Standard | IEEE Xplore." https://ieeexplore.ieee.org/document/1225051 (accessed May 27, 2021).

[30] O. S. Nduka and B. C. Pal, “Quantitative Evaluation Of Actual Loss Reduction Benefits of a Renewable Heavy DG Distribution Network,” IEEE Trans. Sustain. Energy, vol. 9, no. 3, pp. 1384–1396, Jul. 2018, doi: 10.1109/TSTE.2017.2776610.

[31] V. Quintero-Molina, M. Romero-L, and A. Pavas, “Assessment of the hosting capacity in distribution networks with different DG location,” Jul. 2017, doi: 10.1109/PTC.2017.7981243.

[32] H. HassanzadehFard and A. Jalilian, “Optimal sizing and location of renewable energy based DG units in distribution systems considering load growth,” Int. J. Electr. Power Energy Syst., vol. 101, pp. 356–370, Oct. 2018, doi: 10.1016/j.ijepes.2018.03.038.

[33] A. A. Khan, Z. Mehmood, and A. Shahzad, “Evaluation of Wind Energy Potential alongside Motorways of Pakistan,” Asian J. Appl. Sci. Eng., vol. 3, no. 4, pp. 375–381, 2014, doi: 10.18034/ajase.v3i4.597.

[34] M. H. Baloch et al., “A research on electricity generation from wind corridors of Pakistan (two provinces): A technical proposal for remote zones,” Sustain., vol. 9, no. 9, 2017, doi: 10.3390/su9091611.

[35] A. M. Eltamaly, Y. S. Mohamed, A. H. M. El-Sayed, and A. N. A. Elghaffar, “Analyzing of wind distributed generation configuration in active distribution network,” 2019 8th Int. Conf. Model. Simul. Appl. Optim. ICMSAO 2019, 2019, doi: 10.1109/ICMSAO.2019.8880291.

[36] J. Ouyang, S. Li, and Y. Zhou, “Research on the Influence of Distributed Wind Power Access Location on Power Supply Reliability of Distribution Network,” IOP Conf. Ser. Earth Environ. Sci., vol. 440, no. 3, 2020, doi: 10.1088/1755-1315/440/3/032130.

[37] S. Khan, S. U. Rehman, A. U. Rehman, and H. Khan, “Optimal Placement of Distributed Generation in Power System for Power System Loss Reduction Using ETAP,” Int. J. Eng. Technol., vol. 16, no. 0, pp. 7–19, 2019, doi: 10.18052/www.scipress.com/ijet.16.7.

[38] E. Hau, Wind turbines: Fundamentals, technologies, application, economics. Springer Berlin Heidelberg, 2006.

[39] F. González-Longatt, P. P. Wall, and V. Terzija, “Wake effect in wind farm performance: Steady-state and dynamic behavior,” Renew. Energy, vol. 39, no. 1, pp. 329–338, Mar. 2012, doi: 10.1016/j.renene.2011.08.053.

[40] “Week 6: Wind energy: 5.2 Estimating annual energy production - OpenLearn - Open University - RENBOC_1.” https://www.open.edu/openlearn/ocw/mod/oucontent/view.php?id=73763&section=6.2 (accessed May 27, 2021).

[41] V. Wind System, “Reliable technology proven over generations.”

Chapter 3

Materials and Methods

Techno-economic evaluations of a project, addresses and evaluate the impacts of various economic and technical variables impact on the project's feasibility. There are various approaches and tools used to evaluate the techno economic feasibility of a project. Some of them are discussed in the sections below.

3.1 Methodologies for Techno-Economic Assessment

Various tools and techniques are used for the techno-economic assessment of wind farms. Cem EMEKIZ et al. in his study for wind farm power plant in Tokat region used RETScreen for the techno-economic assessment of the proposed system. They used RETScreen tool for analyzing the feasibility and potential of wind rnergy in a region or site location. The RETScreen tool is the most promising tool for feasibility assessment of any renewable related project. The only downside to this tool is that it can only be used for assessment of a region as RETScreen uses the data from the nearest weather station available to the site [1].

In another similar study, Mazhar H. Baloch et al. used MATLAB model for analyzing the wind power generation in the wind corridors of Pakistan. The approach used by them is quite efficient and the results obtained are well calibrated. The main issue with such mathematical model for estimated and calculation is that, such equations are complex as many variables are included in it. Moreover, the model itself is complex and the chances of miss calculation are high [2]. Y. Himri et al. used WAsP alongside the RETScreen for wind potential analysis. In his paper, he then compared the results from both the software's. The results had the error of less than 1%. WAsP Software on the other hand is excellent tool for data interpolation and to analyze a specific location or region. The WAsP provides the additional information like wind direction rose and frequency. These tools help in the exact feasibility assessment of wind farm in any area. [3]. Suhail K. et al. used SAM for analysis of technical and economic feasibility of large-scale wind farm in Jordan. SAM was used for economic factors analysis like IRR, payback time and NPV assessment which are key variable for attracting investment in a project[4].

Emeka K. et al similarly used SAM for simulation and modelling of concentrated solar thermal power plant and compared it with the actual performance data. The results provided a clear comparison between the actual performance and the proposed model achieving very low LCOE[5]. Similarly, Gardenio D. et al used SAM to estimate the electricity generation by grid tide photovoltaic system in various regions of Brazil. SAM was used to model the proposed system in different regions of Brazil[6].

3.2 Methodology for Techno-Economic Evaluation of Wind Farms in Pakistan

Techno-economic evaluation consist of assessment of various technical and economic variable on the production and economic feasibility of the wind farm. Various tools and techniques are used by different researchers for the analysis. However, among those discussed in the section above, SAM is a promising software tool for the techno economic evaluations of Wind farm.

SAM (System Advisory Model) is being used for technical and economic assessment of various site location. SAM is being used as it provides a detailed and comprehensive set of variables to analyze and simulate the effect of different variables on the proposed system design and feasibility. Additionally, RETScreen will be used for validation of energy production, payback time and to calculate the GHG emissions reduction.

The data from ESMAP was uploaded in the SAM software library as a weather file for the site location. Followed by this SAM will be used for the optimal turbine selection and spacing according to the weather file data, as well as to stimulate different real-world cases like curtailment and technical losses and help visualizing their effect. Moreover, SAM also provides the control over economic variables like inflation rate, cost and debt fraction etc. and help visualizing their effect on the overall system viability. However, RETScreen will use the weather data from its data base and will provide the net energy production and GHG emission reduction through comparing it with the emission of other conventional source of energy.

The research study follows the following methodology as described in the Figure 3.1. The methodology is divided into 3 Step. In step 1, the site description is provided along with the data description which will be used for site selection purposes. In step2, the wind data is used to analyze the wind speed characterization, such as Weibull distribution and wind speed frequency. Based on these variables, the optimum wind turbine selection is made based on the wind speed characterization.

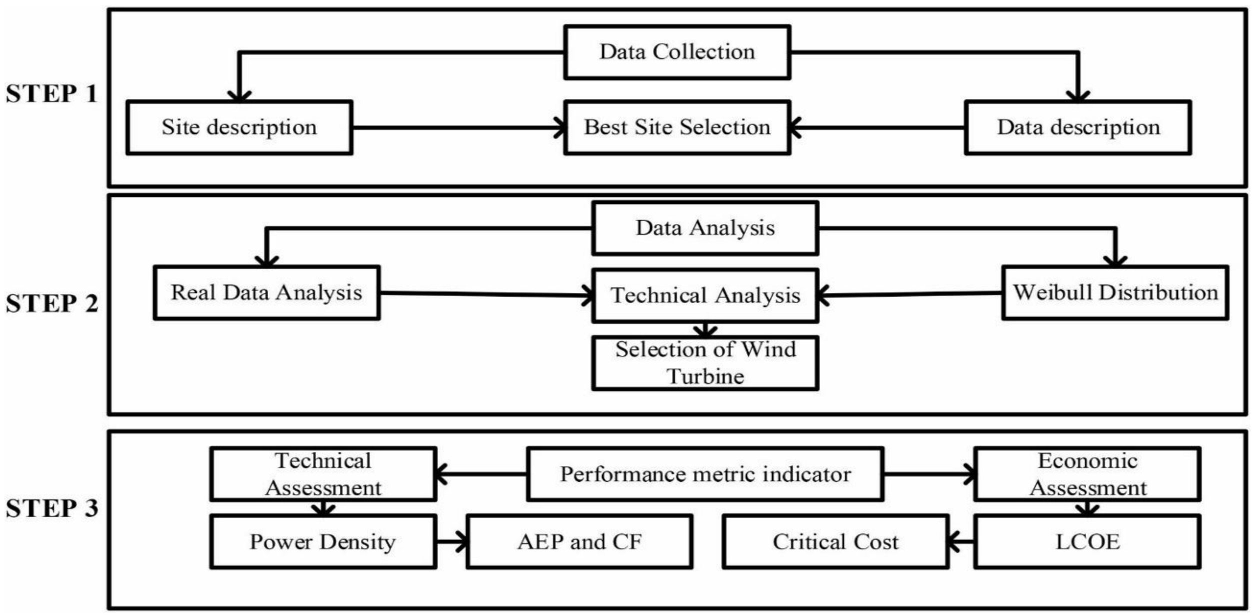

Figure 3.1: Methodology for Wind Farm Analysis

In step3, various performance metrics indicators of wind farm are assessed. These indicators are both technical and economical. These include, the CP, the annual energy production as well as the LCOE, the system cost and payback time. Based on the assessment of these variables, the techno-economic feasibility of the wind farm is assessed.

3.3 Site Description

In our research study four different site location are assessed for techno-economic evaluations. Gawadar, Chakri, Bahawalpur and Quetta are the site location for techno-economic analysis. The reason for the techno-economic evaluation of these site location, that these site locations are strategically important and have a forecasted development under CPEC.

Due to the development in these areas, the energy demand is forecasted to rise. However, if the forecasted demand is met by using the wind resource at these locations, will not only reduce the carbon foot print of development but also boost the share of renewable in the Pakistan energy mix along with the DG advantages. Renewable resource utilization will not only be beneficial environmentally but also will be comparative to the cost of electricity production otherwise through other resources. The wind speed data was collected through ESMAP program under USAID and Global Wind Atlas. Some of the major site description of the weather data is presented in Table 3.1.

