ASSESSMENT OF WIND RESOURCE POTENTIAL AND POWER PRODUCTION FOR SELECTED SITES IN PAKISTAN

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DECLARATION

I certify that this research work titled *"Assessment of Wind Resource Potential and Power Production for Selected Sites in Pakistan"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources as been properly acknowledged/referred.

Rabab Rabbani

00000103646

Dedicated to my parents for their continued belief in me and for their unwavering support in all my life's endeavors

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ABSTRACT

In the first part of this study, correlation between MERRA-2 reanalysis wind data and ground data is assessed for 12 selected locations. The correlation coefficient ranges from 0.17 to 0.75 among the sites. Sites with higher average wind speeds show comparatively stronger correlation. Besides, site specific factors are also investigated. In the second part, wind energy potential at same 12 locations across Pakistan is evaluated for the first time using 10-min interval ground observed data. The diurnal, monthly and annual means for the sites are calculated and wind speed variance is observed utilizing wind data recorded at four altitude levels (20m, 40m, 60m and 80m), and wind speed calculated at further two levels (10m and 50m). Wind roses were developed for 50m and 80m wind data. The data is fitted to the Weibull distribution, which is widely accepted method for wind frequency distribution. Most probable wind speeds, wind speeds carrying maximum energy and wind power densities for all the locations are calculated for 50m and 80 height wind data. Wind power density is calculated by 2 methods, using wind speed and Weibull distribution analysis, both producing comparable results. Significant variation of wind power density is observed along the height. High values for average wind power density are calculated for four locations, namely Sujawal (355.6 W/m^2), Sanghar (312.9 W/m^2), Tando Ghulam Ali (288.2 W/m^2) and Umerkot (252.8 W/m^2). Finally, Wind farm feasibility studies are developed for the four selected sites utilizing RETScreen Clean Energy Management Software and energy outputs and capacity factors are estimated. It was also found that wind power projects developed under the assumed scenarios will be financially viable and will result in considerable reduction of GHG emissions. Furthermore, 8 scenarios were developed and modeled on the tool to study the impact of policy changes on the wind power sector of Pakistan.

Contents

List of Abbreviations

Above Ground Level	AGL
Alternative Energy Development Board	AEDB
Atmospheric Data Assimilation System	ADAS
Denmark Technical University	DTU
Energy Sector Management Assistance Program	ESMAP
Fifth Assessment Report	AR5
Giga-Watt	GW
Goddard Earth Observing System	GEOS
Greenhouse Gas	GHG
Gross Domestic Product	GDP
Intergovernmental Panel on Climate Change	IPCC
International Electrotechnical Commission	IEC
International Organization for Standardization	ISO
Kilo-Watt	KW
Mega-Watt	MW
Modern-Era Retrospective analysis for Research and Applications	MERRA
National Aeronautics and Space Admiration	NASA
National Center for Atmospheric Research	NCAR
National Centers for Environmental Prediction	NCEP
National Electric Power Regulatory Authority	NEPRA
Pakistan Meteorological Department	PMD
Root Mean Square Errors	RMSE
Surface meteorology and Solar Energy	SSE
Synthesis Report	SYR
Tera-Watt	TW
The World Bank	WB
United States Agency for International Development	USAID
Weather Resource and Forecasting	WRF
Wind Power Density	WPD

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CHAPTER 1

INTRODUCTION

1.1 Background

Dependency on fossil fuels e.g. oil, gas and coal, to meet the ever increasing energy demands for growing global population, urbanization and the associated life style with consequent industrialization has led to a higher concentration of greenhouse gases in the atmosphere and hence, the global warming. Finding solutions for the environmental degradation has become a challenge for governments and policy makers. Switching to renewable energy technologies is the key to reduce greenhouse gas (GHG) emissions; according to the Synthesis Report (SYR) of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), considerable reduction of emissions over the next few decades can substantially reduce the climate risks for this century and beyond. It would also reduce the challenges and costs required for mitigation and provide higher prospects for adaptation [1].

Being decentralized in nature, renewable energy contributes to energy resilience of a country and in turn lowers the burden on economy. A 0.12% growth of real Gross Domestic Product (GDP) and 0.16% of GDP per capita is driven by only a 1% increase of renewable energy consumption in a country; it also results in an increase of 0.44% and 0.37% per capita annual income for rural and urban households respectively [2]. The advent of renewable energy technologies in a country is also known to create jobs, 10.3 million jobs alone in 2017 were generated due to the development of the resource around the world [3].

Wind power has a number of advantages over other renewable energy resources which includes its developed technology, low-cost energy production, ease of installation, long life of turbines and simplicity of infrastructure. Wind energy is expected to grow and play a vital role in meeting load demands in the future [4]

The popularity of wind energy keeps increasing and it is becoming an important resource for power generation around the World [5]. Around 10 million MW wind energy is available in the world continuously with a global potential as high as 35% of the total energy consumption [6]. A 1 MW wind turbine can offset as high as 1500 tons of carbon dioxide, 60 pounds of mercury, 6.5 tons of sulfur dioxide and 3 tons of nitrogen oxides annually. Wind farms also consume less power (17 to 39 times) than they generate, as compared to coal plants (11 times) and nuclear power plants (16 times) [7].

The wind power sector has grown by a factor of around 75 in the two decades, from having an installed wind generation capacity of 7.5 gigawatts (GW) in 1997 to a global capacity of around 560 GW in 2018. The global installed capacity as of 2019 is 597 GW [3][8] as shown in figure 1 and table 1. The increasing growth of the technology indicates the increased contribution and role of wind power for meeting the world's future energy demands. The increase in the wind energy consumption around the world is evident from figure 2.

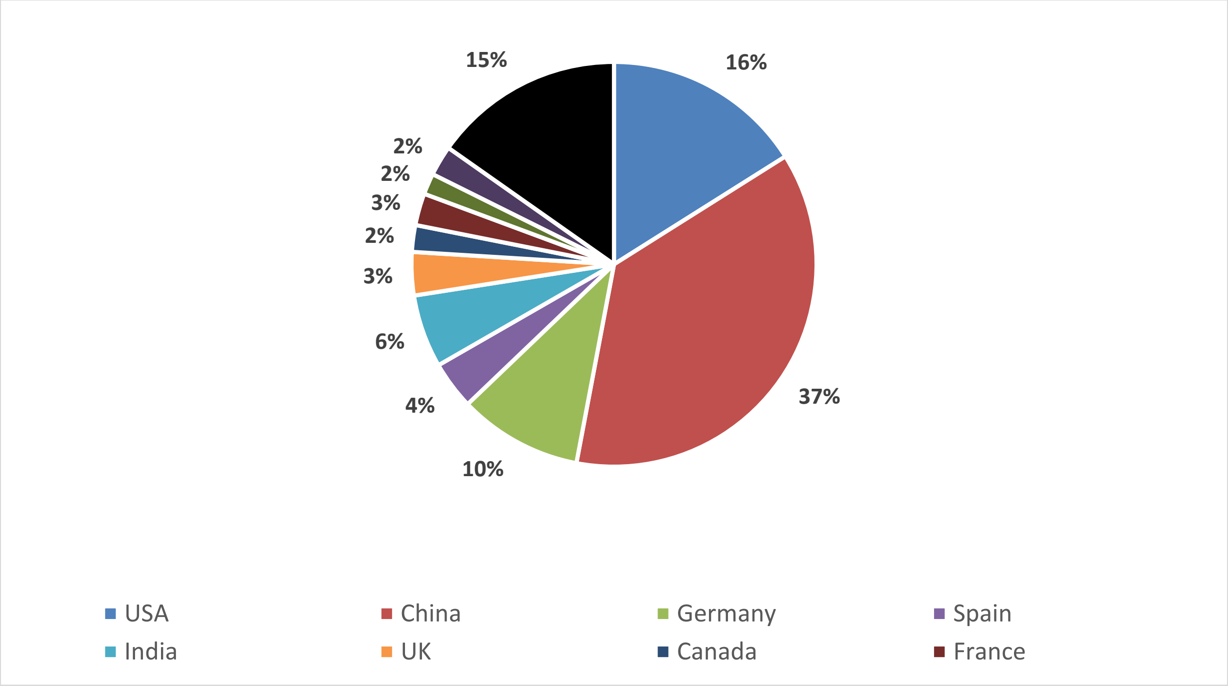


Fig. 1: Country-wise share in global installed wind power capacity in 2018 [8]

Table 1 Global Installed Capacity for Wind (MW)

Country	MW
USA	96363
China	221630
Germany	59313
Spain	23031
India	35017
UK	20743
Canada	12816
France	15313
Italy	10090
Brazil	14490
Rest of the world	91,473

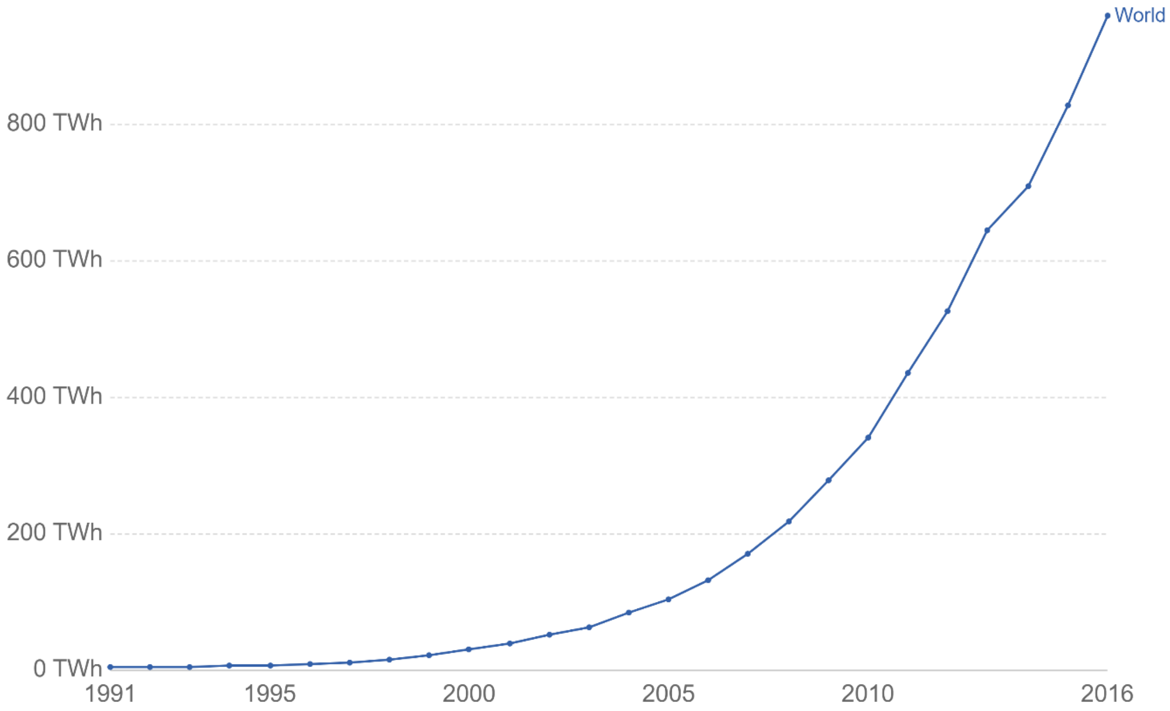


Fig. 2: Annual global wind energy consumption, measured in terawatt-hours per year. Data includes both onshore and offshore wind sources. [9]

Rapidly increasing population, low contribution of renewable energy resources in the energy mix and dependence on limited conventional energy resources is one of the major reasons contributing to the power crisis in the developing countries [10]. Lack of research and development facilities also limit the exploitation of renewable energy resources [11]. The insufficient support at policy level offered by the governments further reduces the chances of growth for the sector [12]. For developing countries, in particular, due to lack of readily available long term high resolution ground datasets, alternative sources of wind characteristic data are needed to be explored. Studies have reported the use of numerical tools e.g. Weather Resource and Forecasting Tool (WRF) [13], satellite based observations e.g. National Aeronautics and Space Admiration (NASA) Surface meteorology and Solar Energy (SSE) dataset [14] and reanalysis datasets like National Centers for Environmental Prediction (NCEP)/ National Center for Atmospheric Research (NCAR) [15].

Reanalysis data has been found to have a supremacy over the other techniques for the assessment of wind energy potentials due to its long term data availability [16]. Various reanalysis datasets have been widely compared with the temporally and spatially matched up ground observations for validation [17–19]. Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) was used for estimation of power generation in European region and the uncertainties in data were discussed [20]. MERRA and MERRA-2 wind datasets have been utilized to model the power production in Sweden [21] and Britain [22] and in a number of other studies as well [17,23–25], due to its high temporal and spatial resolution and reported high correlation with ground observations with correlation coefficients in the range of 0.85 for hourly data and 0.94 for monthly data for simple terrains [26]. However, in most studies high spatial bias was reported, emphasizing the analysis of its suitability for energy potential assessment.

1.1 Wind Power in Pakistan

Out of the 1.3 billion people living without access to electricity in the world, 66% live in 10 countries which include Pakistan, in spite of having one of the world’s lowest (456 kWh) electricity demand per person [27,28]. Consequently, higher dependency on fossil fuels also impacts the economy along with environment, resulting in 6 percent of national Gross Domestic Product (GDP) being spent on managing the environmental damages [29].

Pakistan, being a developing country faces the challenge of increasing population which has resulted in the growing needs of energy, reported to be increasing by over 5% per year in the recent years. Around 51 million people in Pakistan, which accounts to roughly 26% of the population has no access to electric power [30]. This has become a challenge for the government, especially because the country is highly dependent of fossil fuel based technology and is hence vulnerable to the fluctuation of global oil prices. The government has been developing plans and policies to develop its renewable energy sector as it would provide a sustainable and clean source of energy. Private sector was encouraged to invest in the area by an energy policy released in 2006. Under energy security action plan 2006, the task of contributing at least 5% through renewable energy resources in the national energy mix by 2030 was assigned to the Alternative Energy Development Board (AEDB) of Pakistan. The incentives offered, regulatory reforms and policies in favor of the investors has helped in the growth of renewable technologies in Pakistan during the recent years. From 2015 to 2018, 1200 megawatts (MW) were added by renewable resources in the country's energy mix. This included 600 MW of wind energy, 400 MW of solar photovoltaic (PV), 160 MW of biomass and 50 MW from small hydropower [3].The Integrated Energy Plan 2009-2022 developed in 2009 by the Economic Advisory Council and Ministry of Finance set targets for renewable energy for 2022, this included a total of 17400 MW of wind and solar power. Another integrated energy plan was formed in 2011 with the support from Asian Development Bank (ADP), ADP provided technical assistance to the government departments, unfortunately the plans and the subsequent policies were not adopted and no reforms were made for the sector [30].

Like most of the developing countries, unavailability of good quality wind data for Pakistan is one of the major hurdles for the researchers and institutions intending to work on this sector. Although wind characteristic data including wind speed and direction has been recorded through Pakistan Meteorological Department (PMD) masts, under a large-scale project of wind masts installation carried out in 2002, there were flaws reported in the installation of these masts and the reliability of the recorded wind data was further lowered by the use of locally calibrated sensors and data loggers. The record is mostly kept in hardcopies with large data sets getting misplaced over time [31]. AEDB and PMD collaborated with USAID and developed a meso-scale wind map of

Pakistan in 2007 [32], indicating wind speed potential at 50m above ground level (AGL). Analysis undertaken by PMD in 2004 and later in 2007 after the development of wind map confirmed the existence of a wind corridor in the south of Pakistan [31]. Recently, a renewable energy resource mapping project funded by World Bank's Energy Sector Management Assistance Program (ESMAP) has been initiated in cooperation with AEDB. World Bank and AEDB, under this project, wind masts were installed at 12 locations in Pakistan in 2016. These wind masts provide data of unmatched quality [33].

1.2 Research Objectives

The focus of this research was to estimate the wind energy potential across selected sites in Pakistan. High frequency wind characteristic data was collected and assessed. With the available information the following objectives were developed for pursuing the research:

1. Investigation of the wind characteristics and trends in the 12 selected areas across Pakistan
2. Estimation of wind energy resource and power potential
3. Preliminary Feasibility analysis for potential wind farms

1.3 Scope of Research

In this study, for the first time, the high-quality wind data, collected by World Bank & AEDB's project has been used instead of data collected by PMD. Wind analysis at all 12 locations i.e. Bahawalpur, Chakri, Gawadar, Haripur, Peshawar, Quaidabad, Quetta, Sadiqabad, Sanghar, Sujawal, Tando Ghulam Ali and Umerkot has been done to estimate the wind energy potential across the country. In the first part of this study, the ground measured wind data, collected by World Bank & AEDB's project has been used to assess the suitability of MERRA-2 wind data for wind energy estimation. As the study region is part of developing world, with limited ground observatories and radiosonde facilities to be assimilated in MERRA-2 dataset, the accuracy of MERRA-2 needs to be evaluated. Ground wind data was observed at 12 locations spread across Pakistan, at 10min intervals for at least 2 years at four different heights. In the second part, same ground observed wind data is used for wind energy estimation in Pakistan. Weibull Distribution fitting was done to better understand the wind characteristic and wind power density was calculated through two different methods to recommend the most suitable sites of the 12 studied, for wind power projects. Furthermore, the locations have been evaluated for their respective power potential and subsequently are prioritized for development work, also different factors like economic policies and electricity selling price have been discussed. Moreover, 8 different scenarios have been developed to optimize for financial viability and optimal conditions have been determined. Besides benefiting the decision makers for the sector in Pakistan, the results obtained in the study are also important for the development of the wind power sector in other developing countries.

