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Performance Evaluation of Ashegoda Wind Farm Using Key Performance Indicators and Proposing Mitigation Measures

By

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Abstract

The global rise in electricity demand has driven many countries to use fossil fuels; however, environmental concerns have shifted focus toward renewable energy. Ethiopia is leveraging its renewable energy potential, particularly wind energy, with an estimated 10 GW capacity. As part of this initiative, the Ashegoda wind farm, become operational since 2013/14 with a 120 MW capacity. However, data from four Ethiopian fiscal years (EFY) indicate a notable decline in energy output, particularly in the final two years of the study. This thesis evaluates the wind farm's performance using KPIs and proposes mitigation strategies based on the findings.

Wind speed data collected from the SCADA system were processed using Excel and IBM SPSS after missing data were estimated using the Moving Average (MA) model and monthly averages. The analysis revealed the annual average wind speeds at the site are 6.52 m/s (2015/16), 6.96 m/s (2016/17), 7.45 m/s (2017/18), and 7.38 m/s (2018/19), the same all phases. Gross and net energy outputs were estimated using frequency distributions and the turbine power curve, adjusted for site air density and losses. Based on P50 exceedance, estimated net outputs for 2017/18 and 2018/19 were 233 GWh and 229 GWh, respectively. In contrast, the actual measured outputs for the same years were 61.5 GWh and 88.6 GWh, highlighting a significant gap between potential and actual generation.

Performance indicators showed low values: capacity factors of 5.86% and 8.43%, energy-based availability of 26.4% and 38.75%, and time-based availability of 35.12% and 11.93% in 2017/18 and 2018/19, respectively. These figures indicate underperformance, resulting in energy losses of 171.73 GWh and 140 GWh which are mainly caused by long downtime. To improve performance, the study proposes mitigation strategies, including better spare part management, improved SCADA reliability, and optimized maintenance.

In conclusion, the Ashegoda wind farm is underperforming relative to its design expectations. Implementing the proposed mitigation strategies is essential to enhance its operational efficiency.

Key words: Performance evaluation, Key performance indicators, Annual energy production, mitigation measures

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List of Acronyms

AC	Alternating Current
ACSR	Aluminum Conductor Steel Reinforced
AEP	Annual Energy Production
ARIMA	Auto Regressive Integrated Moving Average
CF	Capacity Factor
CMMS	Computerized Maintenance Management Systems
DC	Direct Current
DFIG	Double Feed Induction Generator
EBA	Energy-Based Availability
EEP	Ethiopian Electric Power
EFY	Ethiopian Fiscal Year
GEP	Gross Energy Production
GSC	Grid Side Converter
GW	Giga Watt
GWh	Gigga Watt hour
HAWT	Horizontal Axis Wind Turbine
ICS	Interconnected Systems
IGBT	Insulated Gate Bipolar Transistor
KPI	Key Performance Indicator
KV	Kilo Volt
KWh	Kilo Watt hour
MA	Moving Average
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MDT	Mean Downtime
ME	Mean Error
MPE	Mean Percentage Error
MSE	Mean Squared Error
MTBF	Mean Time Before Failure
MTTR	Mean Time To Repair

MVA	Mega Volt Ampere
MW	Mega Watt
MWh	Mega Watt hour
PCC	Point of Common Coupling
PE	Percentage Error
RSC	Rotor Side Converter
SARIMA	Seasonal Auto Regressive Integrated Moving Average
SCADA	Supervisory Control And Data Acquisition
SCIG	Squirrel Cage Induction Generator
SCS	Self-Contained Systems
SPSS	Statistical Package for Social Science
TA	Technical Availability
TBA	Time-Based Availability
VAWT	Vertical Axis Wind Turbine
WF/WT	Wind Farm/ Wind Turbine
WTG	Wind Turbine Generator

CHAPTER ONE

1. INTRODUCTION

1.1. Background

The world population is increasing every year. The world economic output is also expected to increase with the fast-growing population. Since energy has established a positive correlation with economic growth the energy requirement will also increase. As human wellbeing is highly dependent on energy, providing clean, adequate, reliable and affordable energy is prerequisite to improve productivity and bring economic growth. To fulfill the energy requirements most nations are using fossil fuels which presents associated side effects to the nation's energy security and climate change. Due to high environmental concerns currently, many countries are looking for accelerated use of renewable energy as feasible solution.