Table 3.1: Site and wind data description

	Elevation	**Location**	**Surface Roughness**	**Roughness Class**	V_{avg}	**Ò**	T_{avg}	**ρ**	**PD (W/m^2)**
Gwadar	13m	25.43,62.54	0.0163	0.88	4.669	2.52	26.49	1.16	152.83
Quetta	192m	71.89,32.34	0.114	2.11	4.144	2.60	22.69	1.0	132.40
Bahawalpur	123m	71.8,29.32	0.859	3.79	5.063	2.47	27.28	1.04	174.72

3.4 Technical Variables Impact on the Wind Farm capacity factor

Various technical variables such as the turbine sizing, row spacing and the off-set of rows have a direct impact on the wind farm capacity factor. In order to design and optimal wind farm, these variables need to be optimized to maximize the capacity factor of the wind farm.

3.4.1 Turbine Selection and Sizing of Wind Farm

Turbine selection and sizing of wind turbines is a key factor in feasibility of a wind farm. Increasing the number of turbines and reducing spaces between them can cause not only financial implication like higher capital investment but also cause technical losses like wake effect losses. Moreover, the higher number to turbine optimally placed with minimal losses will requires large amount of area, which then adds up greatly into the capital cost of the project.

Vestas family V80-2.0, V90-2.0, V100-2.0, V110-2.0 were considered for the use at the proposed wind farm location. The optimal selection of wind turbine is based on the power curve matching with the wind speed availability providing the maximum capacity factor. An optimal wind turbine for the proposed wind farm should have a very low cut-in speed around 2m/s, which will provide high-capacity factor. Figure 3.2 provides a graphical comparison between the power curve of the considered turbines for proposed wind farm.

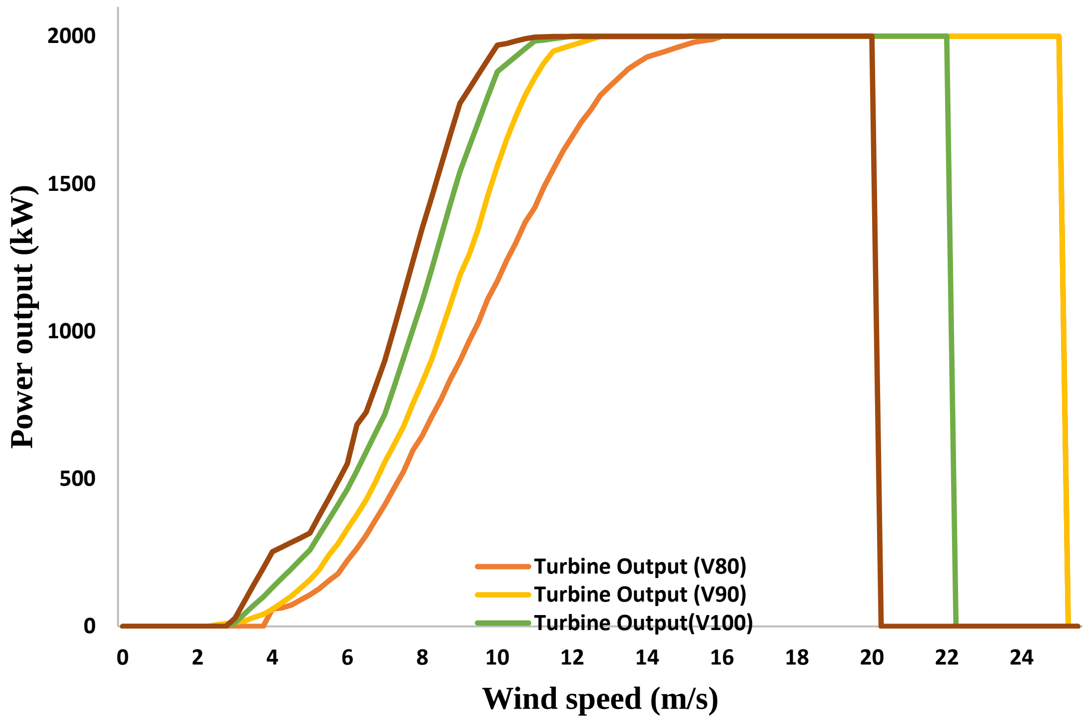

Figure 3.2: Power curve comparison of Vestas family V80, V90, V100 and V110 turbine

Vestas V110-2.0 power curves provides a better match with the wind profile of the site location based on the optimal power curve matching with the wind speed availability which helps in adding up the Turbine availability. Moreover, the Vestas V110 turbine provides a much lower cut in speed at 2m/s with a large range of maximum generation capacity from 11m/s to 25m/s. Vestas V110 wind turbine also provides the maximum capacity factor for wind farm design at around 35.20% significantly higher than the Vestas V100 turbine providing the capacity factor at around 32.10%.

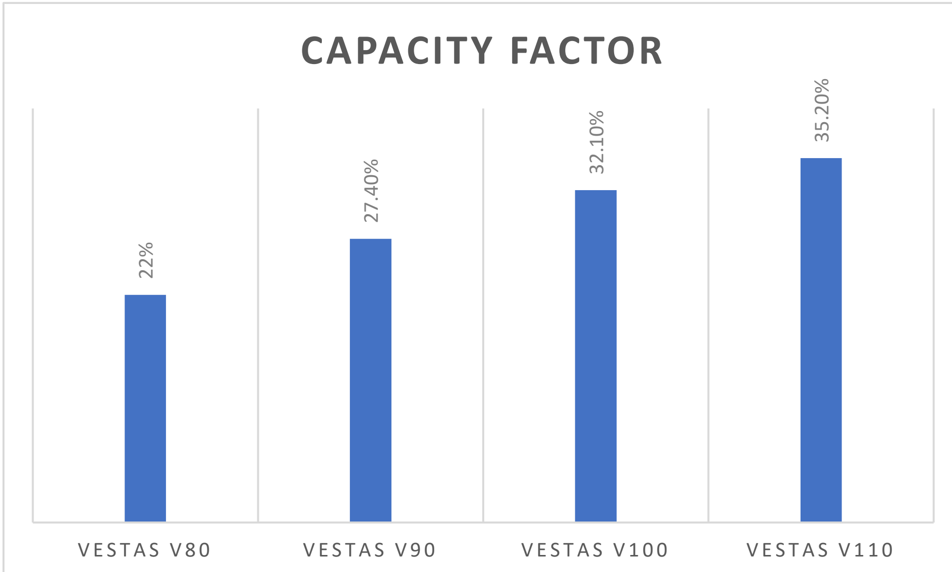

Figure 3.3: Capacity factor at hub height 80m

3.4.2 Analyzing the Impact of Turbine and Row Spacing on Capacity Factor

In order to analyze the impact of turbine spacing on capacity factor and land requirement, the spacing was varied between 4 to 20 rotor diameters spacing. Figure 3.4 shows an impact of turbine and row spacing on capacity factor.

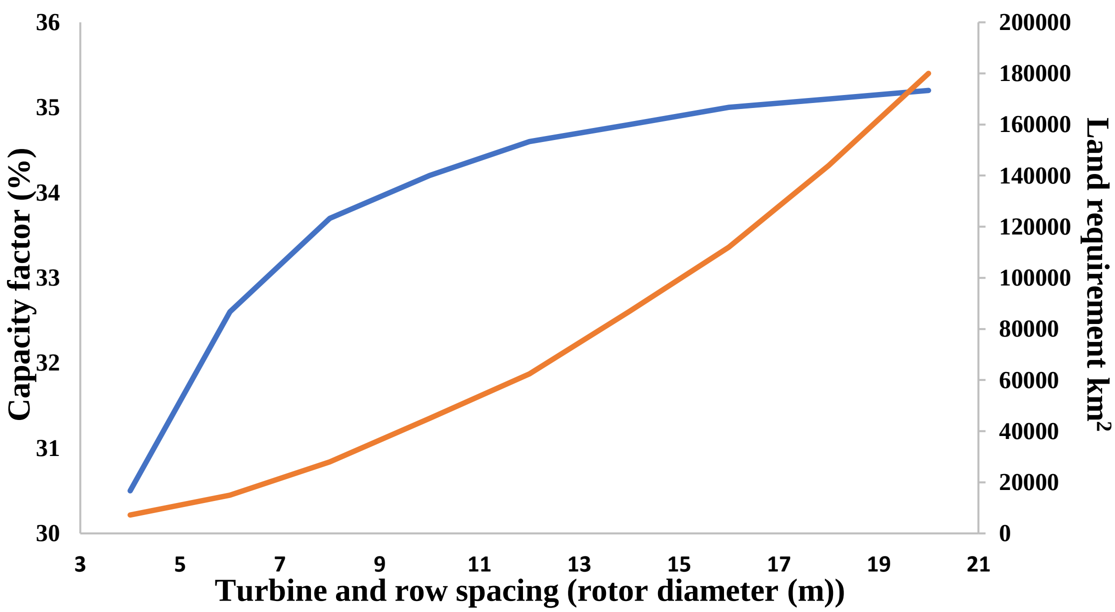

Figure 3.4: Impact of turbine and row spacing on capacity factor and land requirement

It is evident from Figure 3.4 that, the capacity factor has a direct relation with the turbine and row spacing as the lesser the turbine spacing the more the wake effect is faced by the turbine adding up in wake losses of the system.

Turbine spacing has a major impact when changed from 4 to 6 and then to 8 however, afterwards the net increase in capacity factor is fairly low as compared to the land requirement that is increased on increasing the spacing. Therefore, and optimal selection of turbine spacing at 8 rotor diameters is set for the best optimized farm design with minimal land requirement at 28000km^2 of land area requirement.

3.4.3 Analyzing the impact of offset of rows on farms capacity factor

In order to analyze the impact of off set of rows spacing on capacity factor, the spacing was varied between 0 to 8 rotor diameters spacing. Figure 3.5 shows an impact of off set of row spacing on capacity factor.