CHAPTER 2

LITERATURE REVIEW

Research work previously conducted in the area of wind energy development across the world with specific focus on Pakistan has been discussed in this chapter. General overview of the wind farms and feasibility assessment studies carried out are discussed. The gaps in the research and various sources of wind data available in the region are also covered.

2.1 History

Wind energy has been utilized by human beings since very early times. It has been used since the day sails were put into the wind. In 5000 BC wind propelled boats were used in River Nile and in 200 BC China had simple wind mills installed for pumping water. Vertical axis wind mills were also being used for grinding grains in Middle East and Persia at that time.

Fascinated by the operational simplicity, new ways to use wind energy were explored and by 11th Century wind energy was extensively used in Middle East primarily for production of food. The ideas were carried over to Europe by crusaders and merchants. Dutch have been reported to use windmills to drain lakes and marshes in Rhine River. In the 19th century, windmills were initially used from pumping water and later for electricity generation as well. [34] During the 20th Century, both on-grid and off-grid farms were researched upon and developed. [35]

The first of its kind and the largest since 1940’s, a 1.25MW Wind turbine was installed during World War II at Vermont Hilltop which was also known as Grandpa’s knob. It was used to feed power to the local utility network. Wind electric turbines were also operational in Denmark during the 1950’s but were later sidelined to cheap oil prices and availability [36].

The scenario for wind energy was changed in the 1970s when the importance of renewable energy technologies was realized once the oil shortages began to hit the World.

1974 onwards till the mid of 1980’s, the US government worked extensively on the research, development and deployment on commercial scale wind turbines. National Aeronautics and Space Administration (NASA) oversee a program to produce a utility scale wind turbine industry for which large scale turbines were researched and developed. Under the funding of National Science Foundation and US Department of Energy, four wind turbine designs were utilized to develop 13 experimental and operational wind turbines. Several world records were also set in terms of diameter and power output for the large wind turbines produced under this program.

Even though the decline in oil prices during the 1980’s and 1990’s threatened further investment in wind power, wind power still flourished due to the state tax incentives offered to encourage development of renewable energy sources. Wind power was also used for utility electricity for the first time in a large scale due to the incentives offered as turbines clustered in large wind resource areas were considered uneconomical in the development standard of modern wind farms.

The growth of wind energy also declined dramatically in late 1980’s once the tax incentives were ended. But the development of wind energy technologies continued in Europe due to realization of environmental impacts of conventional technologies.

2.2 Wind Turbine Types

There are two basic types of wind turbines, namely horizontal axis and vertical axis wind turbines. Horizontal axis wind turbines also known as head-on machines have the axis parallel to the wind direction and are more common. The typical height of turbines range from 25m high for small and around 120m high for larger scales [37].

2.3 Wind Energy Resource Assessment

A large number of studies have been carried out globally to estimate the wind energy potential at various locations, utilizing a number of methods, tools and datasets. Some of the relevant ones have been tabulated below (Table 2);

Table 2 Literature Review

S.No	Methods	Results and Conclusions	Reference
1	Wind data collected at 50m height at 10 min interval for 30 months at one location. Data analyzed using WAsP.	20MW wind farm simulation resulted in the Annual Energy Production of 111.4 GWh.	[38]
2.	Data from two cities in Iran at 10m height at 3 month interval was collected. Weibull was employed to calculate the wind power density. Later an economic assessment was also done.	Summer months were found with higher wind power potential. Wind Turbines at higher hub height (>10m) can be more advantageous economically	[39]
3.	Three hourly data for 3 sites collected for 8 to 10 years, observed at 10m AGL was used in the study. RETScreen was used for feasibility analysis.	The plant capacity factors and cost of energy (COE) was calculated at 3 locations. Equivalents greenhouse gas (GHG) emission reduction was also reported. A 1% in wind speed measurements can result in roughly 2% error in energy output calculation.	[40]
4.	Data collection from 2008 to 2012 at 10-min interval. Annual mean wind speeds at 3 heights were calculated. Weibull was used and energy output analysis was carried out. Analysis done at one height.	Five turbines were compares and 3MW was found the most efficient.	[41]

5	Weather Research and Forecasting (WRF) was used. Wind farm feasibility studies at 2 locations considering 3 turbine types.	Different conditions and policies including tariffs, wind characteristics, turbine types etc were studied. Two different policy frameworks were also considered in the study.	[42]
6	3 hourly ground measured data for a period of 8 years was assessed for energy potential utilizing RETScreen.	The feasibility proved that the project would be financially viable.	[43]
7	Study on the comparison of Satellite and Ground data characteristics. The impact of irradiance and ambient temperature was studies with different available technologies to calculate performance. Five sites were studied with respect to climatic conditions.	Climate data was found to overestimate the yield for all locations.	[44]
8	2 Met Stations were selected. The satellite scatterometers used are SeaWinds onboard QuikSCAT (1999 – 2009) with data available from July 20, 1999 to November 19, 2009 and ASCAT onboard METOP-A (2006 – present) with data from March 03, 2009 to December 31, 2013. Data was then processed.	Daily & weekly averages calculated from 10-min data. Mean, standard deviation and root mean square were calculated to compare. Some correlation is seen: 0.7-0.8.	[45]
9	Wind energy potential was assessed by developing a wind map of Bangladesh using NASA SSE wind data and HOMER model.	The installation of 4614MW of wind power can be possible in the country if 1000 hr operation in a year is feasible.	[46]
10	Data was collected through SSE NASA and analyzed using HOMER.	A pre-feasibility study under set conditions using	[47]

		wind turbines was found viable.	
11	Wind speed data was collected from NASA for 1 year, and curves were developed. GIS was used for farm siting.	Significant wind power potential is available in the continent, highest being in the north.	[48]
12	Monthly average wind data at 50m height from NASA data base from 1993 till 2005 was studied. WAsP was used for energy output calculation.	No significant relationship was found between NASA's and site specific ground data; NASA overestimating by 25%. Feasibility carried out using NASA dataset resulted in favorable project outcome.	[49]
13	An hourly model of wind power production is presented and explored, for Sweden. Reanalysis data from the MERRA project and information about Swedish energy convertors was used.	Overall no major errors were found in model results.	[21]
14	Wind speed data at 12 m AGL for 19 months was collected for Mankoadze. RETScreen was used for techno-economic feasibility analysis considering different scenarios with respect to available incentives and tariffs.	For a viable project, around 80% capital subsidy, negotiations on tariffs, or finding other sources of revenue is recommended.	[50]
15	Data from three wind masts was collected analyzed using the Weibull statistical method. Energy outputs were calculated by assuming turbine models and a wind farm micro-siting was developed by the use of tools.	Energy map was developed, and farm layout was proposed. The economic analysis showed that the studied case would be viable.	[51]

16	Seasonal and daily wind power patterns were studied using the NASA GEOS-5 wind speed data.	Smart grid application can cater for the regional power fluctuations.	[52]
17	One hour interval wind data collected from a wind mast located at Yeosu airport at a distance of 4km from the site was collected for 3.5 year period at 10m height above ground. WindPRO was used to estimate the energy potential.	Different turbine models were studied, and the most profitable case was recommended on the basis of a economic pre-feasibility study.	[53]
18	Wind energy potential in Zabol, Iran was estimated using ground data for 10 years. Weibull and Rayleigh distribution were employed for potential assessment.	Wind speed mean of 6.5 m/s was found. Summer months were found with higher wind speeds as compared to winter months. Two turbine models were compared, and recommendations were made	[54]
19	44 month hourly data at 10m height above found was analyzed using Weibull and Rayleigh functions for one site.	Wind speed average of 2.23 m/s whereas wind power density of 24.6W/m2 was found.	[55]
20	Five year ground wind data was assessed using Weibull and Rayleigh distribution. A technical and economic feasibility was also carried out for a potential wind farm	Wind speed mean of 6.5m/s at 10m AGL was found. Economic analysis proved the project would be viable and may generate energy with a capacity factor of 56%.	[56]

There have been some studies conducted by the government and the private sector for wind energy potential assessment for different areas of Pakistan, some of which have been summarized in Table 3.

Table 3 Literature Review- relevant work carried out in Pakistan

S.No	Methods	Results and Conclusions	References
1	WAsP was utilized to develop wind data at various heights above ground level and compared with power law. Meteorological data from nearby stations was also used to develop benchmark wind speeds.	Benchmark wind speeds were developed which can be utilized by investors for the financial analysis. Great concern on the quality of data recorded by PMD masts was highlighted.	[31]
2	Hybrid systems were studied under different scenarios using HOMER to find the most feasible arrangement for domestic users.	Wind energy was found to be the most viable source for a hybrid system as compared to others for the selected sites.	[57]
3	Different tubrine models and wind speeds at multiple heights were studied to find the most feasible turbine for the site. ARIMA was used to forecast the data. Statistical tools like Minitab, EViews and Stats graphics were used and verified through RETScreen.	Low wind speed was found which requires an unrealistically high cost of selling electricity to ensure a viable investment.	[58]
4	Wind energy potential at Jamshoro has been analyzed using PMD mast wind data. Weibull was utilized and power output and capacity factor was calculated.	A turbine was chosen and at 50m height above ground 2.1GWh annual energy generation is estimated. Highest output was found in summer months.	[59]
5	Ground data at 3 hour interval for 7 areas in the coastal region of Balochistan was studied power potential was calculated.	Areas with good wind speed were identified and a wind energy generation potential was highlighted.	[60]

6	The meteorological department of Pakistan conducted a study for wind power potential assessment at the coastal areas of Pakistan, utilizing ground data from 44 sites.	Low wind speeds were found in Gwadar and surroundings rendering it unsuitable for commercial scale power projects.	[61]
7	Renewable energy technologies and the economic policies in Pakistan were studied.	Wind is globally the fastest growing renewable energy source. It is cost competitive and environmentally friendly and Pakistan should develop policies to promote the sector.	[62]
8	Concept of Wind Risk has been introduced, where (under specific terms) any loss of energy generation due to wind variability is paid by purchaser.	PMD masts are not installed as per international standards. Wind risk concept will help in the fast development of the sector	[63]
9	Incentives for wind power manufacturers have been detailed.	Wind risk concept and options for tariffs were introduced.	[64]
10	At least 5% share of renewable energy is targeted by 2030 for Pakistan's energy mix. Different incentives for investors have hence been introduced.	Wind Risk concept and guaranteed purchase of electricity is offered. Provision of grid is also the responsibility of the purchaser. Parity of Euro / Dollar is allowed. Carbon Credits can be sold. No Import Duties on Equipment and also Exemption on Income Tax / Withholding Tax and Sales Tax. A tariff (upfront) of US Cents 13.52 per kWh is also offered.	[65]

2.4 Wind Farm Feasibility Studies

For all new technologies, and especially for the renewables the initial cost acts as a major obstacle for the development of the sector in developing countries. In order to assess the benefits, long-term cases are investigated, and pre-feasibilities are carried out to do so. Similarly, wind power projects also require in detail feasibility studies to ascertain the viability of the project, as it is dependent on a number of factors, wind characteristics, capital and annual costs and country's policy being the most important ones [66]. A meteorological mast, ideally as closest in height as possible to the common height of wind turbines and installed meeting the industrial guidelines and international standards if located at the proposed site, reduces the uncertainty in the assessment by the provision of good quality wind resource data. The data must be of more than one year to satisfactorily represent the wind profile [53].

In the past, a number of researches have been conducted on renewable energy covering several purposes. Alishahi et al. studied regulatory frameworks to develop wind power sector by the increase of investment [67], Heagle et al. discussed how the country's policy and incentive program effects the small scale projects [68] whereas, Schaefer et al. assessed the role of tariffs in the wind power sector for New Zealand [69]. A similar study for tariffs in Turkey presented both the cases of onshore and offshore wind power projects [70]. In depth studies for cost of electricity and tariffs by studying long period of data and country specific rules were found for America [71,72] and Malaysia [73]. Wind resource assessment and economic viability for different locations in Iran studied under different economic policies or different turbine types are also presented [74–78]. Quan et al. studied the wind resource and developed an economic analysis for wind farm development in Thailand [79]. The impact of location and load for efficient micro-grid design was presented by Zachar et al [80]. Wind characteristics were evaluated and farm feasibilities were assessed for Algeria in a number of studies [81–83]. A study proposing the installation of residential wind turbines in Karachi suggested a scenario that can help reduce the power deficit for the city [84]. Maryland was found with a good resource potential, able to fulfil as high as 70% of the state's power demand [85]. Economic feasibility of wind power at three heights was studied and compared by Mustafaeipour et al [86]. A study on financial viability of a 50MW wind farm was reported for Gwadar [29]. Similar studies for India [87] and Africa [48]are also found in literature.

A number of tools, techniques and software are being used commercially or in research studies to assess the feasibilities of renewable energy technologies. Engineering economics [88], linear programming [89] and artificial intelligence [90–92] are some of the approaches found in literature, whereas, WAsP [93], RETScreen [94], HOMER [46,57], WindHygen [95] and MATLAB [96,97] are some of the many software reported for the assessment of renewable power projects.

Researchers and renewable energy experts have been known to utilize different software to assess the feasibilities of power projects in order to determine the optimal performance conditions and viabilities of potential projects. RETScreen Expert is a clean energy management tool developed by the government of Canada and is extensively used around the globe to estimate energy potential, costs, savings, greenhouse gas (GHG) emission reduction and economic viability [98,99] involved in solar photovoltaic [100–102], wind power generation [70] and other renewable energy systems [103,104]. It also provides sensitivity and risk analysis option to determine the risks involved by the variation of dependent parameters [105,106]. RETScreen Expert is the latest version of the RETScreen tool and has replaced RETScreen 4 and RETScreen Plus [107].

All details on the functionality of the software and the associated operations have been given by the developers [99].

CHAPTER 3

METHODOLOGY

3.1 Site Description

As mentioned, under the World Bank funded project, 12 locations in Pakistan were identified and 80m high wind masts were installed on 11 of those locations. The coordinates of sites under study can be seen in Table 4. One mast (Quetta/ S7) had a height of 67m due to the local authorization of allowable height and hence the wind speed at 80m height for Quetta was calculated using eq.1. EIA 222-G/ TIA was followed while designing the masts and IEC Standard 61400-12-1 was followed for the installation. Design verification was done through independent studies and quality was assured through all the steps of civil and installation works [65]. In this section, all locations are briefly discussed with respect to topography, geography and meteorology. [65,108]

Table 4 List of sites and their locations

Site	**Site Annotation**	**Longitude**	**Latitude**
Bahawalpur	S1	71.81	29.33
Chakri	S2	72.74	33.32
Gwadar	S3	62.35	25.28
Haripur	S4	73.03	33.97
Peshawar	S5	71.79	33.92
Quaidabad	S6	71.89	32.35
Quetta	S7	66.94	30.27
Sadiqabad	S8	70	28.21
Sanghar	S9	69.04	25.82
Sujawal	S10	68.18	24.52
Tando	S11	68.87	25.12
Umerkot	S12	69.57	25.08

3.1.1 Bahawalpur, Punjab

Bahawalpur is a city in the province of Punjab, having a hot climate. The annual temperature varies between 7°C and 41°C, with June being hottest month and January being the coldest month. The wind data used in this study has been measured at a site inside the Quaid e Azam Solar Park. The elevation of the area is 123m and the terrain is desert like, mostly flat, free from obstructions.

3.1.2 Chakri, Punjab

The site of the wind measurement at Chakri is mostly flat and at an elevation of 360m. Chakri is a city in the Province of Punjab and lies in the district of Rawalpindi. The nearest population is situated at a distance of 2km from the mast. The temperature at Chakri ranges between 4°C and 38°C.

3.1.3 Gwadar, Balochistan

Gwadar lies in the southwest of Balochistan and is a coastal city located on the Arabian Sea with a hot desert climate. The summers in Gwadar are hot and arid, whereas, the winters are comfortable and dry. The temperature varies between 16°C and 36°C, with January being the coldest month having a mean low temperature of 16°C and June being the hottest with an average high temperature of 34°C. The elevation of Gwadar is 13m with rocky terrain. The mast is installed in an educational institute on a flat location with negligible roughness in the surrounding.