Ethiopia is one of the nation's focusing on production of electricity from renewable energy sources such as hydro, wind, solar and geothermal. Currently EEP grid system is highly dependent on generation from hydropower which is affected by rainfall variation from year to year. Besides, the nation has around 45 GW potential from hydropower two third of it is within the catchment of Blue Nile which makes it very dependent on international agreements and relationship with Sudan and Egypt [1].

According to Ethiopian electric power load projections by 2025 and 2030 the nation will need 9232 and 13210 MW respectively. Due to the availability of huge potential currently the government of Ethiopia has developed policy and strategy to produce electric energy from solar and wind. This will help the Ethiopian Electric power (EEP) to diversify the grid and to fulfill the energy demand of the nation.

According to the solar and wind energy resource assessments (SWERA) study the total national potential for grid-based wind electricity system is about 10 GW. Due to this promising resource wind farms have already constructed at Ashegoda and Adama (I and II) [2]. From these projects 324 MW electricity is expected to be produced which is 3.24% of the total potential. To exploit the untapped potential many anemometer stations at different locations were preselected such as, DebreBirhan, Nazareth, Bahir Dar, NefasMeewcha, Sululta, Ashegoda, Harena, Messobo, Bilagg, Yabelo, and Maymekden [3]. The majority of sites lie in altitudes between 2,000 and 2,400 m, with the exception of DebreBirhan (2,818 m).

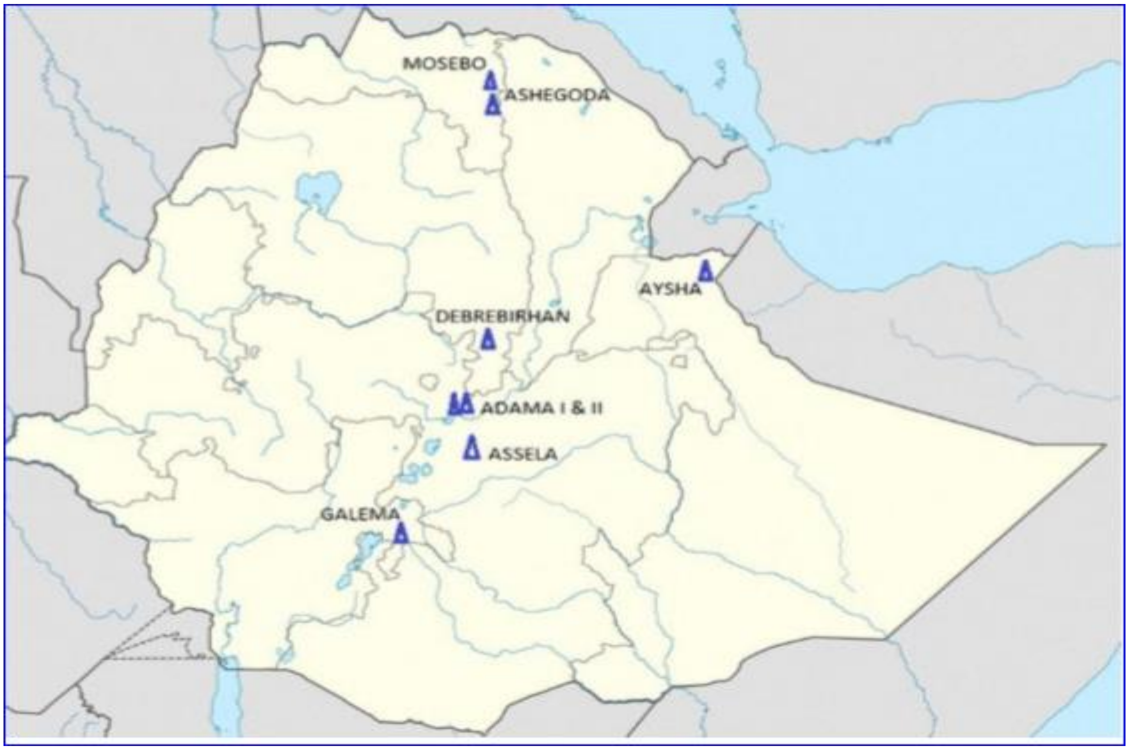

Figure 1.1:Geographical location of 8 wind farms [4]