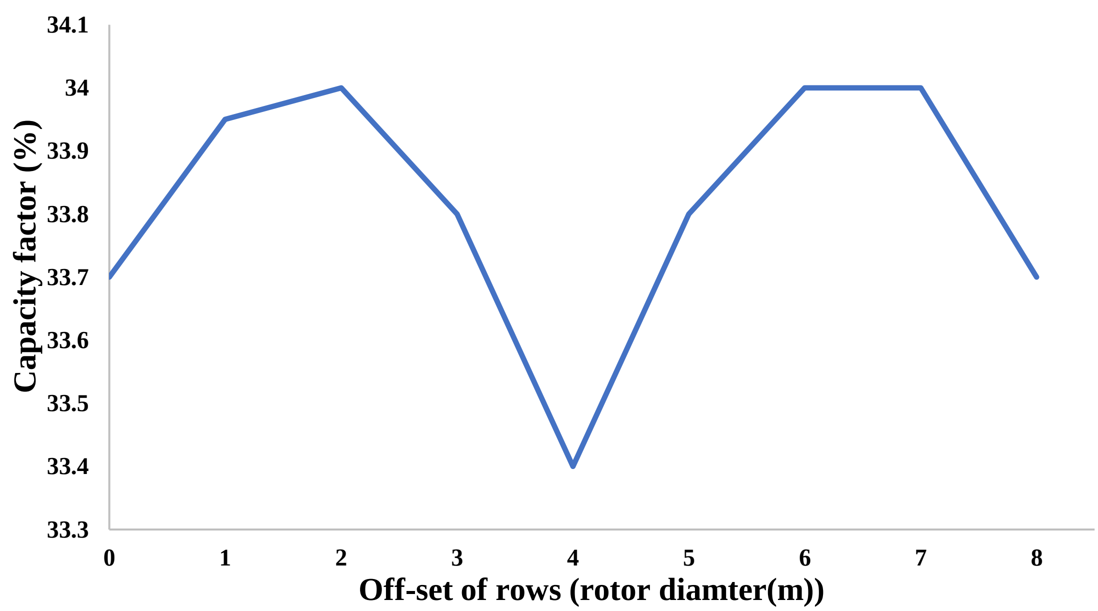

Figure 3.5: Impact of off-set of rows on capacity factor

It is evident from the Figure 3.5 that the maximum rise in capacity factor is seen at off set value of 2. This is due to the reason that at the offset spacing of rows at 2 rotor diameter spacing, the wake effect from the upfront turbine is minimized which leads to an increase in the capacity factor of the farm.

3.5 Economic Variables Impact on the Wind Farm Viability

Economic variables such as inflation rate, and debt fraction have major impacts on the viability of the wind farm. The effect of these variables needs to be analyzed in order to design a policy for increasing the wind farm viabilities in different regions and countries. These variables and their impact on the LCOE and payback time are discussed here below.

3.5.1 Impact of Inflation Rate on the Payback Time Period and LCOE

Inflation rate is defined as the percentage of increase or decrease in prices during a certain time period. Inflation rate can affect a project feasibility as it directly impacts the payback time, the cost of energy production and the net present value of the system.

Currently, Pakistan has an inflation rate of around 12% [7] which can both increase or decrease in the coming future. In order to analyze the sensitivity of inflation rate, inflation rate is varied between the 10% to 14%. Figure 3.6 presents the relation between the inflation rate and its impact on the payback time and LCOE respectively.

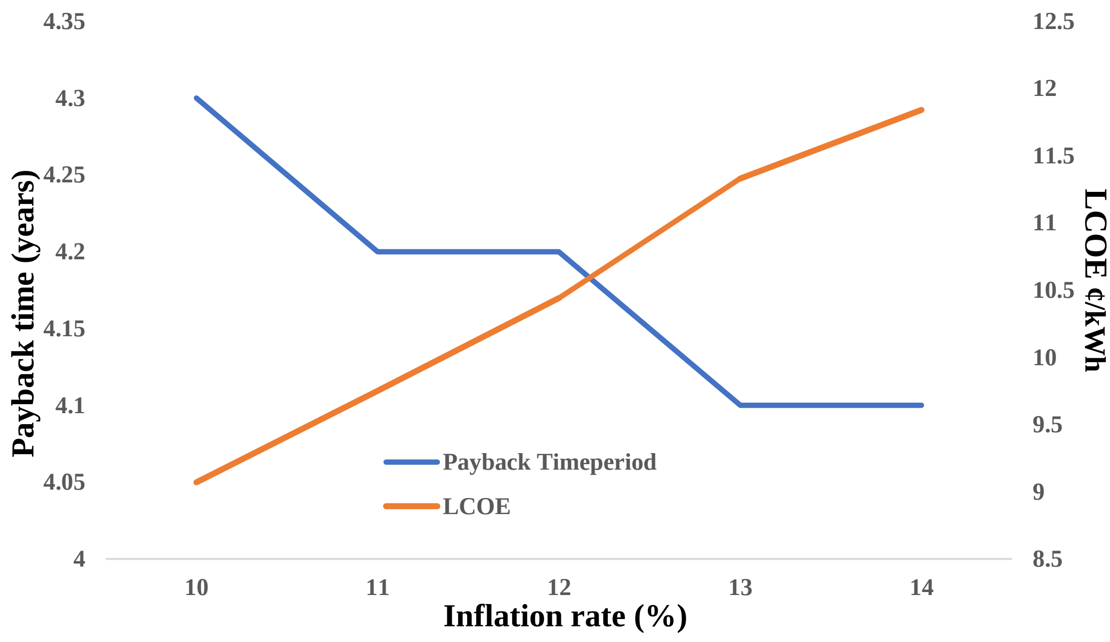

Figure 3.6: Relationship between the inflation rate, payback time and LCOE

Inflation Rate has a direct relation with the LCOE of a wind farm. On decreasing the inflation rate the LCOE is also reduced. However, it has an inverse relation with the payback time. Moreover, it has also an inverse relation with the NPV. Lower the inflation higher will be the NPV. Lower LCOE is the most desired from the government perspective as low-cost energy can help meeting the demands at a much lower price and always requires less subsidizes. However, from an IPP perspective higher inflation cost tough reduce their payback time period or increase their rate of return however the NPV is significantly reduced in terms of long-time investment.

3.5.2 Impact of Debt Fraction on Payback time and Net present value

Debt fraction is the ratio between the total debt to total assets on a project. It can also be defined as the ratio between the total cost and the debt of a project. Large scale projects are majorly based a debt taken for financial institution on a fixed interest rate. The interest rate in Pakistan for the renewable energy projects is fixed at 6%.

In order to analyze the sensitivity of debt fraction on the LCOE the debt fractions are varied between the 0% to 75%. The varying debt fraction provides a clear image for investment and also allows the government to design policies to encourage the investment in a project while keeping the LCOE minimum. Figure 3.7 represent the effect of varying debt fraction to the LCOE.

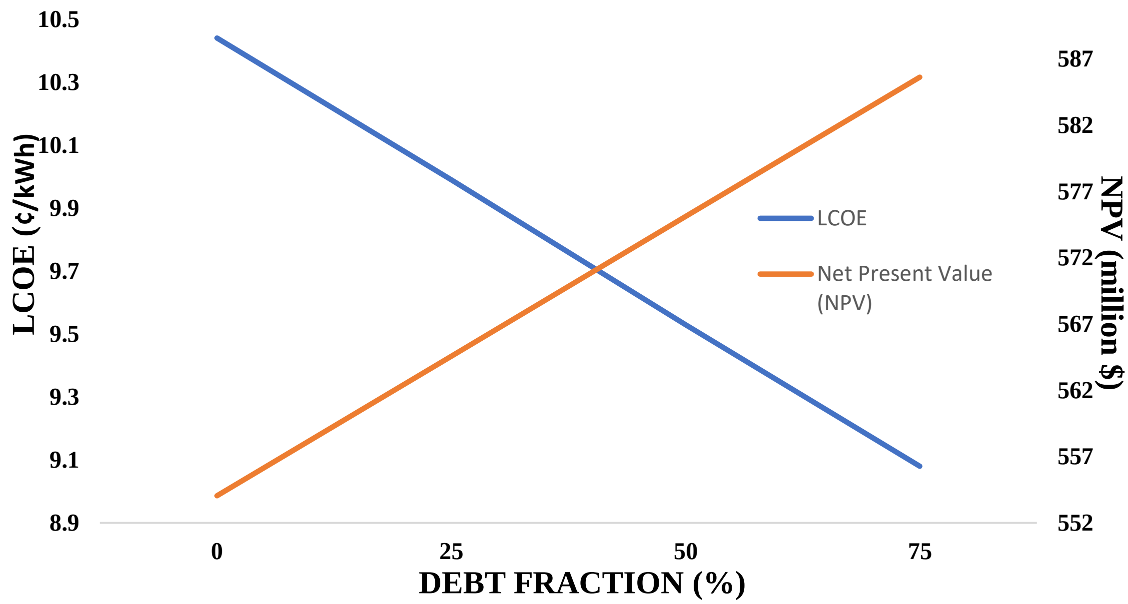

Figure 3.7: Relationship between the varying debt fraction, LCOE and NPV

Increased debt fraction has a positive impact on the LCOE with no impact on the payback time period and an increased NPV. Moreover, higher debt fraction also helps reducing the calculated risk for the investor for such renewable projects and also provides then sense of security as the government as a stake holder is directly involved in such projects. LCOE is a critical factor in feasibility of a wind farm. The least LCOE is available at 75% or above debt fraction. Mostly projects in Pakistan and globally are initiated and completed through shared investments mostly by the government entities. In case of Pakistan almost all projects have a debt fraction of 75:25.

References

[1] C. Emeksiz and Z. Dogan, "Wind Power Plant Feasibility Study in Tokat with RETScreen Analysis Program," *J. New Results Sci.*, vol. 5, no. 11, pp. 56–63, 2016.

[2] M. H. Baloch *et al.*, "A research on electricity generation from wind corridors of Pakistan (two provinces): A technical proposal for remote zones," *Sustain.*, vol. 9, no. 9, 2017, doi: 10.3390/su9091611.

[3] Y. Himri, M. Merzouk, N. Kasbadji Merzouk, and S. Himri, "Potential and economic feasibility of wind energy in south West region of Algeria," *Sustain. Energy Technol. Assessments*, vol. 38, no. January, p. 100643, 2020, doi: 10.1016/j.seta.2020.100643.

[4] S. Kiwan, E. Al-Gharibeh, and E. Abu-Lihia, "Wind Energy Potential in Jordan: Analysis of the First Large-Scale Wind Farm and Techno-Economic Assessment of Potential Farms," *J. Sol. Energy Eng.*, vol. 143, no. 1, Feb. 2021, doi: 10.1115/1.4047580.

[5] E. K. Ezeanya, G. H. Massiha, W. E. Simon, J. R. Raush, and T. L. Chambers, "System advisor model (SAM) simulation modelling of a concentrating solar thermal power plant with comparison to actual performance data," *Cogent Eng.*, vol. 5, no. 1, pp. 1–26, Jan. 2018, doi: 10.1080/23311916.2018.1524051.