3.1.4 Haripur, KPK

Haripur is located in the district Hazara in the province of Khyber Pakhtunkhwa. The site is primarily flat with some fruit trees of 5-7m height in the surrounding at a distance of 150m from the mast. The only constructed building in surrounding is a storage barn, that too at a distance of

150m from the mast location. The summers in Haripur are wet, sweltering, muggy and long, whereas the winters are short and partly cloudy. The hottest day of the year falls in June, and the coldest in January.

3.1.5 Peshawar, KPK

At an elevation of 387m, this site is located inside the boundary of an educational institute with the closest building at a distance of 400m and the hills of Cherat roughly 15km of its South. The terrain of the area is flat with muddy soil type. In summers, the average maximum temperature is 40°C and in winters the average minimum temperature is 4°C.

3.1.6 Quaidabad, Punjab

The Tehsil of Quaidabad is very near to the province of KPK, Quaidabad lies in the north western region of Punjab province. The land elevation is 192m and the surrounding is flat. The temperature goes as high as 50°C in summers and as low as 0°C in winters.

3.1.7 Quetta, Balochistan

Quetta is the capital of Balochistan province and also the largest city of the province. The climate of Quetta is semi-arid. The temperature usually stays between -2°C and 35°C throughout the year. The hottest and the coldest days of the year fall in July and January respectively. The wind mast is located in an educational institute, at an elevation of 1582m, with the closest building at a distance of 250m. The area is mostly flat with some ridges present at a distance of more than 5km.

3.1.8 Sadiqabad, Punjab

Sadiqabad lies in the district of Rahim Yar Khan, Punjab. The wind mast is situated in the Cholistan desert; the area has some sand dunes but is mostly flat. The elevation is 76m. Sadiqabad has usually very high temperatures, being the highest in June with an average of 43°C and the lowest (9°C) in January.

3.1.9 Sanghar, Sindh

The district of Sanghar is located in the center of Sindh province with a dry climate and temperatures mostly stay between 9°C and 44°C. May is the hottest while January is the coldest month. The land elevation of wind mast area is 20m and the terrain is mostly flat. The nearest population is at a distance of 1km.

3.1.10 Sujawal, Sindh

Sujawal town lies in the district Sujawal, Sindh province. The elevation of the area is 17m and the climate is dry with the highest and lowest means at 32.4°C and 18.2°C respectively. The land of the wind mast is flat with the nearest community at a distance of 2km. The closest construction is of a farmhouse that lies roughly 250m away.

3.1.11 Tando Ghulam Ali, Sindh

Located at an elevation of 25m, Tando Ghulam Ali lies in the district of Badin in Sindh province. The land is mostly fertile and is utilized for agriculture. The climate is also moderate with sea breeze blowing for 8 months in a year. May is the hottest month with a mean high temperature of 41°C, and January is the coldest with a means low of 12°C. The area of the wind mast is flat and free from obstructions.

3.1.12 Umerkot, Sindh

Umerkot city lies in the district Umerkot, Sindh Province. The elevation is 17m and the wind mast is located at a flat terrain, free from influence of any nearby obstructions. The temperatures usually stay between 12°C and 41°C.

3.2 Data Description

3.2.1 MERRA-2 Reanalysis Data

MERRA-2 is developed with the Goddard Earth Observing System (GEOS-5.12.4) atmospheric data assimilation system (ADAS) and has a horizontal resolution of 0.5º x 0.625º. It utilizes a number of satellite observations and model generated outputs [109]. MERRA-2 reanalysis data is available from 1980 onwards and significant improvements have been made in MERRA-2 since freezing of MERRA system in 2008. Hourly time averaged data for 50m height above ground level was downloaded from Goddard Earth Sciences Data and Information Services Center (GES DISC) [110] to be used in this study.

3.2.2 Ground data

The data collection by AEDB/WB network got started in the year 2016 and data for 2 years or more had been collected for all sites till the end of year 2018, which is used in this study. Earlier studies have shown that a two year ground monitored wind data can be used for a preliminary assessment of wind energy potential of a particular site [111–113]. The datasets are maintained updated and are available for download online [33]. The wind data was recorded at four different heights, i.e. 20m, 40m, 60m and 80m. Wind data at 10m and 50m was later calculated using the power law (eq.1). Observations recorded at all heights were preliminarily considered and later on, 50m and 80m data was selected for more detailed wind potential assessment. Typically, wind turbine hub height is considered to be 80m [111,114,115]. The temporal resolution of wind data was 10min. Details of data used in the study have been summarized in Table 5.

Table 5 Details of data set used in study

Parameters	**Units**
Date and Time	according to ISO8601 (YYYY-MM-DD hh:mm)
Wind Speed Min, max, mean and standard deviation	m/s
Wind direction Mean and standard deviation	Wind direction in degrees North
Air Pressure Mean and standard deviation	Mean sea level air pressure in hPa
Relative Humidity and standard deviation	%
Ai Temperature and standard deviation	Celcius

3.3 Wind Data Analysis

3.3.1 MERRA-2 Data

MERRA-2 is developed with the Goddard Earth Observing System (GEOS-5.12.4) atmospheric data assimilation system and has a horizontal resolution of 0.5 x 0.625. It utilizes a number of satellite observations as well as model generated outputs [109]. The U and V components for wind data were collected and analyzed utilizing MATLAB 2012 [116]. After the initial data refinement (outliers and missing values removal), the 50m AGL reanalysis data for 12 locations was compared with the ground based data for the same height. A limited number of statistical techniques have been utilized in literature to evaluate the validity of simulated output wind data using ground observations. Pearson's correlation coefficient (R) is the most widely used [117] and was adopted in this study. The variation of the correlation between two data sets among 12 sites was further analyzed considering site specific factors.

3.3.2 Wind Speed vertical profile

Wind speed varies with height and besides having measurements recorded at 20m, 40m, 60m and 80m, wind speed was also calculated for 10m and 50m to get more detailed profile. Though various methods and techniques have been reported for calculation of wind speed variation with height [118][119], wind power law (eq.1) is the one used most commonly. [120] [121]

$$U = U_{ref} (Z/Z_{ref})^{\alpha} \qquad (1)$$

Where U is the wind speed at height Z, U_{ref} is the known wind speed at height Z_{ref}. and α is the power law exponent. Value of α was first calculated for each time step using combinations of known wind speeds i.e. at 20m & 40m, 40m & 60m, 60m & 80m, 20m & 60m, 40m & 80m and 20m & 80m. Wind speed at 50m was calculated using all 6 α values and was then averaged to get a wind speed values representative for 50m height. Wind Speed at 10m was calculated with the α values calculated using wind speeds closer to the ground level, i.e. 20m & 40m. Eq.2 was used for α values calculations [122].

$$\alpha = \frac{log\frac{Uref}{U}}{\log\frac{Zref}{Z}} \qquad (2)$$

3.3.3 Diurnal and Monthly Wind Variation

Diurnal and monthly mean wind analysis was carried out for all sites at 50m & 80m heights. Individual diurnal patterns for each month of the year were developed and analyzed. To calculate the average wind speeds (V_{avg}) and variance eq.3 and eq.4, respectively were utilized.

$V_{avg} = \frac{1}{n}\sum_{i=1}^{n} Vi$ (3)

$\text{Variance} = \frac{1}{n-1}\sum_{i=1}^{n}(Vi - Vavg)$ (4)

3.3.4 Wind Speed Frequency

Wind speed bins were created to estimate the frequencies of occurrences of different wind speeds throughout the year. This is an important characteristic while studying wind speed for wind energy estimation as it gives the duration of required wind speed availability.

3.3.5 Weibull Distribution Function

Probability distribution functions are found to be a reliable way of wind speed probability distribution description [123–125]. Weibull is one the most widely used distribution function for statistical analysis of wind energy potential due to simplicity, flexibility and accuracy [78][126] which is reflected by The International Standard (IEC 614-00-12) declaring it as a suitable method [126][127]. It has been thoroughly discussed in literature and also compared with other available techniques [128].

Weibull is a 2-parameter distribution which is expressed as f(v), the probability density function (eq.5) and F(v) the cumulative distribution function (eq.6).

$f(v) = (k/c)(v/c)^{k-1} \exp[-(v/c)^{k}]$ (5)

$F(v) = 1- \exp[-(v/c)^{k}]$ (6)

Where k (dimensionless) is the Weibull shape parameter which describes the width and shape of the distribution and c (m/s) is the Weibull scale parameter. k represents how the distribution peaks, whereas, c, the scale parameter reflects how windy the site is.

The wind power density can also be calculated using the Weibull parameters (eq.7), which is an important indicator in wind energy potential estimation [111] [129] [130].

$$P/A = \frac{1}{2}\rho c^3 \Gamma(1 + \frac{3}{K}) \qquad (7)$$

Here, P/A is power (Watts) per unit area (m^2) and ρ is the density (kg/m^3). To develop the Weibull distribution 1m/s bins of wind speed data were created for all sites, starting from 0-1m/s bin till all the wind events occurring significantly, got covered. The percent of events for the actual wind data were plotted on a histogram and then the Weibull distribution was plotted against it.

3.3.6 Weibull Parameter Estimation

A number of methods exist for the calculation of Weibull parameters, least-squares-fit, maximum likelihood, moment, standard deviation and curve fitting being few of many. Results from all mentioned methods are widely accepted and are found to be comparable in the literature [131]. More than one studies comparing six methods; empirical, graphic, power density, moment, maximum likelihood and modified maximum likelihood concluded the same [128] [131]. However, moment method was selected in this study as it has been reported to be the better considering Root Mean Square Errors (RMSE) at data on six different locations, in a very recent study [129].

According to the moment method, K and c can be calculated using eq.8 and eq.9, respectively [132];

$$k = (\sigma / V_{avg})^{-1.086} \qquad (1 \leq K \leq 10) \qquad (8)$$

$$c = V_{avg} / \Gamma(1+1/k) \qquad (9)$$

Where V_{avg} and σ are the mean wind speed and standard deviation, calculated by eq.3 and eq.10 respectively;

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(Vi - Vavg)^2\right]^{\frac{1}{2}} \tag{10}$$

The eq.11 explains the Gamma function Γ(x) used in eq.7 and eq.9.

$$\Gamma(x) = \int_0^\infty t^{x-1}\ \exp(-t)\,dt \tag{11}$$

3.3.7 Wind Speed Carrying Maximum Energy

This is an important parameter to help in selection of suitable wind turbines. Calculated using the Weibull shape and scale parameters, wind speed carrying maximum energy (eq.12) is evaluated considering its occurrence frequencies [133][54].

$$V_{max\ E} = c\ (1+2/k)^{1/k} \tag{12}$$

3.3.8 Most Probable Wind Speed

As the name depicts, this parameter indicates the most frequently observed wind speed value for a given probability distribution for a site. It is calculated utilizing the Weibull parameters (eq. 13). [32-33]

$$V_{mp} = c(1-1/k)^{1/k} \tag{13}$$

3.3.9 Air Density

Air temperature and pressure measured by the respective sensors installed at the masts, were used to calculate the air density at each 10min interval using the gas constant, R (287.05J/kg K) by eq.14.

$$P = \rho/\ RT \tag{14}$$

Where, P is the air pressure (Pa), ρ is the unknown air density (kg/m^3) and T is the temperature (k).

3.3.10 Wind Power Density

Wind power density (WPD) was estimated by eq.15;

$$WPD = \frac{1}{2} \rho V^3 \qquad (15)$$

Monthly Wind Power Densities were calculated by averaging the 10-min interval results for respective months. Wind power density is calculated in the units of W/m^2, where m^2 represents the swept area of turbine blades [134][94].

3.3.11 Wind Energy Density

Wind energy density was calculated utilizing the wind power density values for each site, by using eq.16;

$$E = P * t \qquad (16)$$

Where E is energy (kWh) and t is the number of hours of turbine operation. Wind energy density values are calculated in kWh/m^2/yr [135].

3.3.12 Capacity Factor

Capacity factor is the estimation of maximum possible energy that a certain turbine can generate at a given location in reference to the maximum energy that the turbine can produce theoretically if operated at 100% of its capacity. This essentially represents the suitability of a turbine to the wind profile of selected site. It can be calculated by eq. 17 [120][136].

$$CF = E_{actual} / E_{max} \qquad (17)$$

Where E_{actual} is the energy produced by a turbine at given location and E_{max} is the maximum energy, the turbine can produce at some hypothetical place with availability of most appropriate wind speeds for 100% of the time. In this study, the site specific annual wind bins were used against the power available for each wind bin, taken from the power curve of the selected turbine. This resulted in the annual actual energy output by using eq.16. The maximum energy output was calculated using the turbine rated power output value.

3.3.13 Wind Direction

Since, the wind speed characteristics were studied to evaluate the potential for wind energy extraction; wind direction data was also assessed. Wind roses were developed for all locations with the wind data at all directions and frequency of wind speed at both 50m and 80m AGL.

3.3.14 Wind Farm Feasibility

RETScreen considers the energy resource at the selected site, equipment type and specification, expected initial and recurring costs and savings, financial requirements including taxes, insurance and incentives, tariffs and subsidies, environmental impact in terms of emissions saved and ultimately helps to decide if the project will render cost effective in the given scenario. The financial analysis model incorporates asset depreciation, debt, pre-tax and after tax cash flows, payback, net present value and other feasibility indicators. The sensitivity and risk model utilizes Monte Carlo simulation, impact graph, confidence interval, and model validation [137].

Under the economic assessment, the initial costs and the operations and maintenance costs were assumed after studying various recent wind power projects installations in Pakistan. The costs assumed by NEPRA while development of policies and tariffs are USD 2.15 million/MW and

USD 2.26 million/MW for projects based on 100% foreign and local financing, respectively. This has been kept into consideration while assuming the costs for the cases discussed in this study.

The total capital cost is calculated by RETScreen through the eq. 18;

$$\text{Total Initial Costs} = FS + PD + E + PS + BM \tag{18}$$

Where,

FS = Cost related to feasibility studies
PD = Cost related to project development
E = Cost related to engineering
PS = Cost related to the power system
BM = Cost related to the balance of system and miscellaneous

To understand the capital cost better, the broad categories which make up the initial costs are discussed below; [138]

The first and the major one is the cost of the turbine including its production, equipment like blades, transformer, transportation and installation at the site. These costs take up to around 71% of the total capital cost. The second largest constituent are the costs of grid connection which are usually around 12% of the total capital cost. The cost of cables, connection, substations and power evacuation systems are included in this head.

The third and fourth constituent of the total costs are civil and miscellaneous costs taking up around 9% and 8% of the total costs, respectively. The miscellaneous costs include cost of licensing, consultancy, engineering and costs related to permits.

Eq. 19-22 are the built-in mathematical expressions used to undertake the economic evaluation by the tool [4].

$$\text{NPV} = \sum_{t=1}^{T} \frac{Ci}{(1+d)^t} - Ct \qquad (19)$$

Where,

NPV = Net Present Value (USD)

T = time (s)

Ci = Net cash inflow (USD)

d = Discount rate (%)

t = Number of time periods (%)

Ct = Total net cash flow (USD)

$$\text{IRR} = \text{NPV} \rightarrow 0 \qquad (20)$$

Where,

IRR = Internal rate of return (%)

$$\text{PB} = 1/\text{Cp} \qquad (21)$$

Where,

PB = Payback period (years)

Cp = Net periodic cash flow (USD)

$$\text{GHG reduction} = (\text{GHGb} - \text{GHGp}) \times \text{E} \qquad (22)$$

Where,

GHGb = Base case GHG emission factor

GHGp = Proposed case GHG emission factor
E = End energy delivered annually (KWh/y)

These financial indicators are vital in deciding the viability of a project. An NPV of zero or above is one indicator for that. IRR also plays a vital role; the required rate of return which is decided based upon the capital cost of a project is set, the calculated project IRR by the tool equal or higher to the set required rate of return renders that a project is profitable. Negative NPV's and IRR's result in cancellation of the proposed project. All the financial indicators produced by RETScreen are of individual importance and collectively support the decision making process.

The net wind energy produced by the turbines is depicted by ET which denoted the total renewable energy collected (eq. 23).

$$ET = EG * CL \quad (23)$$

Where, EG is the gross energy production and CL is the losses coefficient. CL is calculated though the eq. 24;

$$C\text{L}=(1-\lambda\text{a})\times(1-\lambda si)\times(1-\lambda d)\times(1-\lambda\text{m}) \quad (24)$$

Where,
λa = Array losses
λsi = Airfoil soiling and icing losses
λd = Downtime losses
λm = Miscellaneous losses

To estimate the reduction of green gas emissions through the wind farm development is also an important component of the tool. The 2018 energy mix values for Pakistan were used to develop a baseline for the study [139]. Table 6 summarizes the energy mix by source for Pakistan as of year-end, 2018.