Ashegoda wind power plant is one of the operational wind power plants in Ethiopian which is located 720 Km far from Addis Ababa and 20 Km away from Mekelle. The total installed capacity of the wind farm is 120 MW which is generated from 30 Squirrel cage induction generators of each 1 MW and 54 double feed induction generators each 1.67 MW. It is obvious that constructions of wind power plants alone can't be guarantee to meet the demand and diversify a grid. Power plants should operate efficiently to meet the load demands and to recover their investment costs. Although, Ashegoda wind power plant is in operation since 2013, the operational performance of the wind farm is not satisfactory. In this thesis performance evaluation measures such as capacity factor, time-based availability, energy-based availability and mean downtime are determined and improvement measures are proposed.

1.2. Statement of the problem

Ashegoda wind farm is in operation since 2013/14 G.C with total installed capacity of 120 MW. The wind farm consists three phases, phase 1 includes 30 Vergnet squirrel cage induction wind turbine generators each 1 MW and phase 2&3 contains 54 Alstom double fed induction generator (DFIG) wind turbines. The estimated gross annual energy yield was 99.858 GWh for phase 1 and 304.641 GWh for phase 2&3. Generally, 404 GWh energy was expected in each year from the wind farm during the planning stage [5]. However, this yield doesn't consider unavailabilities, electrical losses, maintenance stops, grid failures, uncertainties, and any other effects leading to production losses. Even considering a common value of 10% for the sum of such losses the estimated yield is around 364 GWh based on 50% probability (P50). Considering 75% and 90% probability the annual yield was estimated 335 GWh and 290 GWh respectively [5]. However, based on available historical data from four years indicate a notable decline in energy output, particularly in the final two years of the study 2017/18 and 2018/19. During the first fiscal year of operation considered in this study (2015/16 G.C), the measured output energy was 227 GWh. But at the end of the two fiscal years considered in this thesis, the annual energy yield of the wind farm was reported as 61.5 GWh and 88.6 GWh. This difference is huge amount of energy which could power several villages. In this thesis operational performance assessment of Ashegoda wind farm will be carried out, possible causes of underperformance will be investigated to come up with the possible mitigation measures.

1.3. Objectives

1.3.1. General Objective

The general objective of this thesis work is to evaluate the performance of Ashegoda wind farm using the KPI's and to propose possible mitigation measures.

1.3.2. Specific Objectives

The specific objective of the task includes;

- To estimate annual energy production of the wind farm
- To determine the key performance indicators
- To assess the possible causes of underperformance

- To propose possible underperformance mitigation measures

1.4. Scope of the study

This study is focused on evaluating the performance of Ashegoda Wind Farm, one of the major wind power plants in Ethiopia. The primary objective is to assess the operational performance of the wind farm using selected key performance indicators (KPIs), including capacity factor, energy-based availability, time-based availability, curtailment loss, and total downtime. The evaluation is confined to the Ashegoda Wind Farm and does not extend to other wind farms or forms of renewable energy. The performance analysis will be conducted over a defined time period, based on the availability of historical operational data.

Performance data is obtained from supervisory control and data acquisition (SCADA) systems, maintenance records, and operator reports. These data will be analyzed to calculate the selected KPIs and to identify performance trends, inefficiencies, and possible areas of concern. The study also compares the current performance of the wind farm against industry standards and best practices in some literatures to identify performance gaps. Based on the findings, the study will propose feasible and practical mitigation measures aimed at improving operational performance and efficiency. These may include technical interventions, enhanced maintenance practices, and operational strategies to reduce curtailment losses and downtime.