[6] G. Diogo and P. Da Silva, "Utilisation of the System Advisor Model to Estimate Electricity Generation by Grid-Connected Photovoltaic Projects in all Regions of Brazil Poluição em estacionamentos em Belém View project Floating PV systems and its environmental impacts View project Utilisation of the System Advisor Model to Estimate Electricity Generation by Grid-Connected Photovoltaic Projects in all Regions of Brazil," *J. Softw. Eng. its Appl.*, vol. 11, no. 7, pp. 1–12, 2017, doi:

10.14257/ijseia.2017.11.7.01.

[7] "Government of Pakistan Ministry of Planning, Development and Special Initiatives PAKISTAN BUREAU OF STATISTICS PRESS RELEASE ON CONSUMER PRICE INDEX (CPI) INFLATION FOR THE MONTH Analysis of Consumer Price Index (CPI) Base Year (2019-20) 1," 2021. Accessed: Jun. 10, 2021. [Online]. Available: http://www.pbs.gov.pk

Chapter 4

Results and Discussion

Various technical and economic analysis are presented in the prior section. Based on the analysis in the Chapter # 3, the optimal design of wind farm is made for each site location. The turbine selection and other parameters for each site location is discussed in the sections below.

4.1 RESULTS

4.1.1 Gwadar Site Location

Gwadar is located in the down south western region of the country in the province of Baluchistan sharing the coastal line with India and Iran along the Arabian Sea. This region has gained immense importance specially after the inauguration of the CPEC under which Gwadar will act as a major key player in the economic activity of Pakistan and China. Gwadar region receives many air currents throughout the day due to the temperature difference between land and sea surfaces. Moreover, there is a forecasted rise in the energy demand in this region due to new economic corridors and activities which need to meet in order to keep the development on going.

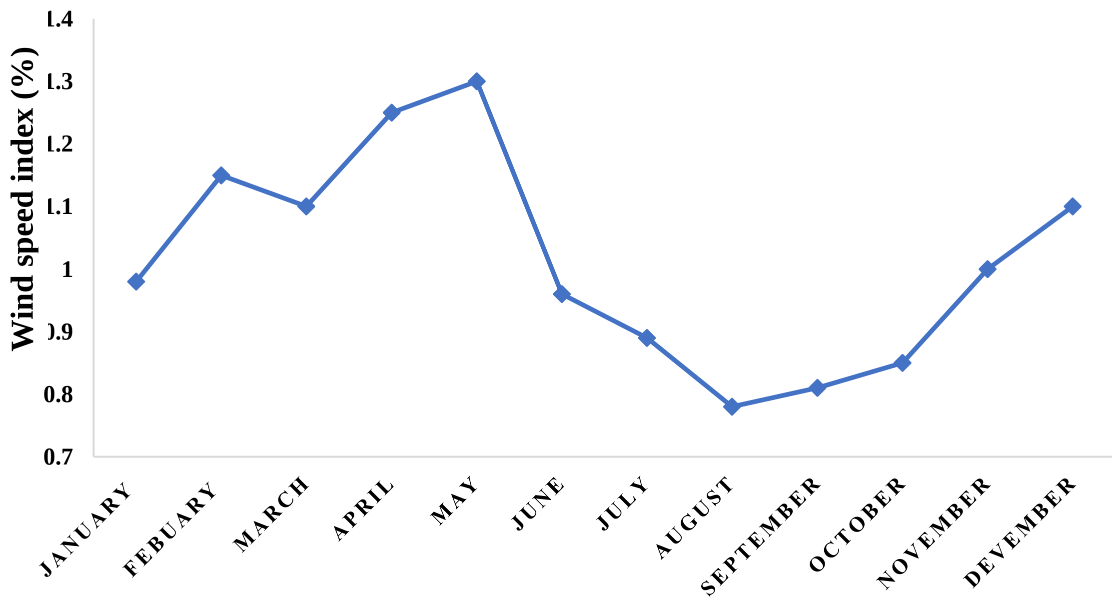

Figure 4.1: Monthly wind speed variation at Gawadar

Gwadar has a significant and predictable wind energy potential available almost throughout the year. Maximum amount of wind is available in the afternoon. The avg. variability between the maximum and minimum wind speed index are 1.2 and 0.77 respectively. Moreover, the maximum wind energy is available in the 2nd Quarter of the year while minimum is available in the 3rd quarter with progression in 4th followed by the 1st Quarter of the year as shown in Figure 4.1

The energy contained in the wind is very site-dependent. If the selected site has uniform high wind speed throughout the year, then that site will be considered as an economically favourable option for the installation of wind turbines. It is evident from Figure 4.2 the wind speed frequency that significant amount of wind speed is available at the proposed site which can been used for economically extracting energy in form of electricity through wind turbine.

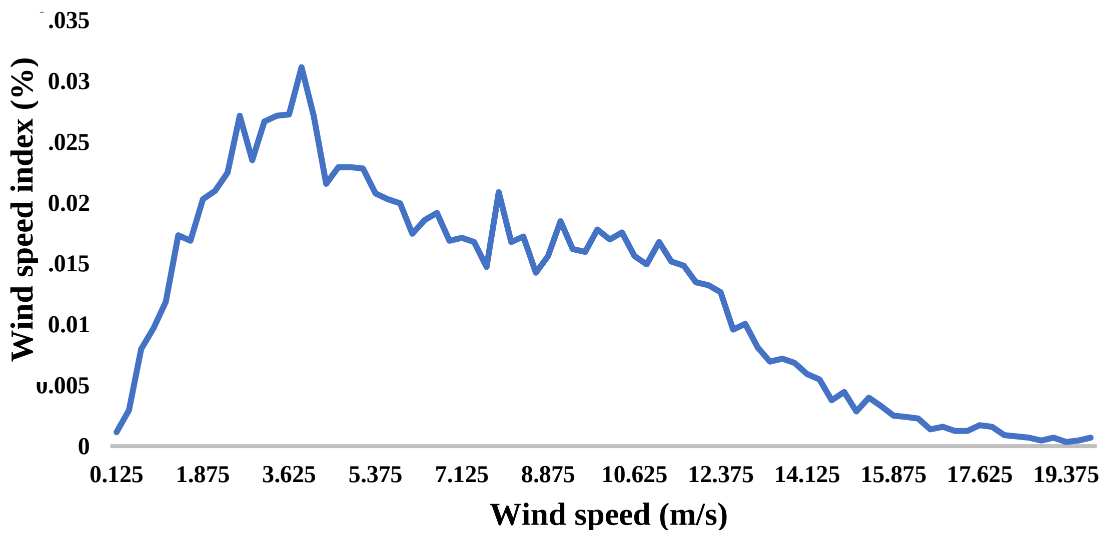

Figure 4.2: Wind speed frequency at 80m height at Gawadar Site Location

The average wind speed of a year calculated in the data set of Gwadar is around 4.65m/s at 80-meters height with a variance of 6.31. However, the average wind speed on the proposed location can reach up to 9m/s at 100-meters on proposed location for wind farm. The roughness factor of the site location is moderate, as there are no or few drag causing obstacles.

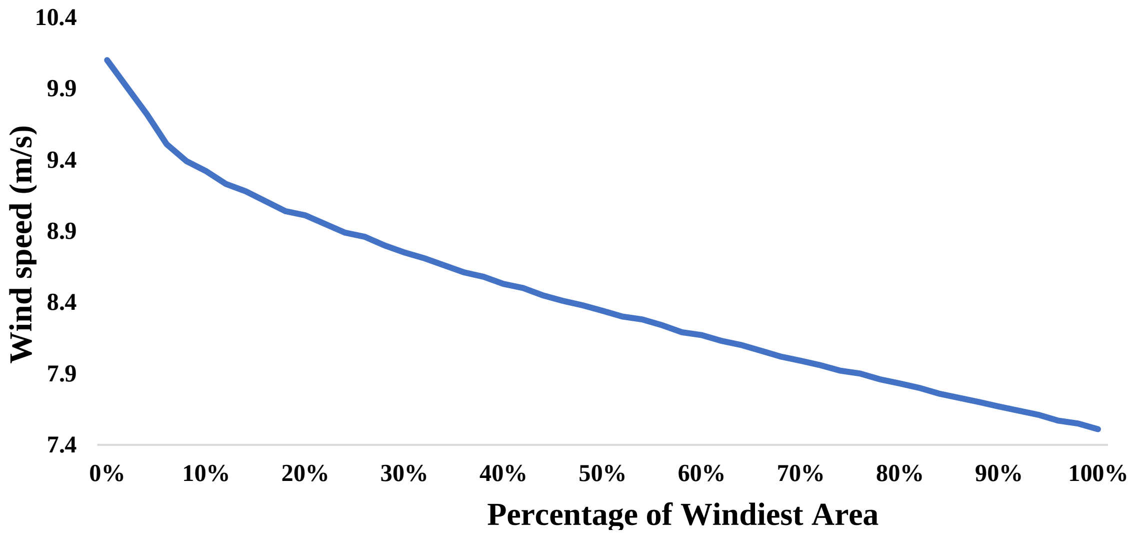

Figure 4.3: Mean wind speed availability at 100m height Gawadar

4.1.2 Techno-Economic Analysis of 100MW Wind Farm in Gawadar using SAM

As discussed in the earlier section the impact of various economic and technical variables on the viability of the wind farm. An optimized wind farm design is created. Some of the key technical and economic variables of the optimized system analysis are presented in this section. Key parameter of optimized wind farm is presented in Table 4.1

Table 4.1: Summary of the technical parameters of optimized wind farm design

Technical Parameter	Values
Wind Turbine Type	Vestas V110 (Horizontal)
Rated Power output	2000kW
Rotor Diameter	110m
Hub Height	80m
Turbine Per Row	5
Total No. of Rows	10
Shape of Farm	Square/ Rectangular
Turbine Spacing	8 rotor diameters

Row Spacing	8 rotor diameters
Off Set of Turbine	2 rotor diameters
Capacity Factor	34%

Vestas V110-2.0 turbine presented the optimal match with the wind speed frequency presented in Figure 5. A capacity factor of 35% was calculated at 80meter heights for the Vestas V110-2.0 turbine. A total number of 50 turbine each having the name plate capacity of 2MW is used for the wind farm design.