Table 6 Energy mix of Pakistan

Source	**Percent Share (%)**
Oil	31.2
Gas	34.6
LNG Import	8.7
LPG	1.2
Coal	12.7
Hydro Electricity	7.7
Nuclear Electricity	2.7
Renewable Electricity	1.1
Imported Electricity	0.1

The global warming potential for carbon dioxide, methane and nitrous oxide were used as expressed in the IPCC fifth assessment report (AR5) [140]. The GHG reduction credit rate of 25.65 USD/tCO2 was assumed [141–144].

3.3.15 Scenarios

The cost-competitiveness of renewable technologies has tremendously increased around the world. From 2010 till 2017 the electricity costs for onshore wind power decreased by roughly a quarter, becoming one of the most cost-competitive electricity source in the market. By increasing economy of scale, technological advancements and new policies, the prices for wind and solar power have come down [30]. The same trend has been observed in Pakistan, and the tariffs for wind energy have significantly declined. Initially, NEPRA offered an up-front tariff facility for investors in the sector, the up-front tariff in 2011 was USD 0.1466/KWh and 0.20/KWh for foreign and locally funded projects, respectively. In 2017, NEPRA instead announced a benchmark tariff and discontinued the earlier scheme of up-front tariffs for wind power. Subsequently, AEDB and provincial level departments were assigned the responsibility to conduct competitive bidding for wind power projects. The benchmark tariff, taken as a ceiling price while conducting reverse auction was set at USD 0.0675/KWh for foreign and USD 0.0773/KWh for local funded projects [145]. This study would investigate the impact of the new tariffs on the wind energy market in Pakistan, by the development of eight similar scenarios and incorporating the policy changes to quantify the effect of project economics and financial viability. All the tariffs announced by the government from 2011 till present are utilized to develop alternate scenarios and their impact on project feasibility is evaluated. Some of the incentives which are offered by the government of Pakistan for wind power sector have been outlined below [65][146]:

- Guaranteed purchase of electricity
- Power purchaser deemed responsible for provision of grid connection
- Reimbursement for damages in case of an unforeseen political events not covered well by insurance.
- Exemption from custom duties or sale tax for equipment, spares, special vehicles and machinery, including those imported temporarily.
- No income tax, turnover rate tax and withholding tax on imports.
- Under specific rules by the State Bank of Pakistan, permission to repatriate equity along with the dividends
- Subsidized loans offered by State Bank of Pakistan (SBP), under a scheme launched in 2009 and revised in 2016. Private banks were also allocated funds to finance renewable energy projects (4-50 MW capacity).
- Amendment in grid codes by NEPRA to support interconnection for wind and solar power projects.

- Support by provincial governments for land acquisition, development of energy parks and assistance in approvals and negotiations with federal departments.

For our scenarios, a capacity of 50MW was chosen as it is the most common size of wind power projects being planned and developed, in Pakistan. Level 3 analysis (level 2 for financial) in RETScreen Expert, which is the one having the highest detail, had been used for all inputs and calculations in the tool. More details about the assumptions and scenarios are given in Table 7.

Table 7 Assumed case, inputs to the tool and selling cost for foreign financed (FF) and locally financed (LF) projects

	Scenario 1A & 1B	**Scenario 2A & 2B**	**Scenario 3A & 3B**	**Scenario 4A & 4B**
Capacity	50MW	50MW	50MW	50MW
Turbine	Vestas V110-2.0	Vestas V110-2.0	Vestas V110-2.0	Vestas V110-2.0
Project Life	20 years	20 years	20 years	20 years
Array Losses	4%	4%	4%	4%
Airfoil Losses	2%	2%	2%	2%
Miscellaneous Losses	6%	6%	6%	6%
Availability Factor	98%	98%	98%	98%
Electricity Export Cost	6.75 US Cents (FF) 7.73 US Cents (LF)	10.45 US Cents (FF) 12.52 US Cents (LF)	13.52 US Cents (FF) 16.69 US Cents (LF)	14.66 US Cents (FF) 20.10 US Cents (LF)

Scenario 2, 3 and 4 are based on tariff schemes announced in 2015, 2013 and 2011 respectively. Whereas, scenario 1 utilizes the latest policy and tariff.

For each location, the coordinates of the facility were manually entered in the tool. The monthly measured wind speed at 80m above ground level (AGL) was entered to reduce any errors of calculation through power law. Monthly measured air temperature and atmospheric pressure were also entered; these were calculated through taking averages of the 10-min interval measured data.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Wind Characteristic Study

4.1.1 Validation of Reanalysis Data

The correlation among the hourly ground and reanalysis data was studied and correlation coefficient along with site elevation and annual average wind speed for each site is given in Table 8. Generally, a low correlation was observed for the study area as compared to that reported in earlier studies [26,147,148]. This may be due to the lack of radiosonde stations and other reliable data sources in each locality in particular, and in the region in general, available for data assimilation. Hence, applicability of MERRA-2 data for wind energy estimation in similar regions may be further investigated.

Table 8 Correlation values found between MERRA-2 and ground specific wind speed data, average wind speed (m/s) and elevation (m) for all locations.

Sites	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Correlation Ground & MERRA-2	0.42	0.29	0.47	0.19	0.18	0.25	0.46	0.37	0.69	0.73	0.75	0.75
Wind Speed Average (m/s)	4.59	2.94	4.45	3.62	2.98	3.82	3.85	4.40	5.94	6.63	6.23	5.78
Elevation (m)	123	360	13	673	387	192	1582	76	20	17	25	17

Interestingly, the correlation varied significantly among the selected sites, ranging from an R value of 0.17 to 0.75. The potential role of site characteristic including topography and wind characteristics in determining the correlation between two data sets was investigated. A high proportionality among the wind speed and correlation coefficient was found i.e. for the locations having higher annual average wind speeds, the MERRA-2 data was found to be comparatively better correlated with ground observations. A correlation coefficient of 0.94 was found between the annual average wind speeds of 12 sites and their respective R values between two data sets. Hence it may be inferred that the MERRA-2 data sets match with ground observations more in the areas with high wind speed. Further, it was also observed that the R values between the two datasets were high for the sites with lower elevation which may be attributed to the smoothed topography feature used in MERRA-2 (due to coarse resolution of numerical weather prediction model), leading to underestimated wind speed for peaks [149]. Besides elevation, the site surface roughness also seemed important as in case of S3, having low elevation but rocky area, lower correlation was found between MERRA-2 and ground observation. Previous studies have also reported the influence of terrain complexity on the reanalysis data quality [20]. Appropriate bias removal strategy needs to be applied for correction of reanalysis data before it can be used effectively.

4.1.2 Wind Characteristics Analysis and Potential Estimation

Wind data at two heights (50m and 80m AGL) have been discussed in this section, except where mentioned otherwise. Variation in monthly average wind speeds for 12 sites observed at 80m height is presented in Fig. 3.

From this point onwards, for the ease of readers' understanding, the sites will be referred by their annotations as given in Table 4.

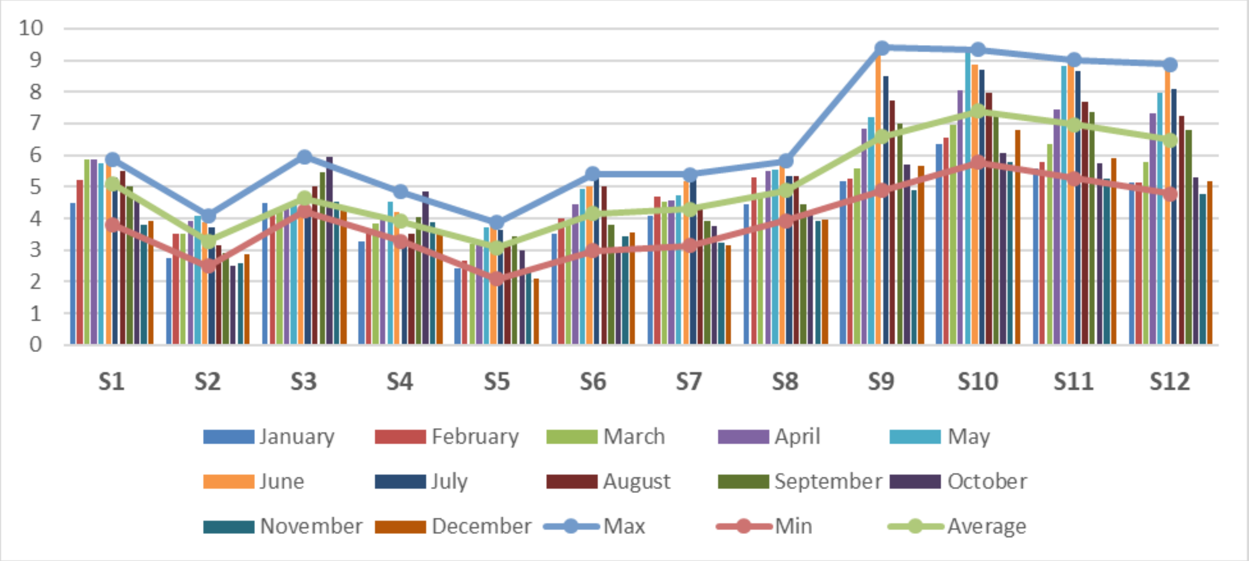


Fig. 3: Monthly average wind speeds observed at 80m AGL for all sites

The summer months, mostly, were found to have highest mean wind speeds, which is synchronizing with the peak energy demands in Pakistan (also occurring in summer) and hint the potential reduction in use of fossil fuels to meet those demands. Highest mean winds for S8 (5.8m/s), S5 (3.9m/s), S9 (9.4m/s), S11 (9.0m/s) and S12 (8.9m/s) were observed in June. S2 (4.1m/s) and S10 (9.3m/s) had the highest mean wind speeds in May, S6 (5.4m/s) and S7 (5.4m/s) in July S3 (5.9m/s), S4 (4.4m/s) in October and S1(5.9m/s) had highest wind speeds in April. Higher wind speeds in summer months were also reported previously for other similar sites [150].

Wind speeds in winter months were observed to be the lowest for almost all locations. S1(3.8 m/s), S8 (3.9m/s), S9 (4.9m/s), S10 (5.8m/s), S11 (5.3m/s) and S12 (4.8m/s) had lowest mean winds in November, S5 (2.1m/s) and S7 (3.1m/s) in December, S4 (3.0m/s) in January, S3 (4.2m/s) in February and S2 (2.5m/s) and S6 (3.0m/s) had the lowest mean wind speed in October.

A similar trend in monthly average wind speed variation was found at 50m height wind data and is presented in Fig. 4.

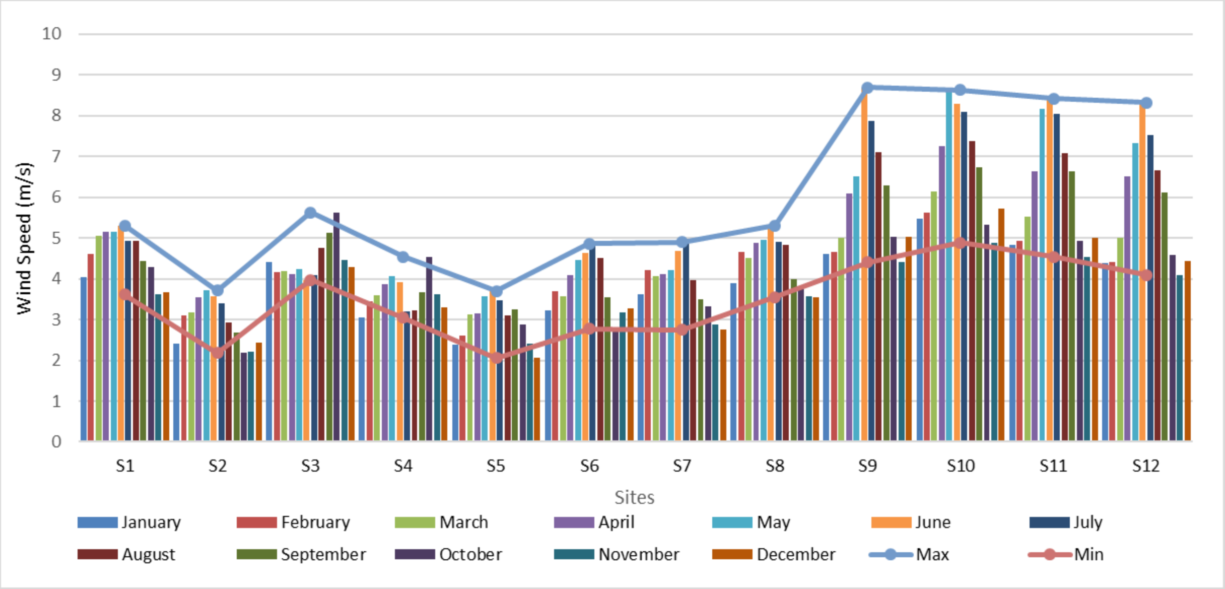


Fig. 4: Monthly average wind speeds observed at 50m AGL for all sites

Similar to the monthly variation, diurnal variation in wind speed at 50m and 80m height was also investigated for all sites and results are shown in Fig. 5 and Fig. 6 respectively. The diurnal variation in wind speed was identical for both heights. Almost all sites displayed stronger winds from late afternoon till midnight and lower winds during the earlier part of day. The diurnal variation indicates the sustainability of wind for power generation due to stable winds for long hours.

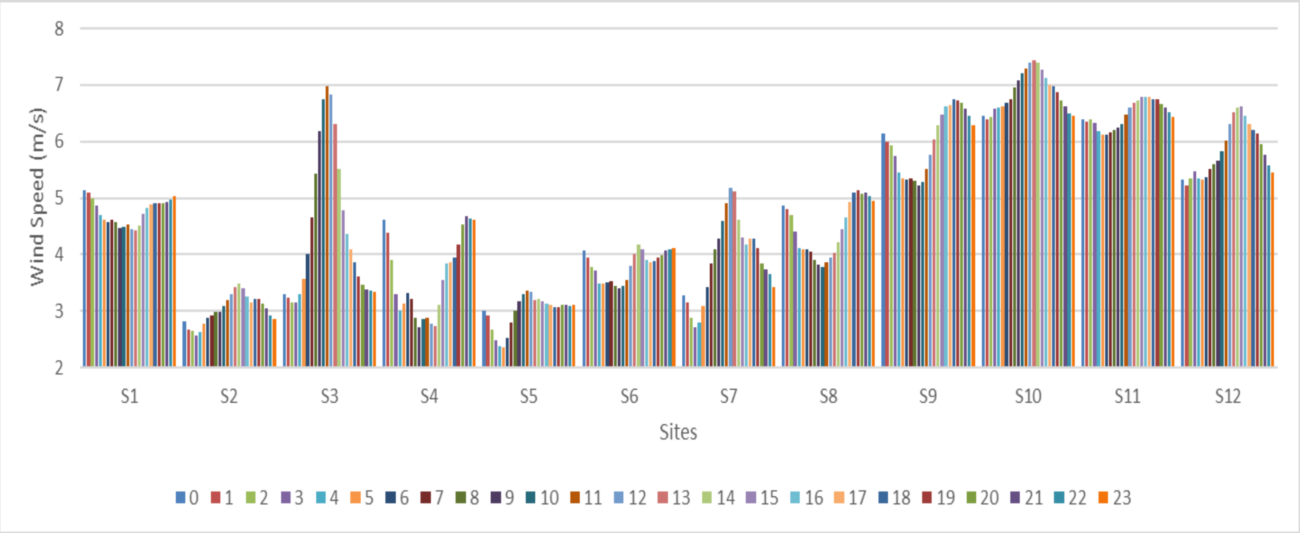


Fig. 5: Mean Diurnal Wind Speed variation at 50m AGL

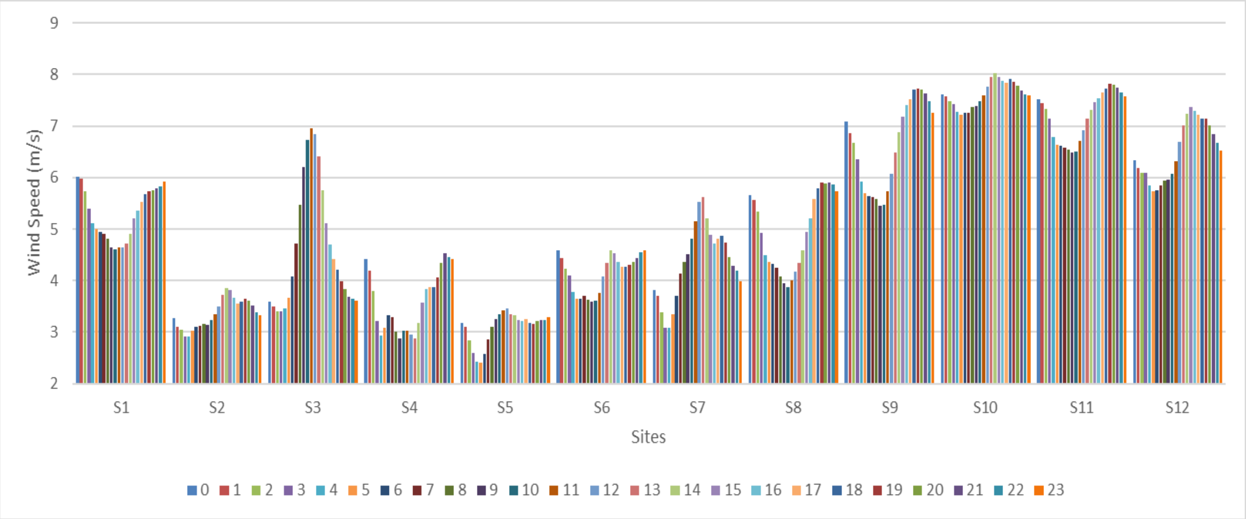


Fig. 6: Mean Diurnal Wind Speed variation at 80m AGL

Wind speed variance with height was observed to be noticeable for most of the locations. The mean wind speed recorded at, 20m, 40m, 60m and 80m as well as calculated for 50m and 10m for all 12 locations have been summarized in Fig. 7. As mentioned earlier, for each site, values of α were calculated using combinations of known wind speeds at different heights (eq.2), Fig. 8 shows the α values calculated for each site. It was interesting to find that for some sites, the spread among α values was more significant than others. Similarly, in order to calculate wind speeds at 10m and 50m heights, all α values obtained at a site were averaged to calculate one representative value of α. Fig. 9 shows the variation of α values among the sites. The difference of α values among different sites as well as with height, is attributed to the varying degree of surface roughness among the sites.