1.5. Significance of Study

The significance of this study lies in its contribution to the improvement of wind energy utilization and operational performance at the Ashegoda Wind Farm, a key component of Ethiopia’s renewable energy strategy. By conducting a detailed performance evaluation using standard key performance indicators, this study provides critical insights into the actual operational status and challenges facing the wind farm. Understanding metrics such as capacity factor, availability, and curtailment losses allows stakeholders to make data-driven decisions to optimize performance, reduce energy losses, and increase overall energy output.

Furthermore, the study proposes targeted mitigation measures based on identified performance gaps, offering practical solutions that can enhance the reliability and productivity of the wind farm. These recommendations can support maintenance planning, reduce downtime, and contribute to more stable integration of wind power into the national grid. Beyond the Ashegoda Wind Farm, the findings may serve as a reference for other wind energy projects in Ethiopia. Academically, the research adds to the body of knowledge on wind farm performance evaluation in sub-Saharan Africa, where such studies are relatively limited.

1.6. Methodology

Due to the nature of the study, it is started by reviewing literatures related to wind farm performance assessment and improvement measures. Recent and unpublished important information are collected from wind farm offices and from other offices as needed for detail assessment and investigation to come up with clear solution to the problem at hand.

Reviewing literature: investigation of books, researches and publications related to wind energy, wind power plant performance and mitigation techniques for underperformance.

Data Collection: At this stage important information are collected from wind farm office and other offices as needed for detail assessment and investigation to come up with clear solution to the problem at hand.

Output Energy Estimation: At this stage, based on the obtained field data, estimation of gross and net energy output of the wind farm is performed, the estimated energy from site parameters is compared with the measured value in order to identify the bottle necks.

Performance Evaluation: Based on the energy (power) output of the wind farm from site parameters, the different wind farm performance measures such as, capacity factor, time-based availability, energy-based availability, and total downtime are determined. This is the stage where the major bottle necks for unsatisfactory operation of the wind farm are identified based on the different evaluation criteria.

Mitigation Measures: At this stage all the possible solutions for better performance of the wind farm are explored to come up with feasible solution.

In general, the methodology to be followed is summarized as follow.