Table 4.2:Initial system cost[1]

	Amount (US$ in '000)
EPC Price	130,356
Financial Charges	3085
Non-EPC Cost	100000
Insurance during construction	978
Interest during construction	5573
Sinosure Insurance	11243
Total	**161,235**

The wind farm is optimized after analyzing the impact of varying factors such as off-set of rows and turbines/row spacing. The size constraint is also analyzed in the section 8 and a co relation is presented between the capacity factor, row spacing and the land requirement in Figure 10. Based on the analysis the optimal parameter for maximizing the farm efficiency is presented in Table 1. A capacity factor of 34% is achieved by optimizing the system, with a hub height of 80m with the rotor diameter of 110m. Different economic variables are also discussed and analyzed in prior sections. NPV, payback time and LCOE are on the major variables that predict the economic feasibility of any wind farm. The optimally designed system was analyzed based on these variables and the effect of various economic variables such as inflation and debt fraction.

Table 4.3: Financial summary of optimized proposed wind farm model for Gawadar

Metrics	Value
Annual Energy Output	2,97,859MWh
Levelized Cost of Electricity (LCOE)	9.08¢/kWh
Net Present Value	$585,621,440
Payback Time Period	4.2yrs
Equity	$40,300,000
Debt	$120,900,000
GHG Reduction	1,26,858 tCO_2/yr.

In the current economic condition of Pakistan, with the debt fraction of 75% at a rate loan rate of 6% is assumed for the designing the optimal financial feasibility of wind farm. An LCOE of 9.08¢/kWh is achieved with a payback time period of 4.2 years. A positive NPV is achieved endorsing the financial viability of the project. A Summary of the financial parameter is presented in Table 4.3.

A total of 2,97,859 MWh of energy production is calculated for the proposed designed wind farm annually, which will provide a GHG emission reduction up to 12648 tCO_2 annually when compared will all other fuel types. The results of energy production and financial viability are validated using RET Screen and a variation of less than 0.1% and 7% respectively was calculated as shown in Table 4.4.

Table 4.4: Validation of annual energy output and payback time for Gawadar

Metrics	Values SAM	Values RETScreen	Variations
Annual Energy Output	2,97,859MWh	2,97,849MWh	0.003%
Payback Time Period	4.2yrs	4.5yrs	7%

4.1.3 Quetta Site Location

Quetta is located in the western region of the country, in the mountainous region of Koh-e-Suleman. This region has gained immense importance under the CPEC, as it is a part of western route of CPEC. Moreover, there are special economic zones planned in this area, which will bring industrial development and social up lifting in this region of the country. This economic development will bring along a forecasted energy demand in this region which needs to be addressed.

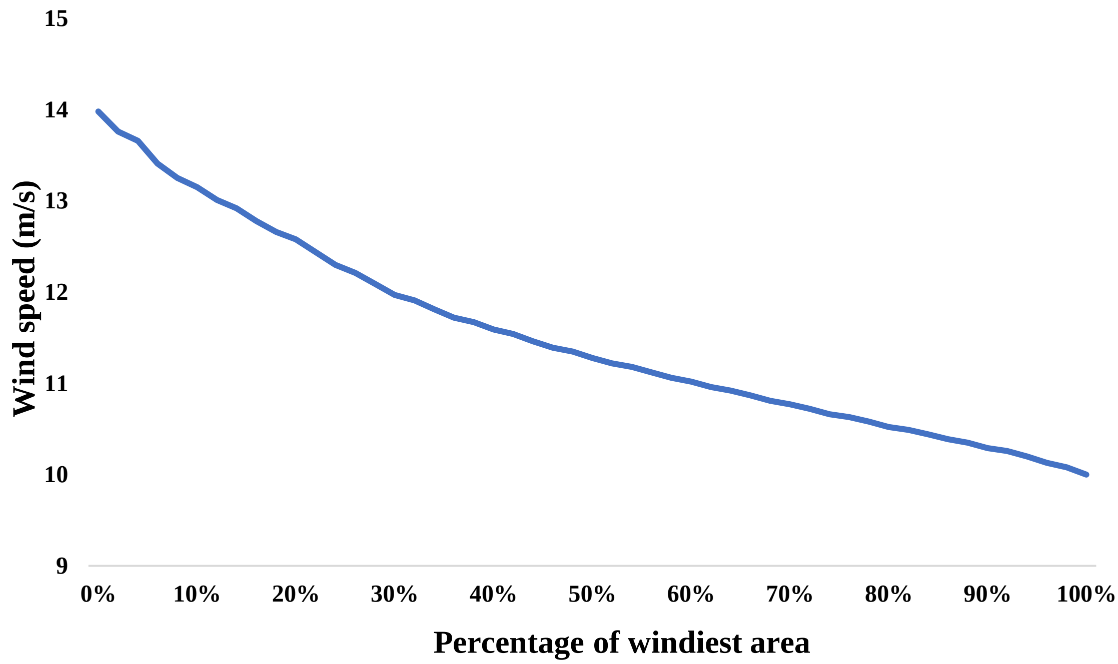

Figure 4.4: Mean wind Speed at 100m height Quetta

This region receives multiple air passages from the western disturbances in the majority part of the year. Moreover, the mountainous regions in this region act as a in gate for the wind and confines them in a specific path, thus increasing their wind speed and pressure. The avg. wind speed in the region is around 4.14m/s, However, at certain site locations can reach up to 13.15m/s.

Quetta has predictable wind potential with availability almost throughout the year. Maximum wind speed is available in the night and early morning hours. The avg. monthly variation of wind speed is between 1.34 and 0.6 wind speed index. Maximum wind speeds are available in the 1st and last quarter of the year mainly due to the westerner disturbances.

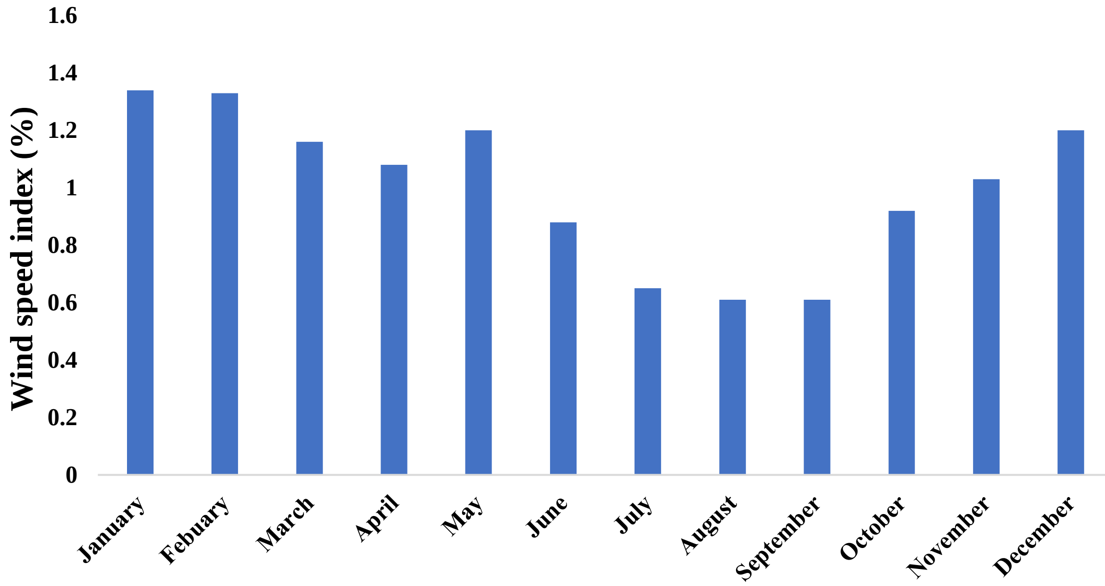

Figure 4.5: Monthly wind speed variations in Quetta

4.1.4 Techno-Economic Analysis of 100MW Wind Farm in Quetta

As discussed in the earlier section the impact of various economic and technical variables on the viability of the wind farm. An optimized wind farm design is created. Some of the key technical and economic variables of the optimized system analysis are presented in this section. Key parameter of optimized wind farm is presented in Table 4.5:

Table 4.5: Summary of the technical parameters of optimized wind farm design

Technical Parameter	Values
Wind Turbine Type	Gemesa G114
Rated Power output	2000kW
Rotor Diameter	114m
Hub Height	80m
Turbine Per Row	5
Total No. of Rows	10

Shape of Farm	Square/ Rectangular
Capacity Factor	23.1%

Gamesa G114 turbine presented the optimal match with the wind speed characteristics of Quetta. A capacity factor of 23.1% was calculated at 80meter heights for the Gamesa G114 turbine. A total number of 50 turbine each having the name plate capacity of 2MW is used for the wind farm design. Different economic variables are also discussed and analyzed in prior sections. NPV, payback time and LCOE are on the major variables that predict the economic feasibility of any wind farm. The optimally designed system was analyzed based on these variables and the effect of various economic variables such as inflation and debt fraction.

Table 4.6: Financial summary of optimized proposed wind farm model for Quetta

Metrics	**Value**
Annual Energy Output	202,515 MWh
Levelized Cost of Electricity (LCOE)	11.0 ¢/kWh
Net Present Value	$367,771,296
Payback Time Period	4.6 yrs.
Equity	$40,250,000
Debt	$120,750,000
GHG Reduction	85,993 tCO_2/yr.

In the current economic condition of Pakistan, with the debt fraction of 75% at a rate loan rate of 6% is assumed for the designing the optimal financial feasibility of wind farm. An LCOE of 11.0 ¢/kWh is achieved with a payback time period of 4.6 years. A positive NPV is achieved endorsing the financial viability of the project. A summary of the financial parameter is presented in Table 4.6.

A total of 20,2515 MWh of energy production is calculated for the proposed designed wind farm annually, which will provide a GHG Emission reduction up to 85,993 tCO_2 annually when compared will all other fuel types. A percentage variation of 0.07% and 43% was between the calculation of SAM and RETScreen.

4.1.5 Bahawalpur Site Location

Bahawalpur is located in the central eastern region of the country. It is located in the Cholistan desert of Pakistan. It is included in the semi-aired climatic condition, which receives a lot of wind produced due to the difference in the climatic regions in the surrounding. Moreover, due to the desert climate. The wind blows from cold sand at night towards the hotter areas of land, due to pressure difference.