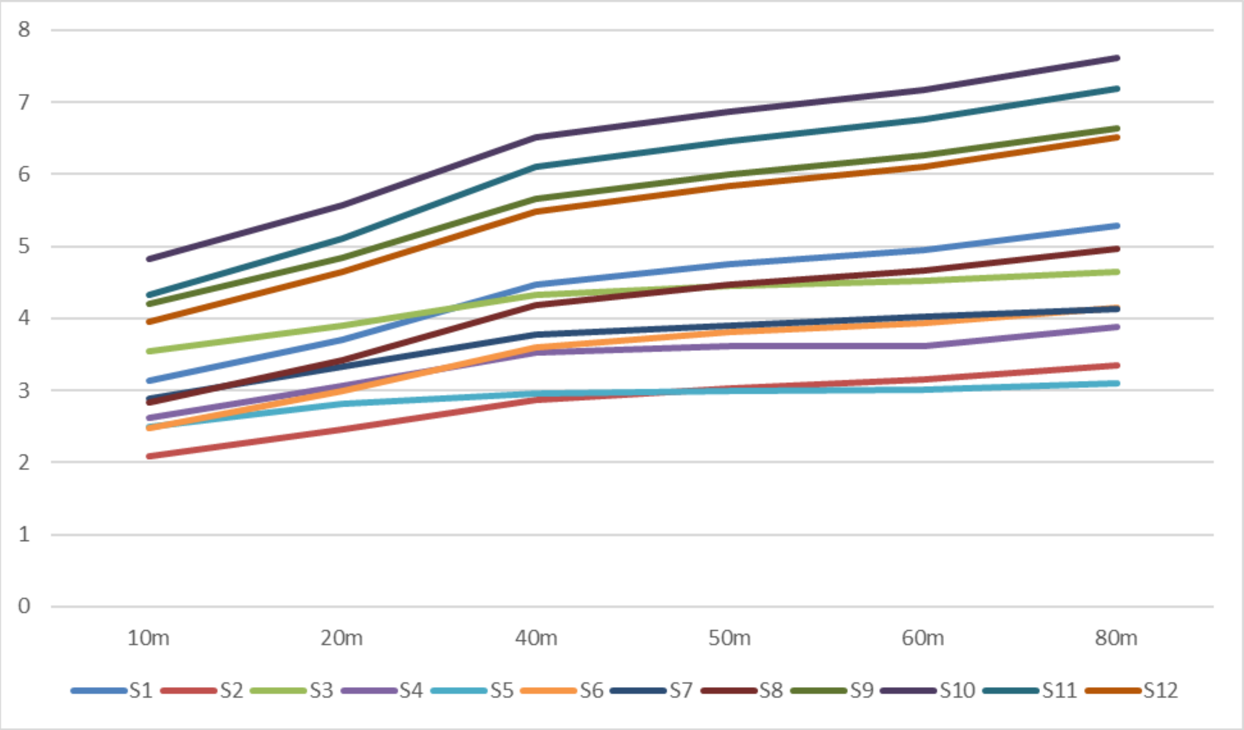


Fig. 7 Variation of mean wind speed with height on all sites

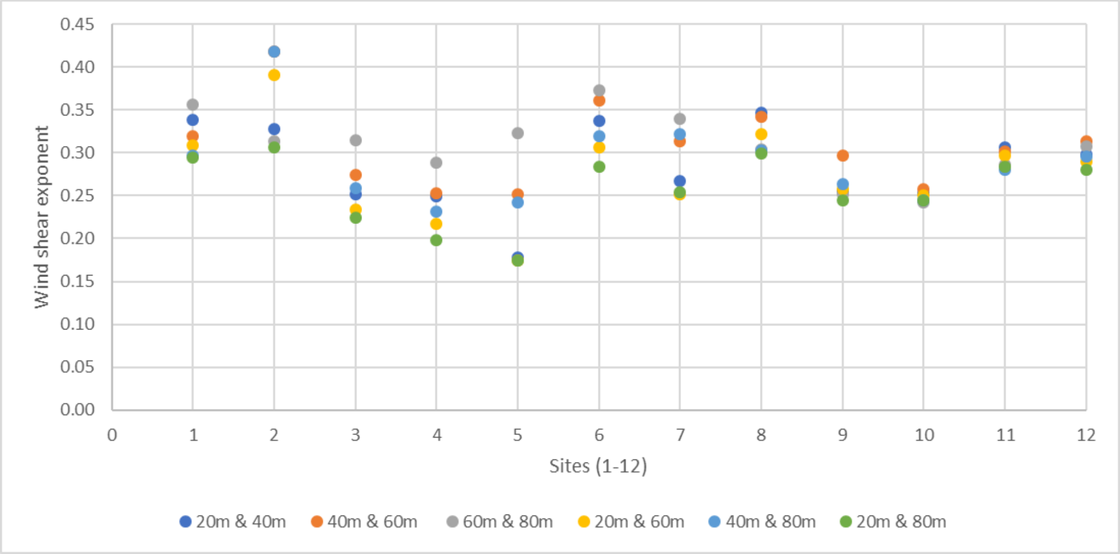


Fig. 8 Wind Shear Exponent values calculated through different height combinations for all 12 Sites

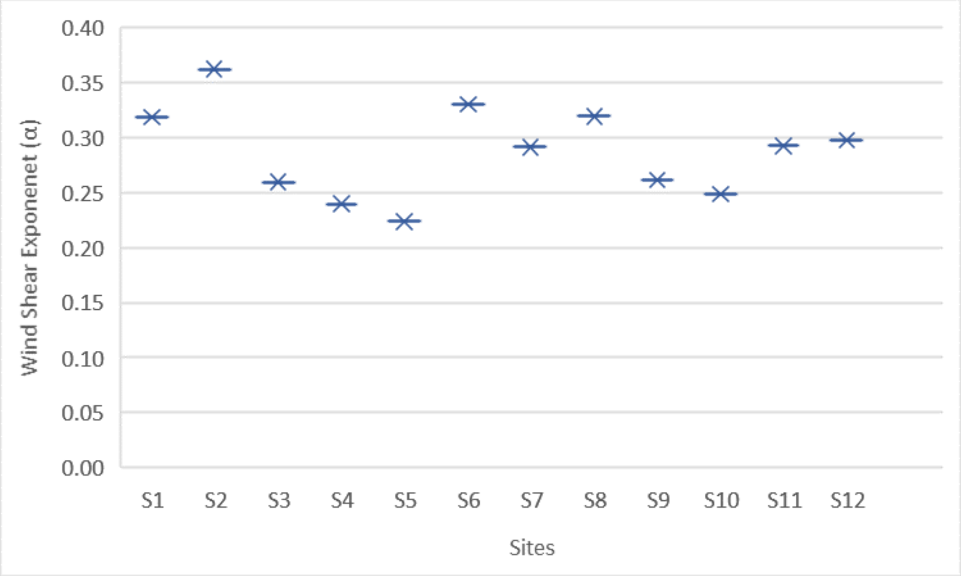


Fig. 9 Average Shear Exponent values calculated for all 12 Sites

Wind directions are supposed to be invariant with height (closer to earth) but naturally [111], different trends with respect to wind speed distribution with direction were seen for all locations. To ensure better representation, wind direction measurements were taken at 78.5m AGL, close to the 80m AGL wind speed sensor; and at for 62m AGL for S7. Wind roses for wind observations at 80m are given in Fig. 10.

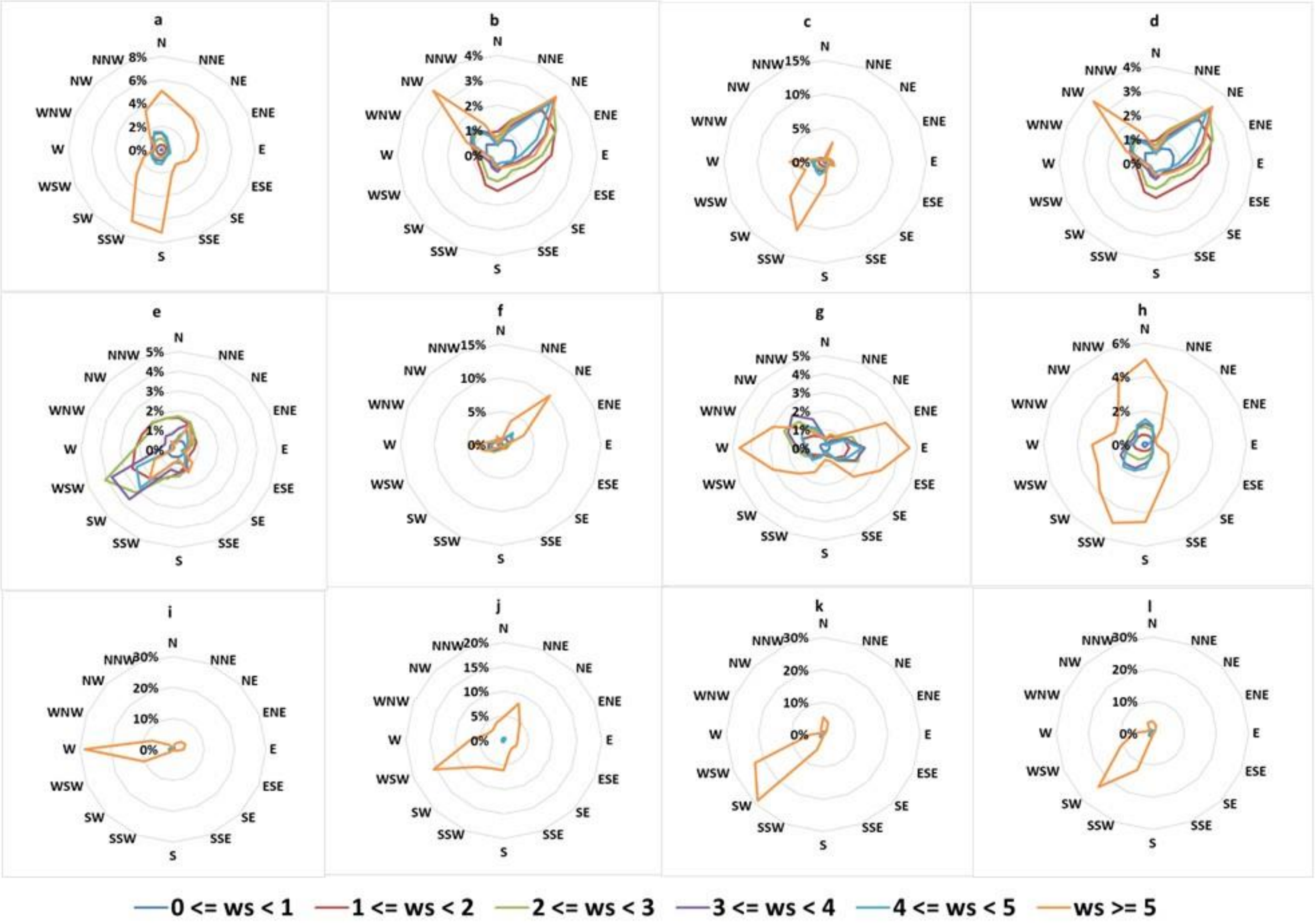
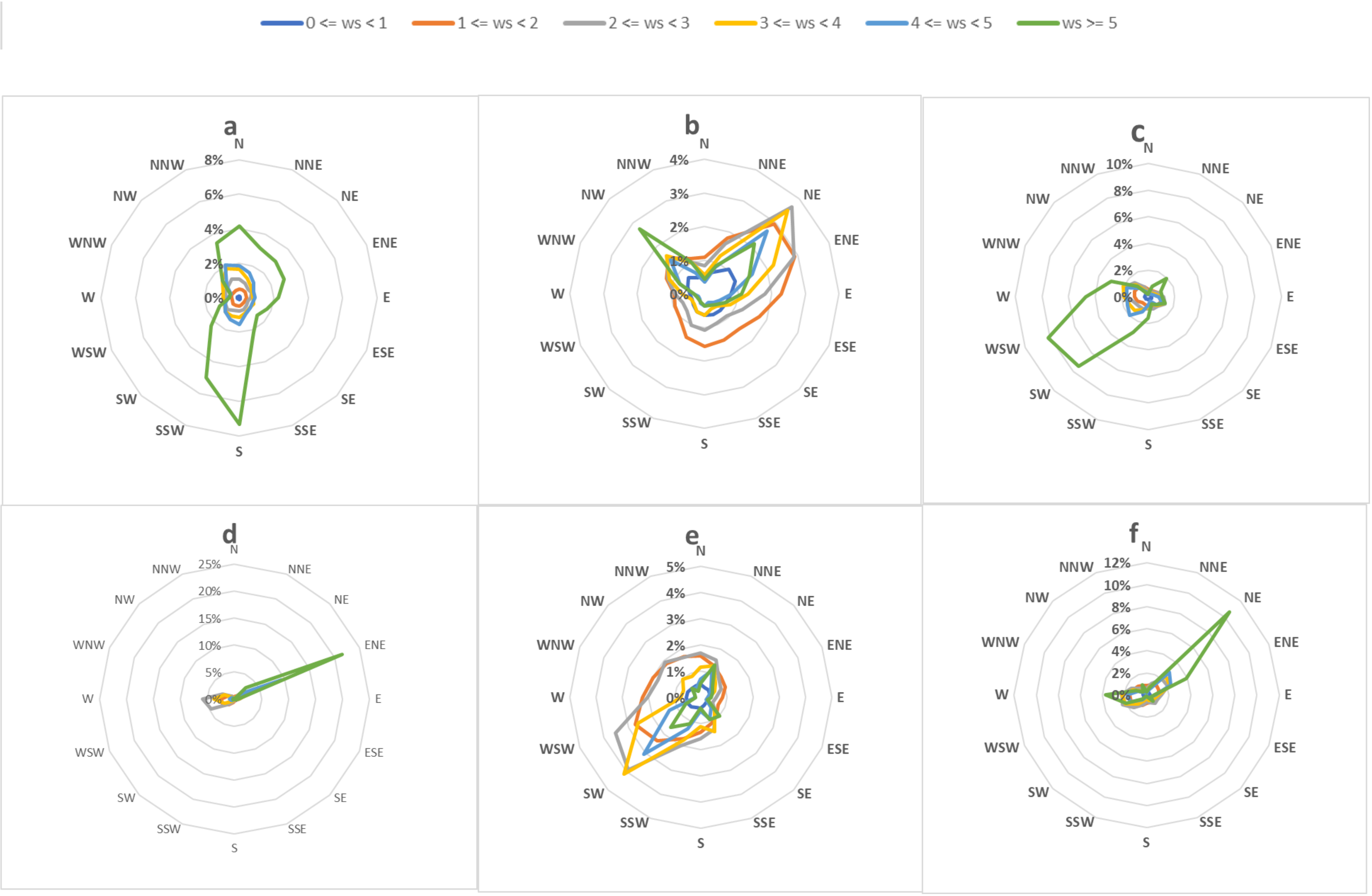


Fig. 10: Wind rose for all sites at 80m AGL; a) S1, b) S2, c) S3, d) S4, e) S5, f) S6, g) S7, h) S8, i) S9, j) S10, k) S11, l) S12