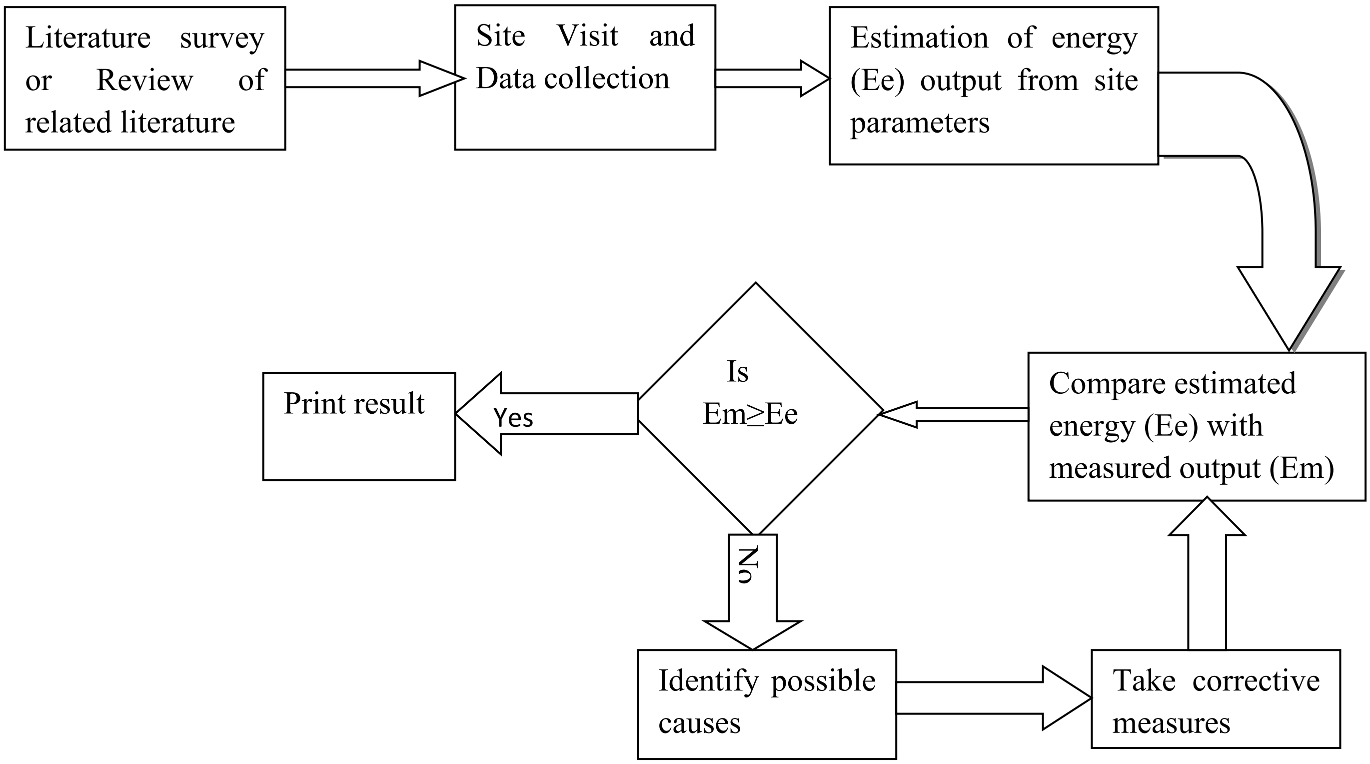

Figure 1.2:Thesis methodology

1.7. Thesis Organizations

The thesis is organized into five chapters which are briefly summarized below.

Chapter one presents the background of the study, statement of the problem, objective of the study, scope of study, significance of the study, methodology to be followed in the thesis work. In addition, it provides the outline of the thesis.

The second chapter deals with discussion of the theoretical background and literature review of the study topic mainly on wind energy, wind farm performance assessment and wind farm performance improvement measures. Here books, research works and publications related to the study topic are also reviewed.

Chapter three deals with wind energy, wind energy output estimation, performance assessment the existing wind farm, causes of underperformance and mitigation measures. In this chapter all the requirements for wind farm performance assessment and their mitigation measures are discussed.

Chapter four is about results and discussions. Here detailed performance evaluation results of Ashegoda wind farm will be discussed. The performance indicators of the existing wind farm are compared with benchmarks. Besides the mitigation techniques for performance improvement of the wind are discussed in detail.

Conclusion, recommendations and future works are incorporated under chapter five.

CHAPTER TWO

2. THEORTICAL BACKGROUND AND REVIEW OF RELATED LITERATURE

2.1. History and Theory of Wind Energy

2.1.1. History of Wind Energy

Since ancient times, people have harnessed the energy in wind. The Egyptians used to sail ships on the Nile River over 5,000 years ago. Later, people-built windmills to grind wheat and other grains. The earliest known windmills were in Persia (Iran). These early windmills looked like large paddle wheels. Centuries later, the people of Holland improved the basic design of the windmill. They gave it propeller-type blades, still made with sails. Holland is famous for its windmills. As early as 1890 a machine called wind turbines appear in Denmark [6].

American colonists used windmills to grind wheat and corn, to pump water, and to cut wood at sawmills. As late as the 1920s, Americans used small windmills to generate electricity in rural areas without electric service. When power lines began to transport electricity to rural areas in the 1930s, local windmills were used less and less, though they can still be seen on some Western ranches [6].

The use of windmills declines gradually and replaced by stem engine due to the industrialization in Europe and later in America. In the 1930s, United States of America rural electrification administration program brought inexpensive electric power to most rural areas. However, industrialization made it necessary the development of large windmills to generate electricity. In the 1940s, the largest wind turbine of the time began operating on a Vermont hilltop known as Grandpa's Knob [3]. This turbine, rated at 1.25 megawatts in winds of about 30 mph (13.4 m/s), fed electric power to the local utility network for several months during World War II. The popularity of using the energy in the wind has always fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines banned. But when the price of oil increased in the 1970s, so did worldwide interest in wind turbine generators [3].