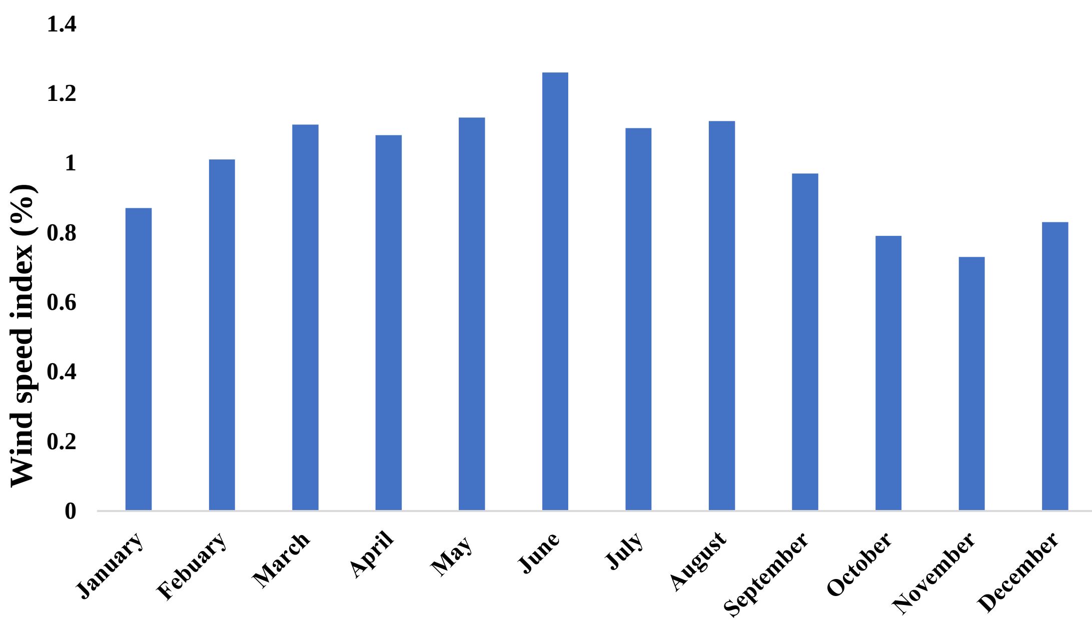

Figure 4.6: Monthly wind speed variations in Bahawalpur

Bahawalpur region is also strategically important as a part of CPEC and has a planned economic zone in the surroundings. There is a very large forecasted energy demand in this region due to the planned industrial development in this area. Bahawalpur has a predictable wind potential with availability almost throughout the year. Maximum wind speed is available in the night and early morning hours. The avg. monthly variation of wind speed is between 1.23 and 0.76 wind speed index. Maximum wind speeds are available in the 2nd and 3rd quarter of the year mainly due to the extreme climatic temperature in the summer morning and comparative cold breeze in the evening.

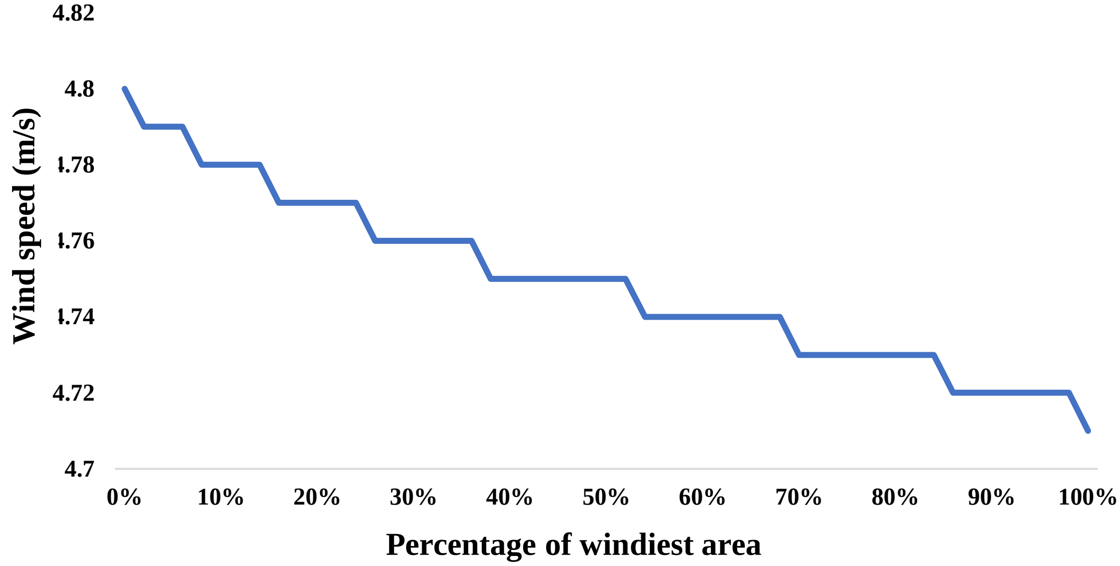

Figure 4.7: Mean wind speed at 100m in Bahawalpur

4.1.6 Techno-Economic Analysis of 100MW Wind Farm in Bahawalpur

As discussed in the earlier section the impact of various economic and technical variables on the viability of the wind farm. An optimized wind farm design is created. Some of the key technical and economic variables of the optimized system analysis are presented in this section. Key parameter of optimized wind farm is presented in Table 4.7:

Table 4.7: Summary of the technical parameters of optimized wind farm design

Technical Parameter	Values
Wind Turbine Type	Gamesa G 114
Rated Power output	2000kW
Rotor Diameter	114m
Hub Height	80m
Turbine Per Row	5
Total No. of Rows	10
Shape of Farm	Square/ Rectangular
Capacity Factor	20.2%

Gamesa G114 turbine presented the optimal match with the wind speed characteristics of Quetta. A capacity factor of 20.2% was calculated at 80meter heights for the Gamesa G114 turbine. A total number of 50 turbine each having the name plate capacity of 2MW is used for the wind farm design. Different economic variables are also discussed and analyzed in prior sections. NPV, payback time and LCOE are on the major variables that predict the economic feasibility of any wind farm. The optimally designed system was analyzed based on these variables and the effect of various economic variables such as inflation and debt fraction.

Table 4.8: Financial summary of optimized proposed wind farm model for Bahawalpur

Metrics	Value
Annual Energy Output	176,848 MWh
Levelized Cost of Electricity (LCOE)	15.30 ¢/kWh
Net Present Value	$261,485,120
Payback Time Period	6.5 yrs.
Equity	$40,300,000
Debt	$120,900,000
GHG Reduction	75,145 tCO_2

In the current economic condition of Pakistan, with the debt fraction of 75% at a rate loan rate of 6% is assumed for the designing the optimal financial feasibility of wind farm. An LCOE of 15.30 ¢/kWh is achieved with a payback time period of 10.3 years. A positive NPV is achieved endorsing the financial viability of the project. A Summary of the financial parameter is presented in Table 4.8.

A total of 130,613MWh of energy production is calculated for the proposed designed wind farm annually, which will provide a GHG Emission reduction up to 55,467 tCO_2 annually when compared will all other fuel types.

4.2 Discussion

Three different site locations spread across Pakistan were evaluated using SAM. Gwadar, Quetta and Bahawalpur site locations were analyzed using the current technological and economical infrastructure of Pakistan. An LCOE of approximately 0.09 $/kWh was calculated for Quetta and Gawadar, whereas 0.15 $/kWh is calculated for Bahawalpur. Payback time of 4.2, 4.6 and 6.5 years is calculated for Gawadar, Quetta and Bahawalpur respectively.

In Pakistan, the avg. power purchasing rate lies between the range of 0.05-0.09$/kWh. Different site locations provide the energy at various LCOE in between this range. Moreover, the power purchasing rate varies greatly in Pakistan based on the DISCO's. In case of our selected site location in Gawadar and Quetta, the QESCO has a power purchasing rate for FY 2019-20 between the range of Rs 10-15/kWh(0.07-0.095/kWh at conversion rate of 150Rs)[2]. The LCOE of our project site of Quetta and Gwadar are at 0.09$/kWh, which lies in between this range and makes it suitable for matching with the existing power purchasing tariff.

All the projects' sites have a positive NPV which is a major indicator for the feasibility of the planned wind farm. LCOE of Quetta and Gwadar are well in range, However, the project site of Bahawalpur will require incentives from government to increase the techno-economic viability of the proposed wind farm location. Additionally, on comparing the techno economic analysis with the similar studies for the proposed site location. The feasibility study shows prominent results in terms of rate of return and the payback time. Samreen et al. presented a techno economic analysis of 50MW wind farm in Gwadar with a payback time period of 9 years, comparing it with our site location and the feasibility approach the study calculates the payback time period of 4.2 years and a higher return on investment[3].

Considering the current, energy crisis situation in Pakistan and the forecasted development in the country, energy security is a critical component. Utilization of wind farms at a cost of $1610/ kW, is not the high and can be invested. The projects have a positive viability and have the potential of returning a good return on investment. On the other hand, it will also help in increasing the green development of Pakistan as well as the global image of CPEC.

Additionally, an Empirical relationship is developed between the cumulative effect of financial parameters (Inflation and Debt Fraction) on the LCOE and NPV. LCOE and NPV are presented as function of inflation and debt fraction. For all site locations, a second-degree polynomial relationship is observed with a perfect match curve fitting equation. Each site location has different coefficient which can be utilized for analyzing and predicting the varying impact of financial parameters on the system feasibility.