0 <= ws < 1
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2 <= ws < 3
3 <= ws < 4
4 <= ws < 5
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a
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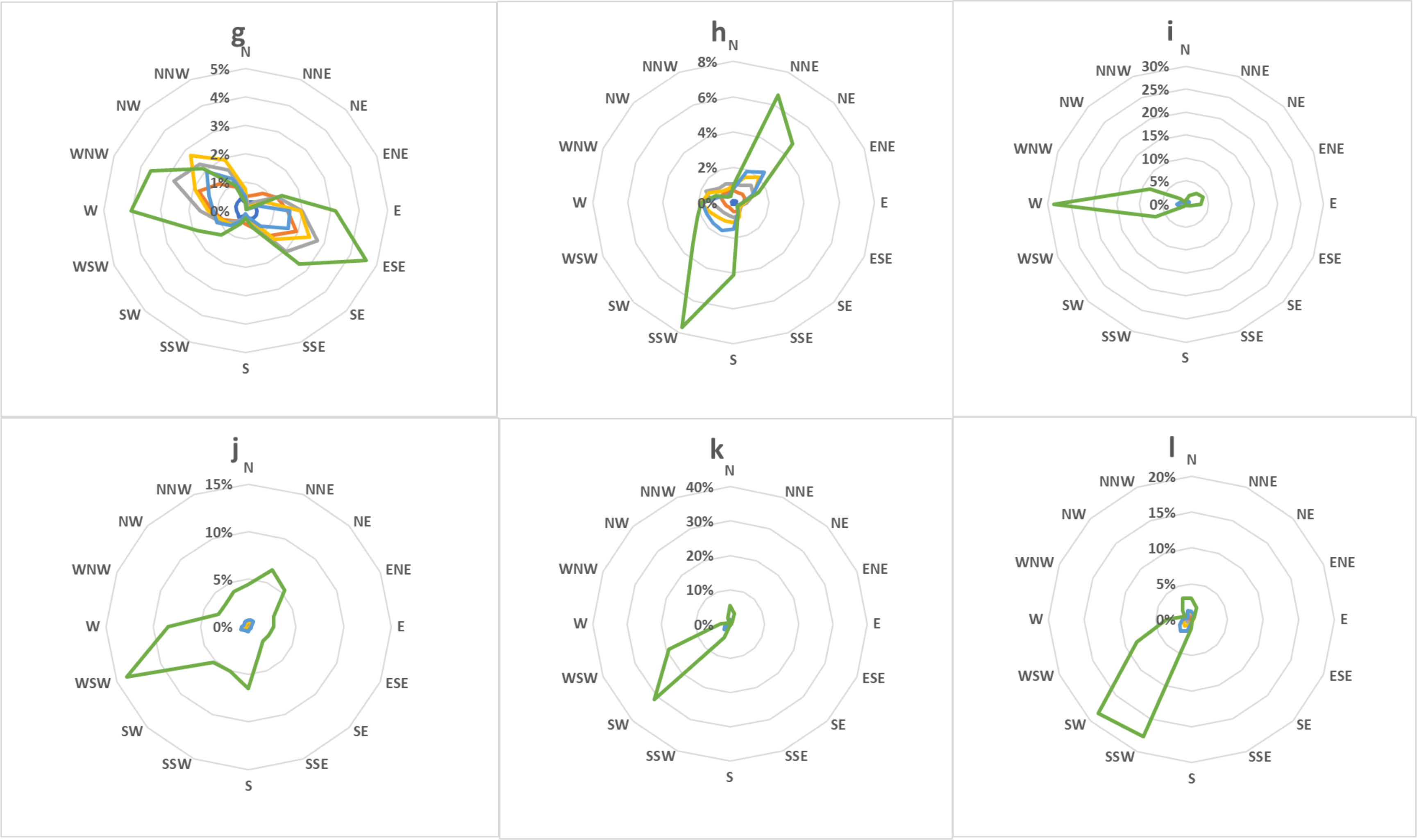

Fig 11: Wind rose for all sites at 50m AGL; a) S1, b) S2, c) S3, d) S4, e) S5, f) S6, g) S7, h) S8, i) S9, j) S10, k) S11, l) S12

Previously, The World Bank, utilizing the micro-siting study data undertaken at Denmark Technical University (DTU), generated wind roses for the 12 sites considered in this study, using Weather Resource and Forecasting (WRF) Tool. [151]. The results of the two studies are found to be in noticeable agreement. Similar trends were obtained in wind roses generated by wind speed data at 50m and direction data recorded by sensors installed at 58.5m as shown in Fig. 11. The information on wind direction is helpful for the orientation and disposition of wind farms [70][152]. As turbines are designed and installed to follow the wind direction [79]. It should be noted that the variance of annual energy production due to the fluctuation in wind direction has not been considered in this study.

Weibull parameters, k and c for all sites have been summarized in Table 9. It can be seen in the Fig. 12 that the wind data is visually satisfactorily categorized by the Weibull distribution. The values of k for the sites range between 1.6 and 3.05, whereas those of c also show significant variance among the sites ranging from 3.5m/s to 8.5m/s. Higher values of c correspond to higher mean wind speeds. The wind power density of a site also depends on the value of c, hence making higher values more favorable. On the other hand, higher values of shape parameter indicate higher variance in the wind speed thus resulting in a higher spread of the distribution, this may result in a better coverage of the turbine’s power curve.

Table 9 Weibull Parameters (k and c) for all sites

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
K *(dimensionless)*	2.26	1.60	1.94	1.9	1.79	1.68	1.86	2.13	2.23	3.05	2.66	2.48
c (m/s)	5.96	3.74	5.24	4.4	3.48	4.64	4.90	5.58	7.49	8.52	8.10	7.34

Fig 12: Weibull distribution compared with actual wind data; a) S1, b) S2, c) S3, d) S4, e) S5, f) S6, g) S7, h) S8, i) S9, j) S10, k) S11, l) S12

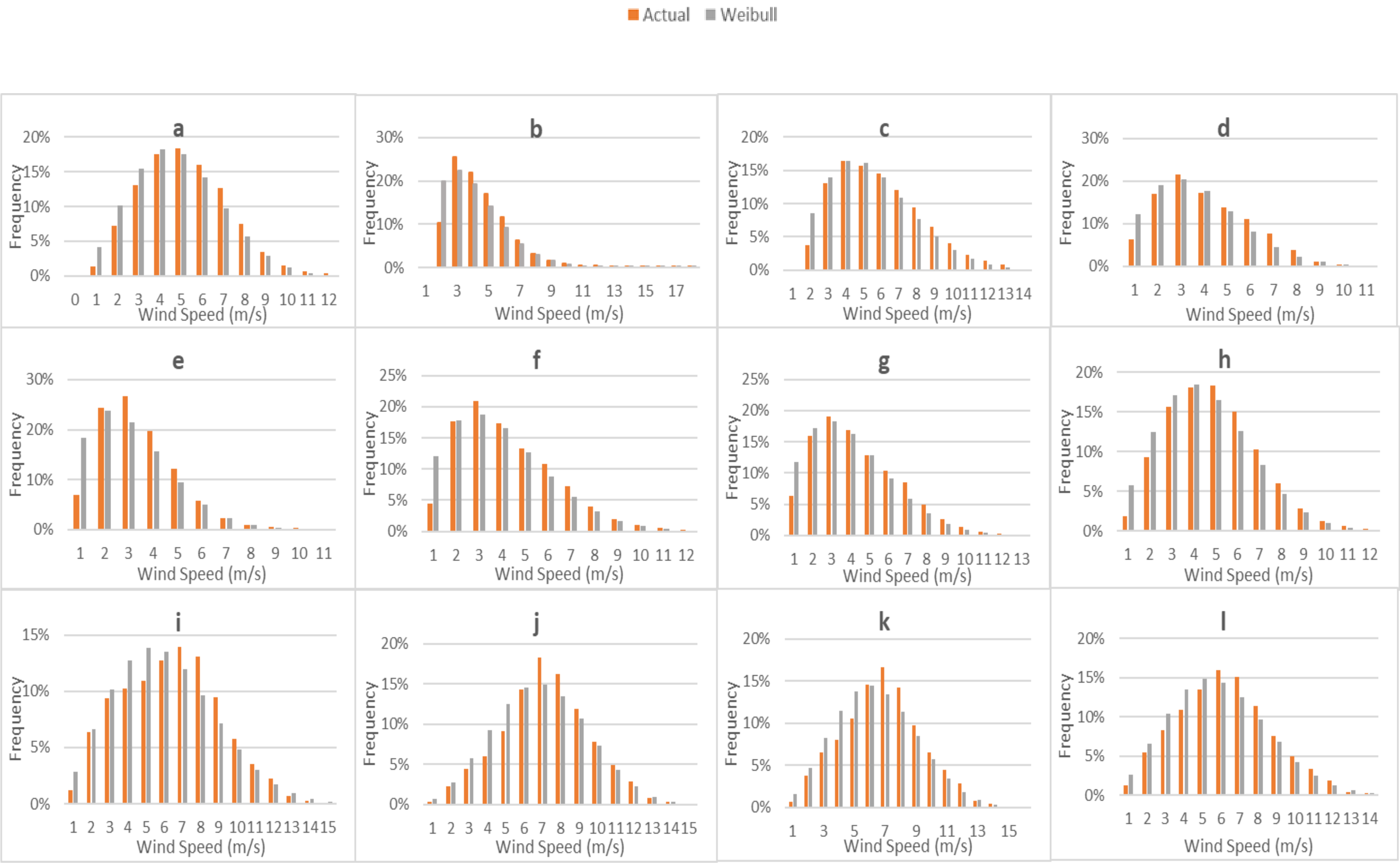

Fig 13: Weibull distribution compared with and actual wind data; a) S1, b) S2, c) S3, d) S4, e) S5, f) S6, g) S7, h) S8, i) S9, j) S10, k) S11, l) S12

S9, S10, S11, S12 and S1 were found to have high values of c with 7.5m/s, 8.5m/s, 8.1m/s, 7.3m/s and 6m/s respectively; whereas, the lowest out of all sites was for S5 (3.8 m/s).

Weibull distribution fitting for wind at 50m AGL was also carried out and can be seen in Fig. 13 whereas the c (m/s) and k values have been tabulated in Table 10. The values for c were again found highest for S10, followed by S11, S9 and S12 successively.

Table 10 Weibull Parameters (k and c) for all sites at 50m AGL

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
K	2.41	1.59	1.89	1.92	1.79	1.81	1.80	2.25	2.29	2.95	2.57	2.40
c (m/s)	5.36	3.37	5.01	4.07	3.36	4.28	4.39	5.04	6.77	7.70	7.16	6.58

The most probable wind speed V_{mp} and wind carrying maximum energy $V_{max\ E}$ were calculated for all sites (as per eq. 13 and 12 respectively) and have been summarized in Table 11 and Table 12 for 80m AGL and 50m AGL, respectively. The closer the two values (V_{mp} and $V_{max\ E}$) are, the higher potential power production is indicated [133]. Least difference in the values were found at S10 for both the studied heights.

Table 11 Most Probable Wind Speed (m/s) and Wind Speed carrying Maximum Energy (m/s) for 80m

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Vmp (m/s)	4.6	2.0	3.6	3.0	2.2	2.7	3.2	4.1	5.7	7.5	6.8	6.0
V.max.E (m/s)	7.9	6.2	7.5	6.3	5.3	7.4	7.2	7.6	10.0	10.1	10.0	9.3

Table 12 Most Probable Wind Speed (m/s) and Wind Speed carrying Maximum Energy (m/s) for 50m

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Vmp	4.3	1.8	3.4	2.8	2.1	2.7	2.8	3.9	5.3	6.7	5.9	5.3
V.max.E	6.9	5.6	7.3	5.9	5.1	6.5	6.7	6.7	8.9	9.2	9.0	8.5

Followed by c and k values, WPD for each site was also calculated; i) through the Weibull distribution method (WPD 1) (eq.7) and ii) using the general method (WPD 2) utilizing air density (eq.15) for all sites and the results are given in Table 13 for data at 80m height and Table 14 for 50m height. The WPDs calculated from both methods were compared with each other and variance was observed between the methods among different sites. For some sites, the methods produced similar results, whereas for others, the differences were considerable. Similar trends were observed at 50m AGL as well.

Table 13 Wind power densities (W/m^2) calculated by two methods and variance for 80m data

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
WPD 1	128.4	53.1	115.5	64.6	36.5	95.5	84.9	126.4	294.1	359.3	318.1	256.7
WPD 2	128.2	55.1	113.8	65.3	39.7	99.1	85.6	126.7	288.2	355.6	312.9	252.8
Variance	0.01	1.02	0.68	0.13	2.69	3.38	0.13	0.02	8.74	3.51	6.57	3.64

Table 14 Wind power densities (W/m2) calculated by two methods and variance for 50m data

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
WPD 1	88.7	38.9	104.0	49.3	32.8	67.7	63.8	88.4	212.9	268.9	232.5	188.7
WPD 2	88.1	42.1	103.1	50.4	34.0	70.7	64.1	87.9	210.3	267.3	236.7	187.1
Variance	0.10	2.55	0.20	0.30	0.34	2.20	0.02	0.05	1.65	0.59	4.37	0.62

Previously, characterization of WPD for magnitude assessment has been reported as following [153];

- Fair: WPD < 100 W/m^2
- Fairly Good: 100 W/m^2 ≤ WPD < 300 W/m^2
- Good: 300 W/m^2 ≤ WPD < 700 W/m^2
- Very Good: WPD ≥ 700 W/m^2

Based on this, the wind resource in S10 and S11 fall in the 'Good' bracket, whereas, S12, S9, S1 and S8 meet the 'Fairly Good' range, showing a reasonable potential of these site.

Variance of WPD with height over a site is another important parameter while deciding the hub height for a wind turbine as cost varies considerably among wind turbines at different hub heights. To investigate this, WPD1 were estimated at 50m & 80m AGL and the differences are shown in Fig. 14.

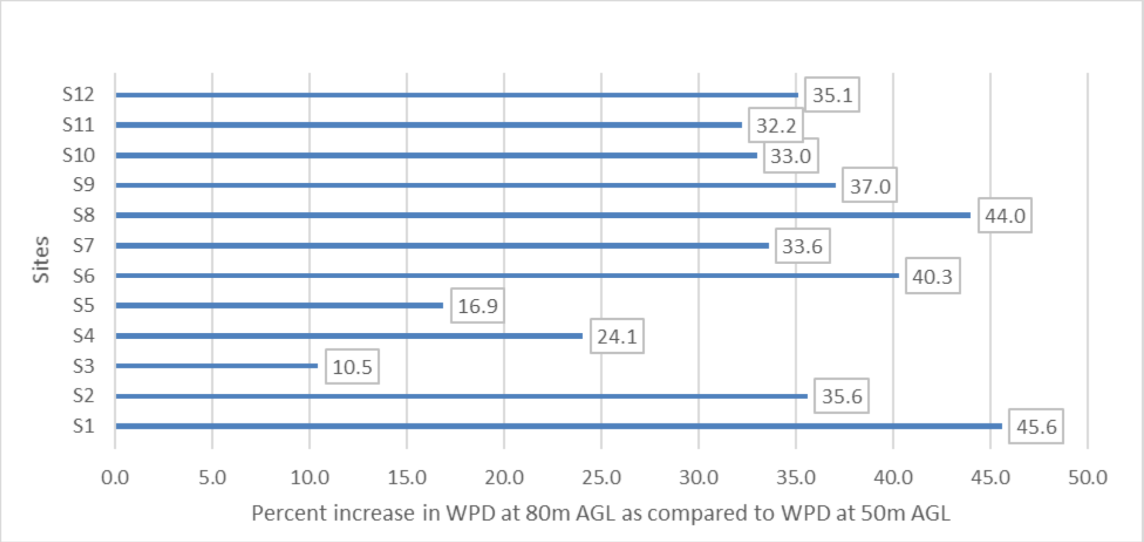

Fig. 14: The percent increase in wind power densities when moving from 50m to 80m AGL

Fig. 14 shows that WPD surges as the height increases from 50m to 80m and for most of the sites, the WPD at 80m is 30 to 50% higher than that at 50m. Besides annual average, monthly WPD at two heights were also compared and the values calculated for 80m height were consistently found to be higher for all sites, shown in Fig. 15. However, it can be seen that for sites like S4, there would be no considerable gain in power output by increasing the hub height, only causing a considerable increase of capital cost. Trends must be analyzed with respect to wind characteristic variance at various height to reach optimal design.