The oil shortages of the 1970s changed the energy picture for the country and the world. It created an interest in alternative energy sources, paving the way for the re-entry of the windmill to generate electricity. In the early 1980s wind energy really took off in California, partly because of state policies that encouraged renewable energy sources. Support for wind development has spread to other states, but California still produces more than twice wind energy as any other state [6].

Today, due to the growing interest in energy and high environmental concerns a group of wind turbines in wind farm generate electricity to feed utility grid and supply remote areas all over the world. Wind energy becomes the fastest growing energy source and will continue to provide electricity for many years to come [3].

2.1.2. Theory of Wind Energy

Wind is simply air in a motion which is caused by uneven heating of earth by the sun. Since the earth’s surface is made of very different types of land and water, it absorbs the sun’s heat at different rates. The sun radiates the most heat over the equator and therefore, the air there is warmer. Air from both the hemisphere is constantly moving towards the equator. As the surface of the earth heats and cools unevenly, pressure zones are created that make air move from high to low pressure areas. Therefore, wind occurs when warm air rises and cooler air moves to fill the space [6]. The rotation of the earth also produces wind.

Since wind is air in motion, has energy which helps to do useful work. Wind energy, a renewable energy source, is an alternative form of energy, which has stood out as the most valuable and promising choice. This is not only due to the fact that wind energy has a decentralized mode of operation that reduces transmission and distribution failures but also because it is cheap, environmentally friendly, inexhaustible, price stable, free from control and is virtually available in every part of the nation in some amount.

2.2. Current Status of Wind Energy

2.2.1. Global Status of Wind

Global energy consumption is raising steadily with technological development, population growth, economic growth and energy dependent habits of use [7]. As presented in [8] the energy production of the world was 17,450 TWh in 2004 and in 2030 it is estimated to be 31,657 TWh. Although coal has the largest share of electricity generation, due to government incentives and policies to support rapid construction of renewable generation facilities, renewable generation will increase from 18% in 2007 to 23% in 2035 [8].

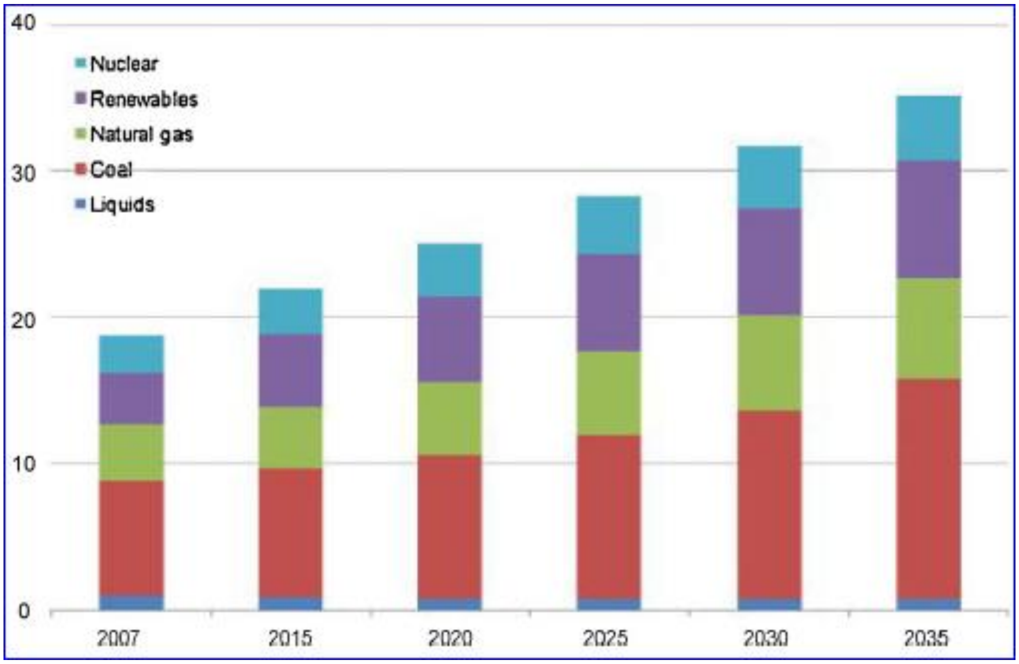

Figure 2.1:World electricity generation by fuel, 2007-2035 [8]