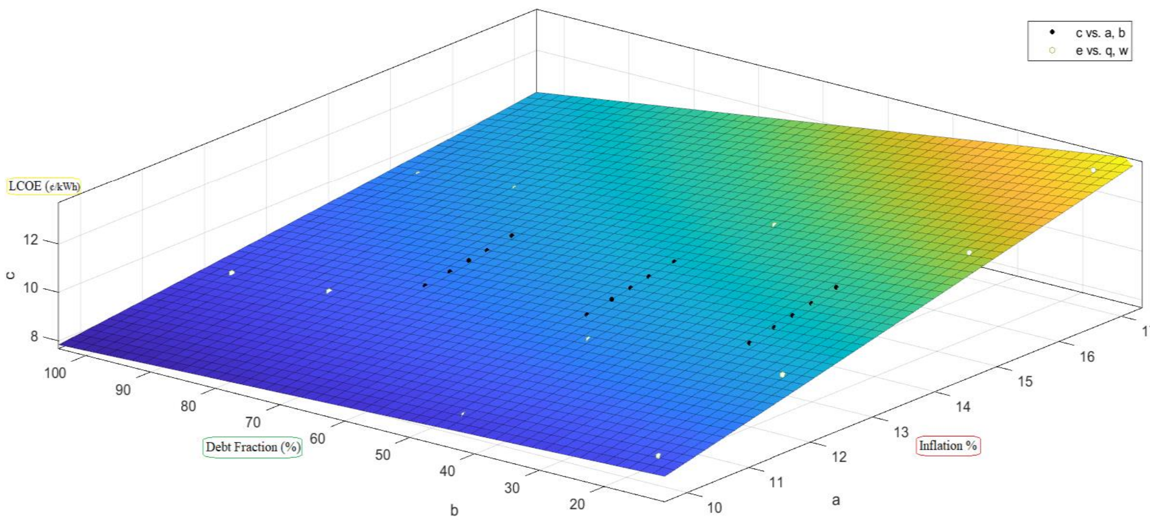

Figure 4.8: Empirical relationship between Inflation, Debt Fraction on LCOE for Gawadar

For Gawadar site location, second degree polynomial equation represents the relationship between the cumulative effect of financial parameters and the LCOE for Gawadar site location. The relationship is given by the following equation with the R-square value of 1, RMSE= 0.003172 and SSE= 9.058e-05.

z= f(x,y) = $p00 + p10x + p01y + p20x^2 + p11xy + p02y^2$ (8)

Where,

p00= 2.417 (0.8988, 3.935)

p10= 0.6433 (0.4136, 0.873)

p01= 0.02657 (0.024, 0.02914)

p20= 0.002083 (-0.006608,0.01077)

p11= -0.003707 (-0.003895, -0.003518)

p02= -1.5e-06 (-7.889e-06,4.689e-06)

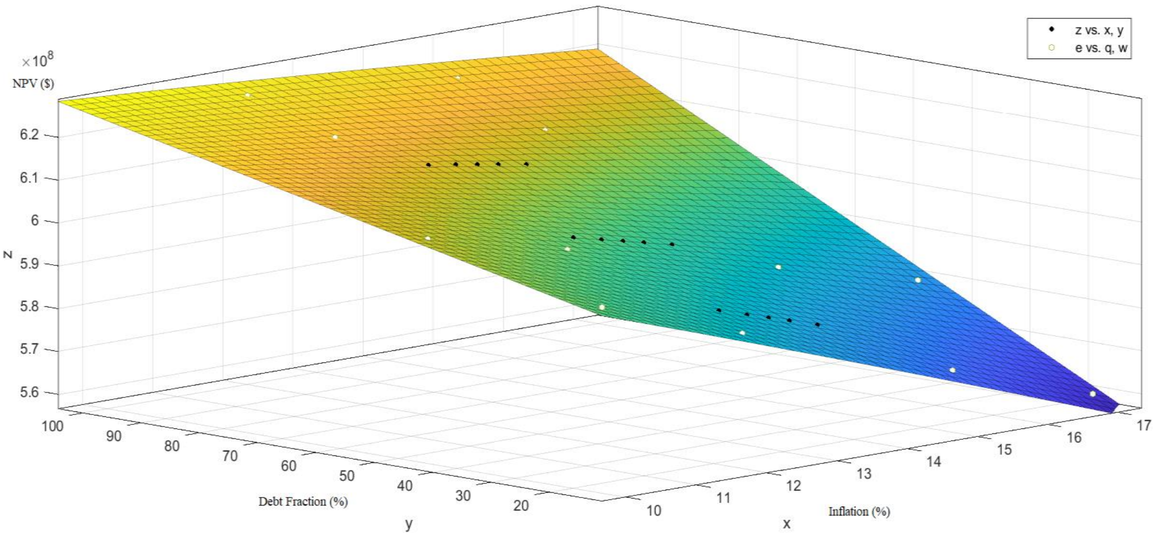

Figure 4.9: Empirical relationship between Inflation, Debt Fraction on NPV for Gawadar

Similar, second-degree polynomial equation represents the relationship between the cumulative effect of financial parameters and the NPV for Gawadar site location. The relationship is given by the equation 8 with the R-square value of 1, RMSE= 1.028e+4 and SSE= 9.512e+08 with coefficients:

p00= 6.538e+08 (6.489e+08, 6.587e+08)

p10= -5.598e+06 (-6.342e+06, -4.853e+06)

p01= -1.836e+05 (-1.919e+05, -1.753e+05)

p20= -3.399e+04 (-6.215e+04, -5824)

p11= 5.057e+04 (4.996e+04, 5.118e+04)

p02= -0.04096 (-20.42, 20.34)

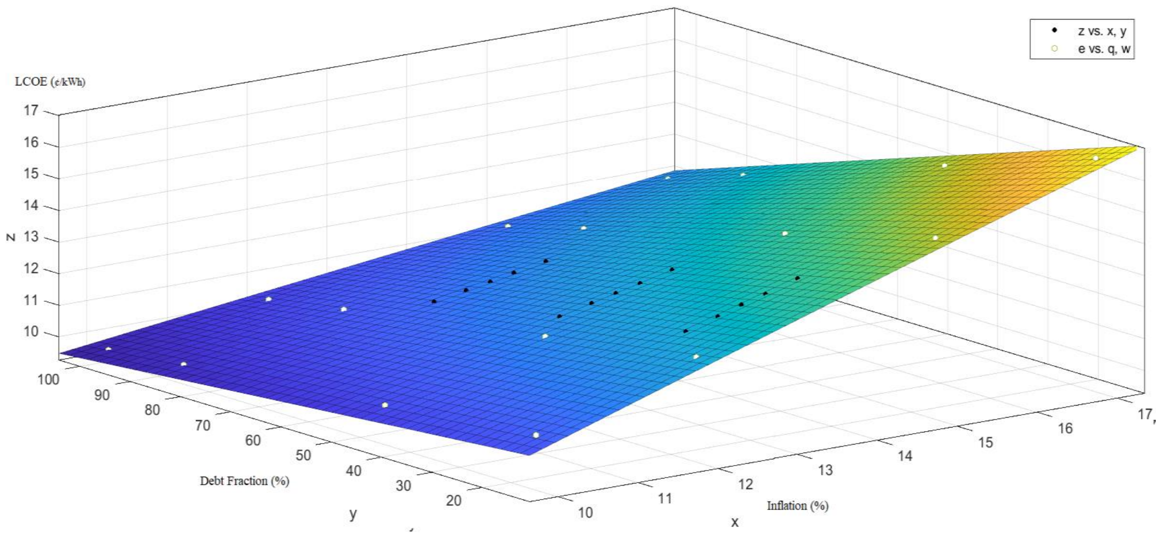

Figure 4.10: Empirical relationship between Inflation, Debt Fraction on LCOE for Quetta

Similarly, For Quetta site location, second degree polynomial equation represents the relationship between the cumulative effect of financial parameters and the LCOE for Quetta site location. The relationship is given by the equation 8 with the R-square value of 1, RMSE= 0.002468 and SSE= 5.481e-05 with coefficients:

p00 = 2.001 (0.8199, 3.182)

p10 = 0.9351 (0.7565, 1.114)

p01 = 0.04094 (0.03894, 0.04294)

p20 = -0.001701 (-0.008462, 0.05059)

p11 = -0.005586 (-0.005733, -0.00544)

p02 = -3.2e-06 (-8.092e-06, 1.692e-06)

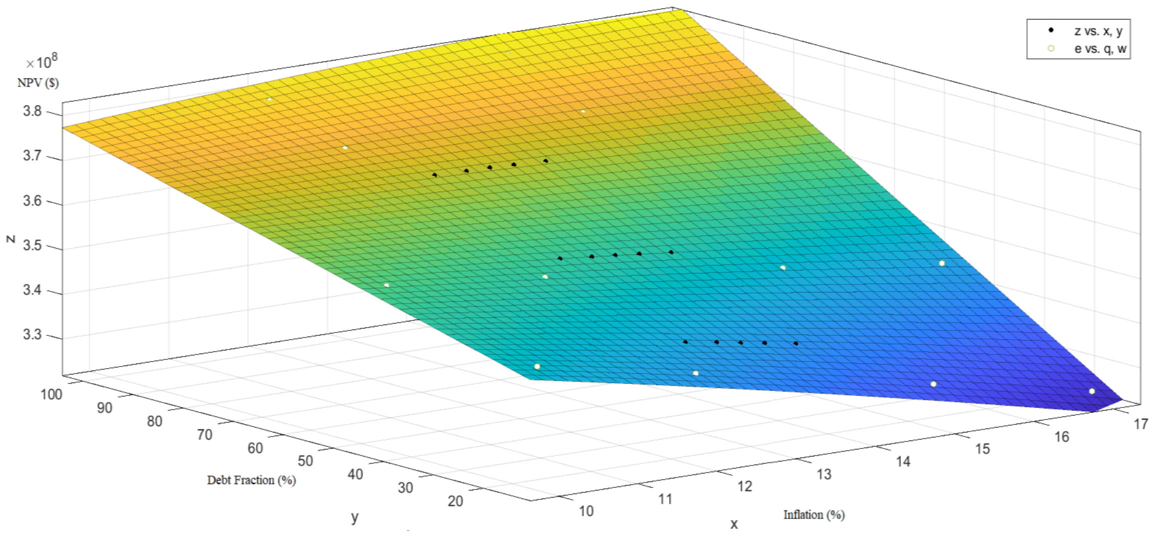

Figure 4.11: Empirical relationship between Inflation, Debt Fraction on NPV for Quetta

Similar to LCOE, second-degree polynomial equation represents the relationship between the cumulative effect of financial parameters and the NPV for Quetta site location. The relationship is given by the equation 8 with the R-square value of 1, RMSE= 1.028e+4 and SSE= 9.512e+08 with coefficients:

p00= 2.417 (0.8988, 3.935)

p10= 0.6433 (0.4136, 0.873)

p01= 0.02657 (0.024, 0.02914)

p20= 0.002083 (-0.006608, 0.01077)

p11= -0.003707 (-0.003895, -0.003518)

p02= -1.5e-06 (-7.889e-06, 4.689e-06)