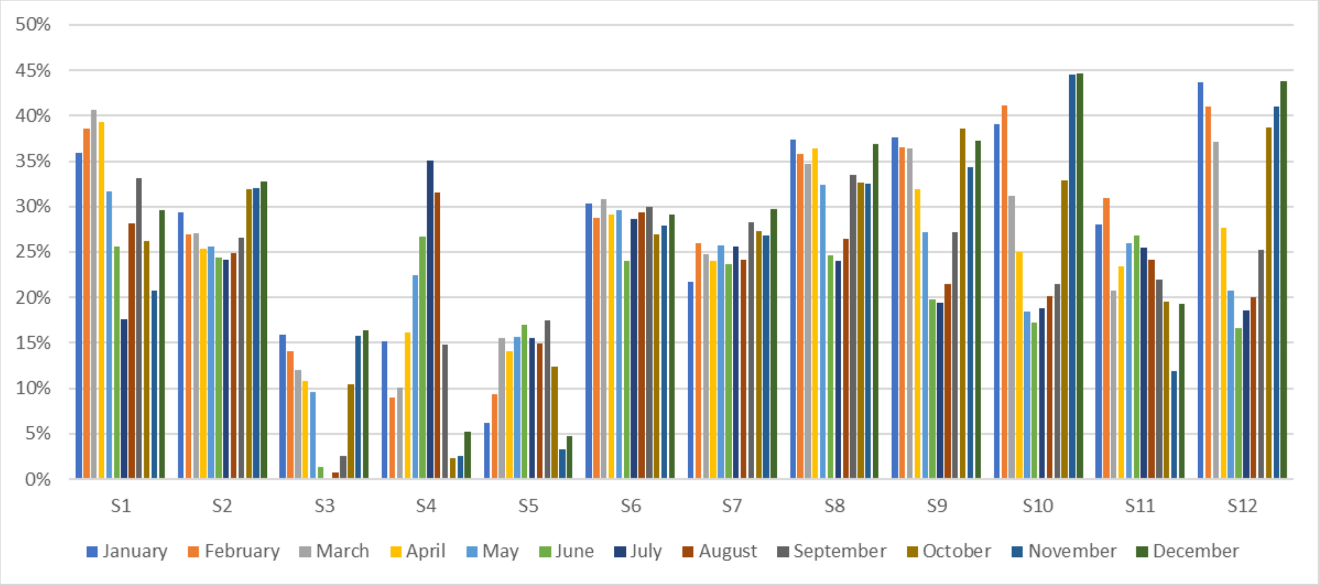

Fig. 15: Monthly increase (%) in Wind Power Densities (W/m2) at 80m as compared to 50m AGL for all sites

4.2 Wind Farm Feasibility

After a detailed analysis of wind characteristics and trends, primarily based on the prevailing wind speed in an area, four sites were recognized for further development of wind farm feasibilities. S9, S10, S11 and S12 are seen with a wind speed mean of above 6m/s which is the wind class IV according to International Electrotechnical Commission (IEC), and is also considerably higher than other sites. Hence, the said locations have been further explored in this study for wind power projects development.

A low cut-in speed wind turbine was selected to calculate the energy output for the four sites using RETScreen Expert. Table 15 summarizes the specifications of the Vestas turbine.

Since the wind speed and wind power density both were considerably higher at 80m AGL for almost all sites, a wind turbine with 80 m hub height was considered to estimate the energy output for the sites.

Table 15 Technical Specifications of VESTAS V110-2.0 MW

Operational data	
Rated power	2,000 kw
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Re cut-in wind speed	18 m/s
Wind class	IEC IIIA
Operating temperature range standard turbine	-20˚c to 40˚c
Rotor	
Rotor diameter	110 m
Swept area	9,503 m2
Air brake	Full blade feathering with 3 pitch cylinders
Tower	
Type	Tubular steel tower
Hub heights	80 m (IEC IIIA)
Sound power	
Maximum	107.6 db

Vestas 110-2.0MW is designed for a wind speed average of 7.5 m/s under the IEC Class III [154]. Adjustments for temperature for different climatic conditions are also offered by Vestas. More

than 10 GW is being produced by the selected turbine model worldwide, as of December 2018 [155].

The coefficient calculated and resultant energy outputs by the tool, for the four selected sites, has been summarized in Table 16.

Table 16 Electricity production, capacity factors and coefficients.

Outputs	**Units**	**Sanghar (S9)**	**Sujawal (S10)**	**Tando (S11)**	**Umerkot (S12)**
Capacity Factor	**%**	30.2	39.1	33.8	29.8
Electricity Exported to Grid	**MWh**	132,114	171,071	147,883	130,357
Unadjusted Energy Production	**MWh/ turbine**	6,436	8,274	7,239	6,299
Pressure Coefficient	**Per Turbine**	0.993	0.996	0.993	0.993
Temperature Coefficient	**Per Turbine**	0.961	0.962	0.956	0.962
Gross Energy Production	**MWh/ turbine**	6,098	7,896	6,825	6,016
Losses Coefficient	**Per Turbine**	0.87	0.87	0.87	0.87
Specific Yield Per Turbine	**kWh/ m2**	556	720	622	549

The highest yield and hence the capacity factor is found for Sujawal which coincides with the higher wind speeds and wind power density found at the site. Two other locations in Pakistan were also explored in another study using a Vestas turbine and similar capacity factors were found (32.8% for Nooriabad and 36.46% for Zorlu) [63].

According to United States Energy Information Administration the annual average capacity factor for wind power plants across the country for 2018 was 37.4% [156]. The capacity factors vary with regions due to the strength on wind patterns. The capacity factors globally are being improved with the increasing advancements in the wind sector, by the introduction of higher hub heights for turbines and rotor scaling. The projects commissioned from 2004 till 2011 in USA had capacity factors on average of 31.5%, considerably lower as compared to the projects developed from 2014 till 2016 having average capacity factors of 42% [157].

The GHG emission reduction was calculated through RETScreen for the four sites and immense benefits in terms of environmental impact were observed. Results are tabulated in Table 17 with equivalent savings in multiple examples.

Table 17 GHG emission reduction (tCO2)

	Annual GHG Emission Reduction (tCO2)	**Annual GHG Emission Reduction (tCO2) Equivalent to:**		
		Crude Oil not consumed (Barrels)	**Gasoline not consumed (litres)**	**Forests to absorb carbon (Acres)**
Sanghar (S9)	82,202.6	191,168.9	35,320,186.6	18,682.4
Sujawal (S10)	106,441.6	247,538.6	45,735,000.7	24,191.3
Tando (S11)	92,013.9	213,985.8	39,535,809.5	20,912.2
Umerkot (S12)	81,109.1	188,625.7	34,850,309.7	18,433.9

Highest emissions can be seen to be saved in the case of Sujawal, this is naturally due to the highest energy production for the said location.

Similar costs for engineering, procurement & commission (EPC), development and other sections were assumed for all four locations and are shown in Table 18. RETScreen also requires other inputs for the calculation of financial viability of a project. For this purpose, same conditions were assumed for all sites as well (tabulated in Table 19).

Table 18 Initial and Annual Costs

Initial Costs	**USD**
Non-EPC & Project Development Cost	3,900,000
EPC Cost	75,600,000
Power Systems	15,000,000
Insurance during Construction	500,000
Financial Charges	2,000,000
Miscellaneous	5,000,000
Annual Costs	**USD/ year**
Operations & Maintenance Costs	2280000

Table 19 Assumptions for financial analysis

Input	**Value**	**Unit**
Debt ratio	70	%
Debt term	12	Years
Project life	20	Years

All inputs to the tool were kept constant for the four scenarios, except the tariffs and debt financing schemes. The tariff regimes that had been issued by NEPRA through the years have been evaluated to see the impact of the changing tariffs on the viability of wind power projects ultimately impacting the development of the sector. Under each scheme by the government, two types of tariffs are announced, one for the locally financed (LF) projects and the second for projects benefitting from foreign financing (FF). This is vital due to a significant different between LIBOR (London Interbank Offered Rate) and KIBOR (Karachi Interbank Offered Rate). Hence, for each of the four scenarios mentioned in table 2, two conditions (A & B) were studied for FF and LF projects incorporating the corresponding interest rates and tariffs.

The scenarios are discussed with respect to their impact on certain financial indicators like NPV, Payback period, IRR and energy production cost.

4.2.1 Net Present Value (NPV)

NPV is an important financial parameter that is used to assess the viability of a project. It basically compares the present value of all cash inflows with the present value of all cash outflows, and a zero or positive value of NPV is desirable. The higher a value of NPV the better a project would be economically. A negative NPV would indicate that a project might not be potentially feasible. For each location and for every scenario, the NPV was calculated and is plotted in Fig. 16.

There is a distinct difference in the NPV for all sites under each scenario, for foreign and local financing (denoted by A and B, respectively). The projects having foreign funding are seen to have higher values of NPV, which indicates better cashflows in the project lifecycle, in contrast to the locally funded projects. It should be noted that despite the NPV being lower for type B scenarios as compared to type A, it is still positive and acceptable for almost all studied scenarios. This indicates that the projects may be viable under both the financing schemes but would be clearly more beneficial under the foreign financing. This is due to the difference in interest rates for the two types, primarily due to the instability in Pakistan's economy from the recent years. This is well addressed by NEPRA as the tariff for locally financed projects is also higher to compensate for the increased interest rates.

For scenario 1, which is the current tariff scheme by the government the NPV for all locations is seen to be the lowest as compared to the other scenarios based on tariff schemes announced in the previous years. The tariff has come down significantly from 2011 till 2017 due to the cost competitiveness in the renewable energy sector. Initially high upfront tariffs were in place to attract the investors but over the years with the development of the technology and business market in Pakistan, the lowered tariffs are now used a ceiling price for competitive bidding. This may appear as a drawback for the investors but in reality, it is not. By studying the NPV calculated for the 4 locations it can be seen that the NPV stays positive for most of the cases. For Umerkot, under the current tariff rates the project may not be viable with local financing as the NPV has come out to be negative. But the same location becomes economically feasible if opting for foreign funding.

Hence, over the years due to the decrease in tariff the financial benefit may have come down but the projects at the discussed locations still remain feasible under the studied conditions. The highest NPV among the four locations has been found for Sujawal.

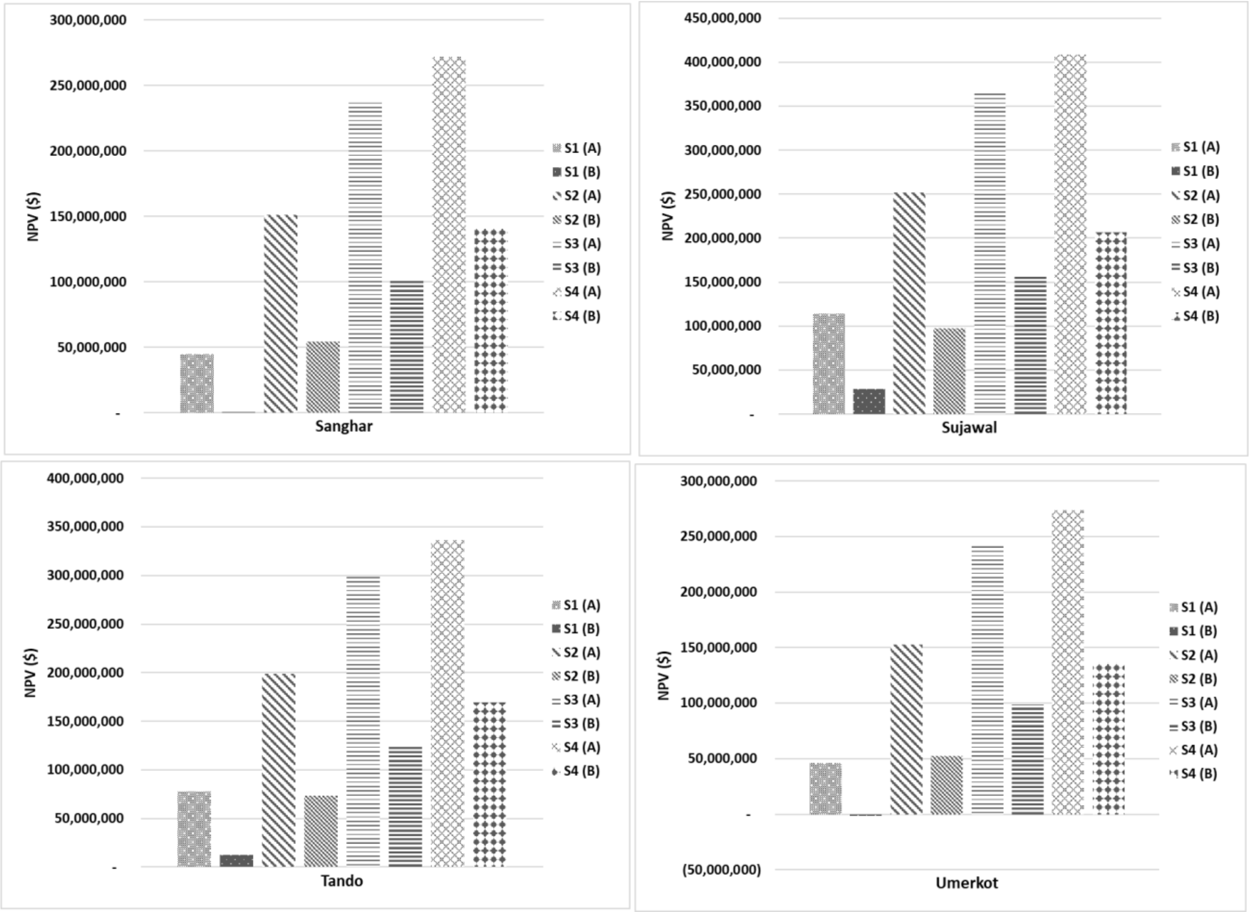

Fig. 16: Net Present Value (NPV) in USD at Sanghar, Sujawal, Tando Ghulam Ali & Umerkot for Scenarios 1-4 (S1-S4). Each scenario has further A and B components for foreign and locally funded projects respectively

4.2.2 Payback Period

The payback period indicates the time required to recover the initial costs or investments made for a project, with net positive income. RETScreen calculates two types of payback periods, one for the equity payback and the other known as the simple payback which covers the entire investment. Quicker the investment is recovered, more desirable the project, hence shorter payback periods are preferred. But it must be noted that this indicator can not be used alone in deciding one project over the other as a shorter payback period does not necessarily indicate a more profitable project. This indicator is useful to assess the risk of investment. Some investors may opt for a longer payback period for a higher rate of return, while others may prefer getting the cask back sooner with a lower rate of return.

We have studied the payback periods for the locations (Fig. 17) under each scenario to assess the risk of assessment. Shorter payback periods indicate less risk in an investment by having a shorter period of recovery.

Projects feasibilities prepared using foreign funding scenarios can be seen with a longer payback period as compared to those having local funding. This is due to higher tariffs i.e., higher cost of selling electricity for locally funded projects. As already mentioned, this may be a choice of the investor to prioritize shorter payback period over higher profitability. This may be evaluated with other indicators while making a decision.

The payback periods were also lower in the previous years when a higher tariff was offered by the government, enabling investors to recover the investment in a shorter period of time. Among the sites, Sujawal is found to have the shortest payback period, due to its highest energy production and hence a shorter return of investment.

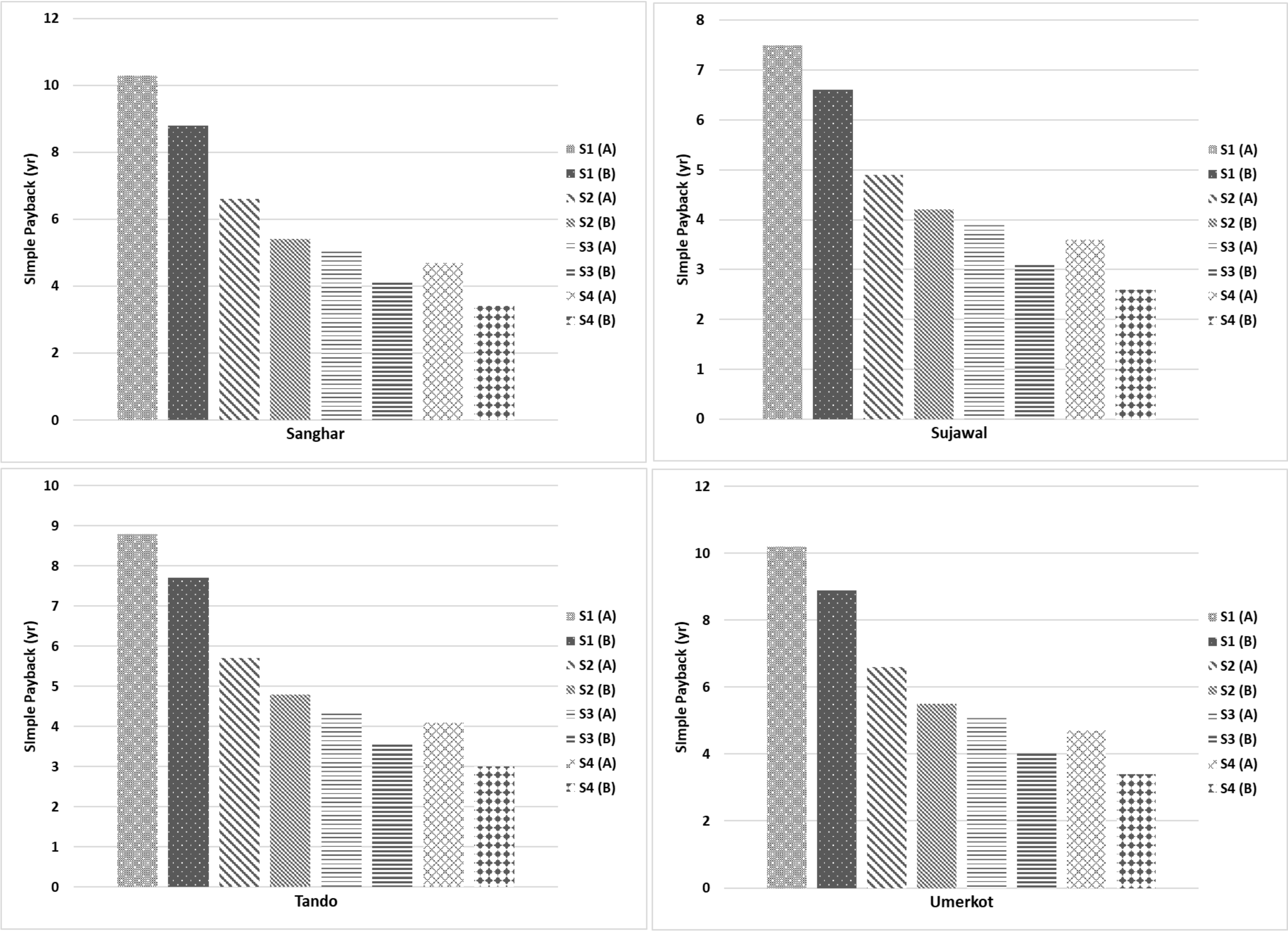

Figure 17: Simple Payback Period (year) at Sanghar, Sujawal, Tando Ghulam Ali & Umerkot for Scenarios 1-4 (S1-S4). Each scenario has further A and B components for foreign and locally funded projects respectively.

4.2.3 Internal Rate of Return (IRR)- Equity

Internal Rate of Return (IRR) also known as Return on Investment (ROI) is the percentage of income per year and original investment. It provides the true interest yield generated by the equity over the project’s life time, hence it is also referred to as time-adjusted rate of return.

To assess if a certain project would be economically viable, the calculated IRR is compared with the expected IRR. The expected IRR is commonly the discount rate used in the analysis. A project may be considered financially acceptable if its IRR comes out to be equal or higher than the expected IRR and is usually rejected in case the IRR is less than the set or expected IRR.

The pre-tax IRR equity has been plotted in Fig. 18 for each location under all the scenarios. The rate of return for foreign funded projects is lower than the locally funded projects, this is mainly due to lower tariffs for foreign funded projects as compared to locally funded project. But to evaluate the feasibility of an individual project we must compare the IRR with its own discount rate or expected IRR. Since local and foreign funded projects have different discount rates due to the difference in interest rates on loans. For S1 and S2, the type A projects are found with a higher IRR difference from the discount rate as compared to the type B projects having the IRR closer to the expected IRR. Whereas, for S3 and S4, the calculated IRR for both A and B projects are either equally higher than the expected IRR or show better outcomes for type B. And hence the IRR comparison for our case does not seem to clearly distinguish the two project types, making it harder to select one project over the other.

To understand it better IRR along with NPV was studied. As shown earlier in Fig.5, the NPV for type A projects was consistently higher, but IRR has not shown the same trend. This type of conflict in NPV and IRR is rare and generally projects having higher NPV's tend to have better rate of returns as well. But the conflict can occur when the two projects being compared have cash flows falling later or earlier than the other. In such cases, where NPV and IRR do not align, NPV is taken as a primary indicator for decision making. This is recommended due to the fact that NPV reinvests future cashflows using the discount rate, which is a realistic choice. On the other hand, IRR method reinvests cashflows without considering the cost of capital or discount rate. Hence, making it less reliable especially for longer duration projects.

Nevertheless, both these methods are frequently used while decision making and mostly provide the same appraisal.

As expected, the rate of return was found the highest for S4, having the highest tariffs and the lowest were seen for S1. But importantly, all scenarios showed positive IRR for each location.

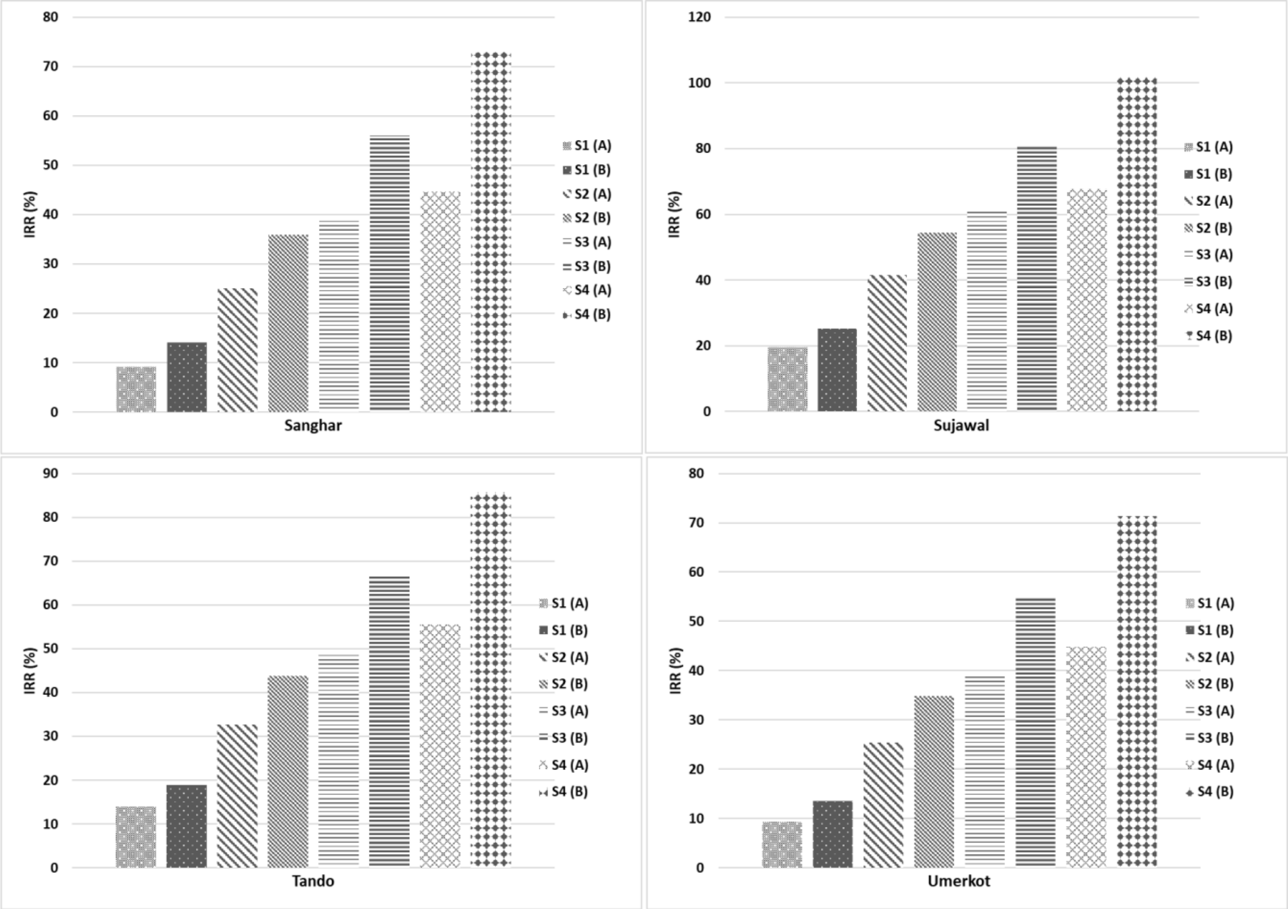

Figure 18: Internal Rate of Return – Equity (IRR) in percentage at Sanghar, Sujawal, Tando Ghulam Ali & Umerkot for Scenarios 1-4 (S1-S4). Each scenario has further A and B components for foreign and locally funded projects respectivel

4.2.4 Levelized Cost of Energy (LCoE)

The levelized cost of energy or energy production cost identifies the minimum cost of selling electricity which would result in an NPV of zero. It is also desirable to have the energy production cost lower than the selected cost of selling electricity i.e., the tariff. For each location the energy production cost for foreign and locally funded have been plotted in Fig. 19 and Fig. 20, respectively.

For S2, S3 And S4 both locally and foreign funded projects have a higher selling cost than the production cost. But for S1, foreign funded projects are found to have an advantage over the locally funded projects.

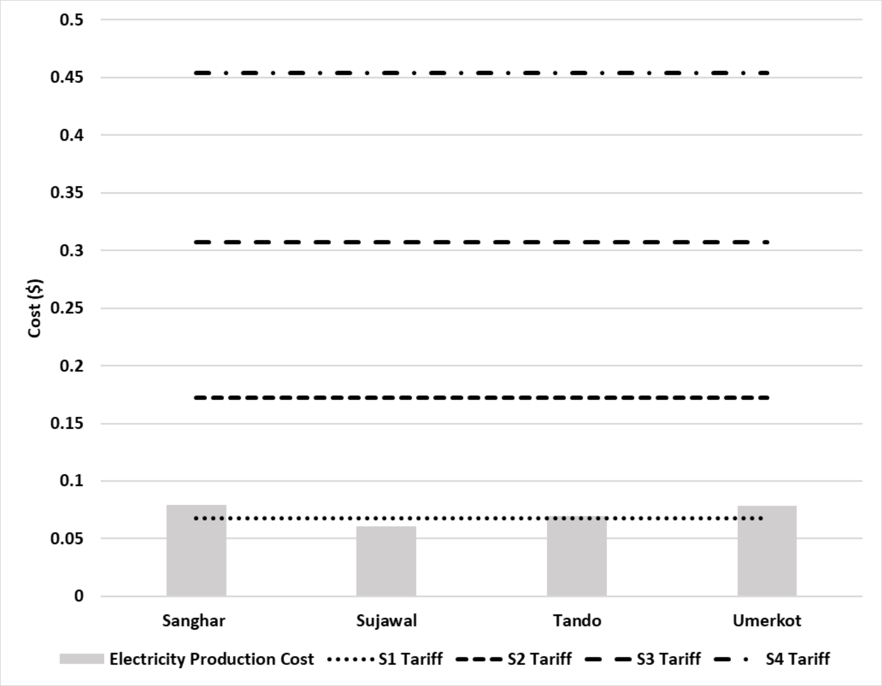

Fig. 19: Electricity production cost (USD) against the electricity selling cost (USD) for Foreign Funded projects

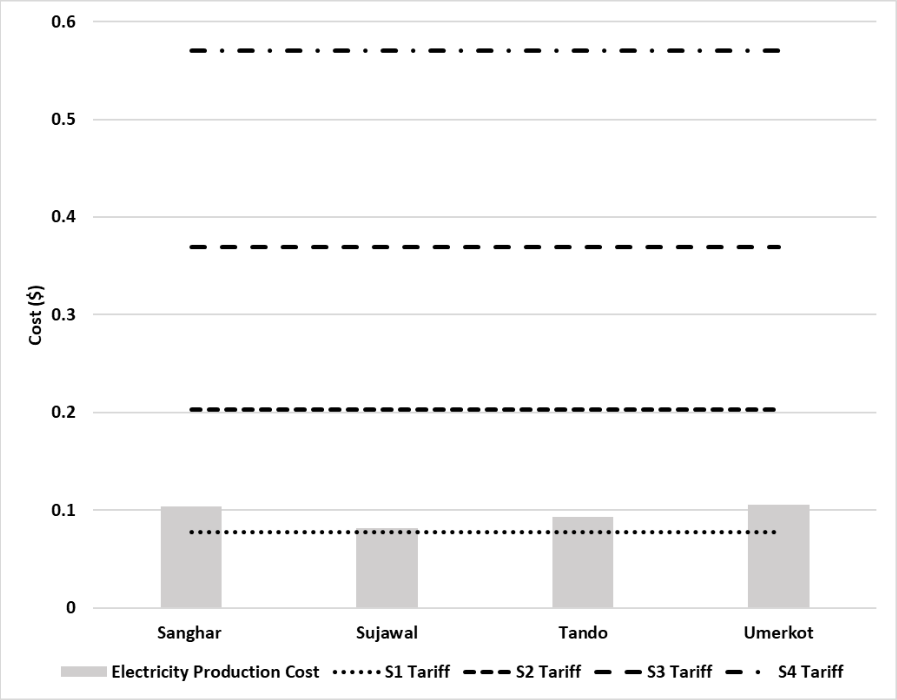

Fig. 20: Electricity production cost (USD) against the electricity selling cost (USD) for Locally Funded projects

This may be alarming as it indicates that the tariff has come down so significantly in the period of years that it is even lower than the cost of electricity production for the case assumed in our study. But over the 20 year life of the project, stable winds, a high NPV and a good capacity factor reassures the success for the investors in the sector.

The government of Pakistan also supports the investors by offering concept of wind risk where even in the case of a low wind speed, the producer is paid for the decided benchmark speed. And, is also paid for the surplus energy production in case the wind speed exceeds the set benchmark. This condition has not been incorporated while developing the cases as the areas which have been explored in our study have not yet undergone the evaluation by the government departments for the setting up of a benchmark speed.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

MERRA-2 hourly wind data was compared with matched up ground observations for 12 locations in Pakistan. Moreover, wind energy potential estimation for the 12 sites across Pakistan was carried out, for the first time using a high-quality ground data. High frequency (10min) wind data measured for at least 2 years for each site was analyzed and the following conclusions have been made:

- Lower correlation was found between MERRA-2 reanalysis and ground measured data, in general, at 12 locations as compared to that reported in previous studies.
- MERRA-2 reanalysis data showed better correlation with ground data for sites with high wind and low elevation.
- Wind speed in the summer months was found to be higher for all the sites. Moreover, stronger winds were observed from the afternoon till late night in the diurnal variation.
- Highest annual mean wind speed of 7.4 m/s at 80m AGL was recorded at S10.
- Dominant wind directions for most of the sites (S1, S3, S5, S9, S10, S11 and S12) were found in the south-western direction. Southerly and easterly winds were seen at the other locations.
- The Weibull shape parameter, k, ranged between 1.6 and 3.05, whereas scale parameter, c, varied from 3.5m/s to 8.5m/s, among the sites. Highest values of k and c (3.05 and 8.5m/s respectively) were found at S10.
- Wind power densities at S10, S11, S19 and S12 were found to be of good resource potential with values of 355.6 W/m^2, 312.9 W/m^2, 288.2 W/m^2 and 252.8 W/m^2, respectively.

- Considerable increase in wind power densities, for all locations, were found with the increase of height above ground.
- The energy output values for Sanghar, Sujawal, Tando and Umerkot were found to be 6,098 MWh, 7,896 MWh, 6,825 MWh, and 6,016 MWh per year per turbine, respectively.
- Highest capacity factors were found for Sujawal and Tando being 39% and 34%, respectively.
- Considerable reduction of GHG emissions was recorded for projects at all 4 locations.
- The projects having foreign funding are seen to have higher values of NPV, which indicates better cashflows in the project lifecycle, in contrast to the locally funded projects.
- Due to the decrease in tariff the NPV is seen to come down but the projects at the discussed locations still remain feasible under the present policy regime. The highest NPV among the four locations has been found for Sujawal.
- Projects feasibilities prepared using foreign funding scenarios can be seen with a longer payback period as compared to those having local funding. The payback period is also found lower in the previous years when a higher tariff was offered by the government.
- All scenarios showed a positive Internal Rate of Return (IRR) for each location.

Finally, it is recommended that MERRA-2 wind data should be used with caution for wind potential assessment in the regions with limited availability of ground data for MERRA-2 data assimilation purpose. Moreover, on the basis of promising results of the project feasibility studies, advance level studies should be undertaken for Sanghar, Sujawal, Tando Ghulam Ali and Umerkot in order to develop the wind power sector of Pakistan.

Developing countries like Pakistan need to prioritize the renewable energy market, which currently is primarily driven through financial and technical vantage points only, with only a little consideration of the environmental and social benefits. The policy makers in Pakistan need to empower the provinces so that they are able develop power policies and procedures according to their specific needs or capacities. Also, like any other development goal, the renewable energy sector can be promoted by the setting of time bound and realistic targets. Pakistan had been setting these goals but due to the political instability, they have not been achieved as it may be desired. Hence having binding targets with the investors would make their investment more secure.

Despite the continuous decrease of cost of renewable energy resources, there has been a higher support for thermal power projects by the government of Pakistan. According to IRENA, without considering the loss of GDP by power shortages, integration of renewable energy system in the national energy mix will reduce costs as compared to an energy mix having no additional contribution from renewable energy.

CHAPTER 6

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