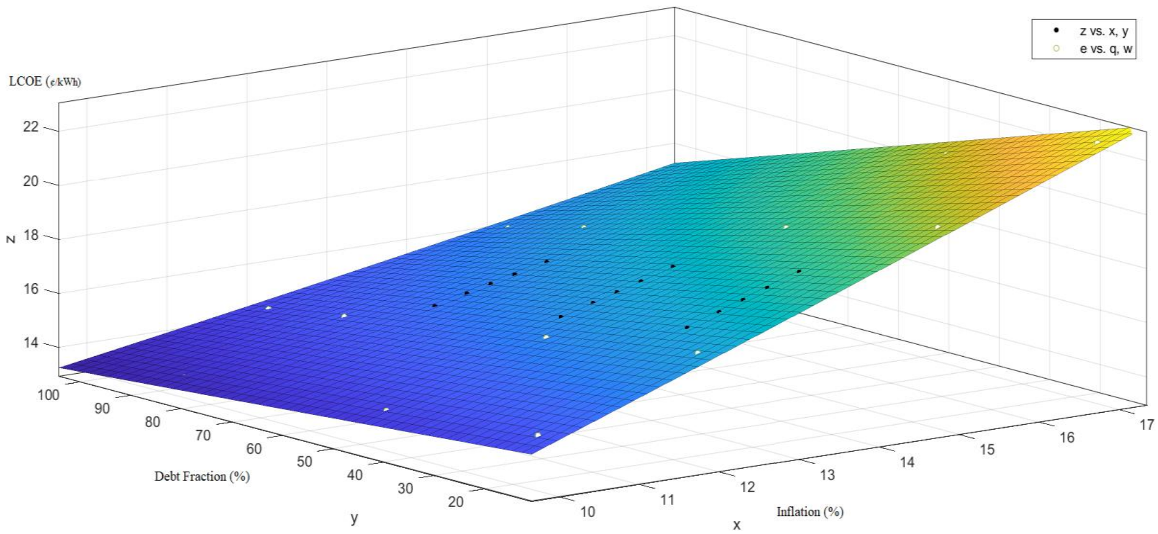

Figure 4.12: Empirical relationship between Inflation, Debt Fraction on LCOE for Bahawalpur

In a similar way for Bahawalpur site location, second degree polynomial equation represents the relationship between the cumulative effect of financial parameters and the LCOE for Bahawalpur site location. The relationship is given by the equation 8 with the R-square value of 1, RMSE= 0.003172 and SSE= 9.058e-05 with coefficients:

p00= 2.417 (0.8988, 3.935)

p10= 0.6433 (0.4136, 0.873)

p01= 0.02657 (0.024, 0.02914)

p20= 0.002083 (-0.006608, 0.01077)

p11= -0.003707 (-0.003895, -0.003518)

p02= -1.5e-06 (-7.889e-06, 4.689e-06)

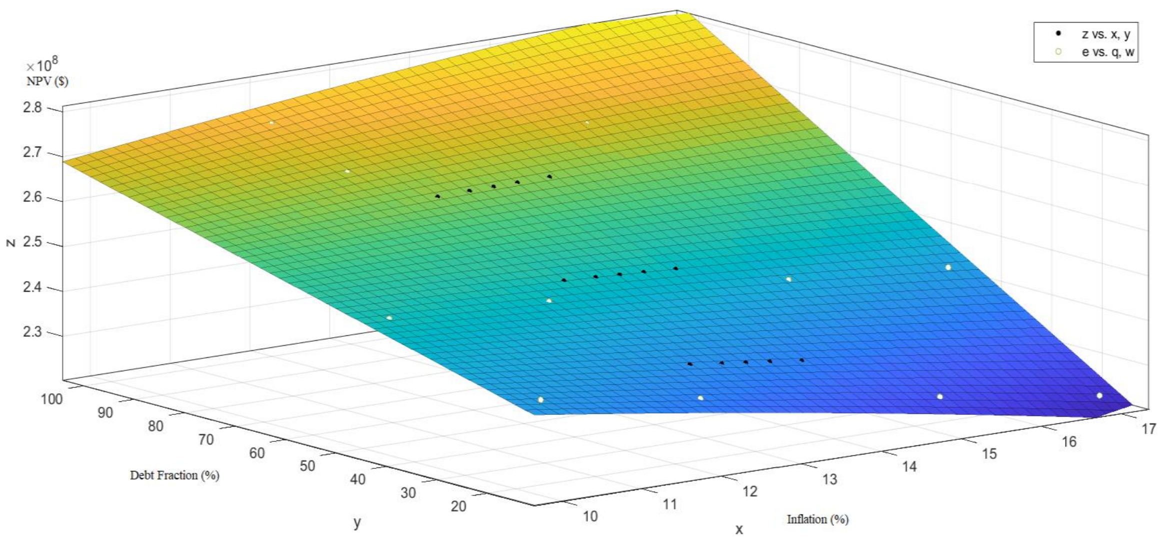

Figure 4.13: Empirical relationship between Inflation, Debt Fraction on NPV for Bahawalpur

Similar to LCOE, second-degree polynomial equation represents the relationship between the cumulative effect of financial parameters and the NPV for Bahawalpur site location. The relationship is given by the equation 8 with the R-square value of 1, RMSE= 0.003503 and SSE= 0.0001104 with coefficients:

p00= 4.055 (2.379, 5.732)

p10= 1.082 (0.8284, 1.336)

p01= 0.04539 (0.04256, 0.04823)

p20= 0.003784 (-0.005812, 0.01338)

p11= -0.006345 (-0.006553, -0.006137)

p02= 4.8e-06 (-2.144e-06, 1.174e-05)

These empirical relationship and equation can be used to analyze the impact of future changing financial conditions and analyze their impacts on the economic feasibility of different proposed wind farms at various location.

References

[1] M. Z. Yong, “Registrar National Electric Power Regulatory Authority (NEPRA) NEPRA Tower, Islamabad Subject: APPLICATION FOR COST PLUS TARIFF BEFORE NEPRA.”

[2] S. Plaza, “Central Power Purchasing Agency (CPPA) All rights reserved.” Accessed: May 18, 2021. [Online]. Available: www.cppa.gov.pkinfo@cppa.gov.pk.

[3] S. Siddique, R. Wazir, Z. A. Khan, and N. Iqbal, “Technical and financial analysis of 50MW wind farm at Gwadar, Balochistan,” Oct. 2015, doi: 10.1109/PGSRET.2015.7312211.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

Pakistan is a developing country, with a huge forecasted demand of energy. Pakistan has an installed generation capacity of 34,000 MWh with a demand of only 25,000 MWh. However, Pakistan still faces the energy crisis. The biggest contributor to these crises is the capacity issue of transmission system. Replacing or upgradation of existing system is a time and money extensive process. Use of renewable as distributed generation source is the most promising option to address the energy crisis and coupe up with the rising energy demand.

Pakistan has a large amount of wind potential available across the country specially along the coastal belt, which can be utilized for meeting the forecasted demand. Pakistan particularly has a regional impact project of CPEC undergoing, planned to bring industrial and economic development all over the country. The province of Baluchistan holds a specific key role in this development as special economic zones and port of Gwadar are the main epicenter for development. There is a massive forecasted demand of energy in the coming years specially along the coastal belt and in the economic zones. The utilization of renewable resource to meet the forecasted demand can not only help in the clean development of the country as well as help in ensuring the GHG Emission reduction in the region.

Numerous, techno-economic analysis of wind potential in Pakistan has been analyzed using approaches like ANN and wind speed distribution. However, our study uses two different software's for calculating the techno economic feasibility of 100MW wind farm in three different locations of Pakistan. The study utilized the Weibull distribution model for calculating the annual energy production from the proposed site location using SAM as well as validates the result using the avg. wind speed to calculate the annual energy production through the proposed wind farm using RETScreen. The study has analyzed the financial feasibility with the latest cost of similar projects as well as current economic conditions of the country.

Three different site locations in Gwadar, Quetta and Bahawalpur were analyzed in our study for their detailed techno economic viability. The results showed positive indicators for all these locations and the system was analyzed using the run-time values of the economic conditions and project costs.

An LCOE of 9.08 ¢/kWh with capacity factor of 34% was calculated for the Gawadar site location in Pakistan with a minimal payback time period of 4.2 years with positive NPV. However, an LCOE of 11.0 ¢/kWh was calculated for site location of Quetta with a payback time period of 4.6 yrs with positive NPV. Bahawalpur site location also showed positive indicators like NPV; however, an LCOE of 15.30 ¢/kWh was calculated with a payback of 6.5 years. The LCOE of Gwadar and Quetta however, lies in between the range of electricity buying tariff of QESCO; however, the Bahawalpur site location will require a feed in tariff to increase its viability.

Energy production of 29,7859 MWh, 20,2515 MWh and 17,6848 MWh was calculated from Gwadar, Quetta and Bahawalpur site location. These site locations are available near the existing or forecasted load centers. Production of the energy at these points will not only reduce the loading on the existing infrastructure as well as help increase the energy security and reliability of the electricity infrastructure as well as reducing the carbon footprint of the infrastructure.

5.2 Recommendations

1. Although, the analysis provides a positive feasibility of the proposed wind farm for all countries. However, financial incentives for such investment will not only promote the investment in this sector but also help reducing the cost of energy production as well.
2. Reducing the loan rate as well as increasing the loan term will also provide better feasibility for the investor along with reducing the LCOE and payback time.
3. The LCOE of wind farm in all location is although higher than the LCOE of coal fired power plants. However, the coal-based plants will have a very high GHG emission which can be mitigated by a tradeoff of a higher LCOE through wind farm at the same location.

4. Considering a cost of 1,610 \$/kW for wind farm, the utilization of wind farm as sources of DG is a promising option in order to keep up the clean and green development as well as to address the energy crisis issue of Pakistan.

Appendix 1

Techno Economic Feasibility Analysis of 100MW Wind Farm in the Northern Coastal Region of Arabian Sea

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Abstract

Northern coastal region of Arabian Sea has an abundant wind potential available which can be utilized. Pakistan, India and Iran are developing countries with an increasing energy demand. The major load centers of these countries such as ports and industries are located around the coastal region of these countries. Energy demand of these load centers can be fulfilled utilizing the wind potential of the coastal region. The study presents techno economic evaluation of 100MW wind farm in the coastal region of Arabian Sea. The study utilized System Advisory Model(SAM) for analysis and accommodated the latest financial and economic parameters for evaluating the feasibility of wind farm. The study presents the relation of various technical and economic variables with capacity factor, levelized cost of electricity (LCOE) and payback time. A parametric optimized wind farm design is presented for this region. Annual energy production of 29,7859 MWh is calculated with greenhouse gas reduction of 12,648 tCO2. A positive net present value (NPV) along with LCOE of 9.08, 6.2 and 17.39 ¢/kWh with a payback time

of 4.2, 4.5 and 3.4 years for Pakistan, India, and Iran, respectively. The LCOE calculated lies in range of average tariff rate of 9.5 ¢/kWh, making it economically feasible for investment.

Keywords

Renewable energy production, Wind energy, Techno-economic assessment, Clean energy, Green development, System advisory model (SAM), Energy system modelling

Journal and Status

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