To meet the energy demand and reduce environmental concerns many countries are adapting policies and strategies for generating of energy from renewable energy sources. Wind is one of the renewable energy sources (RES). Wind energy development has been increasing rapidly for the last two decades globally. This rapid growth is driven by many factors, including impressive improvement in wind turbine technology, rising environmental concern, cost reduction, interest in reducing dependency on non-renewable energy source. The growth trend of wind energy in different continent and countries is presented in [7], [9].

Currently the global wind power markets are dominated by the three major markets, Europe (Germany and Spain), North America (USA) and Asia (China and India) [9]. According reports released on power technology [10] in 2021 and Statista [11] in 2022 the cumulative capacity of installed wind power worldwide amount approximately 906 GW. In that year about 92.94% (842 GW) were obtained from onshore wind farms. The world top ten countries take largest share 78.023% of the world cumulated wind power. China the country with the largest wind power installed capacity took 37.748 % of the cumulative wind power installed capacity.

Table 2.1:The top 10 countries with the largest wind energy capacity in 2021 [10]- [11]

Rank	Country	Installed Capacity (GW)	World's Share (%)
1	China	342	37.748
2	USA	139	15.342
3	Germany	64	7.064
4	India	42	4.636
5	Spain	29	3.200
6	UK	26	2.870
7	Brazil	19.1	2.108
8	France	18.7	2.064
9	Canada	14.4	1.589
10	Italy	12.7	1.402
	Total installed capacity	706.9	78.023

As indicated in Table 2.1 the top 10 countries have the largest share in cumulative wind energy installed capacity. The rest of the world accounts only 21.977% of the total cumulative installed capacity. But when it is compared to 2010; the top ten countries account 86.4% (170,290 MW) [9] reduces to 78.023% in 2021. This indicates that new countries are coming to wind turbine installation or increasing installed capacity.

2.2.2. Current Status of Wind Energy in Ethiopia

The Ethiopian electric power (EEP) has two kinds of energy supply systems. These are self-contained systems (SCS) and interconnected systems (ICS). Mini hydro powers and few diesel power generators installed in different parts of the country are SCS. Whereas, the ICS consists of hydro power plants, wind turbine generators, geothermal power plant and diesel power plants.

With a total amount of 45 GW of exploitable potential, hydropower is the dominant resource for generating electricity. The ratio of hydropower generated is enormous, with the highest ratio in 2006 of 99.69% of the total generation capacity [4]. This makes the grid system vulnerable in dry seasons. Besides the construction of new hydropower plants are becoming new geopolitical issues. But there is high wind during these dry seasons. Therefore, combining wind energy with hydropower plants adds a value the national grid.

Currently about 96.38% of the total demand is met with renewable energy sources, where hydropower alone accounts about 86.53% of the total generation. But for the future the government wants diversify the generation to reduce the dependence on hydropower. In 2030 hydro power will account 87.46% of the total generation from REs, but the contribution of the diesel (nonrenewable source) will be about 0.589% [4], [12] which implies about 99.41% will be from renewable energy sources. The contribution of each source for the total generation is summarized in Table 2.2 below.

Table 2.2:existing and future electricity generation plans of Ethiopia [4]

Type of source	Existing		2030	
	MW	%	MW	%
Thermal	149	3.17	149	0.59
Nonrenewable total	**149**	**3.17**	**149**	**0.59**
Hydro	4071.5	86.53	22000	86.94
Wind	324	6.89	2000	7.90
Geothermal	7.3	0.15	1000	3.95
Biogas	103.5	2.2	103.5	0.41

Waste to energy (repi)	50	1.06	50	0.19
Renewable total	**4556.3**	**96.83**	**25153.5**	**99.41**
Total	4705.3	100	25302.5	100

Regardless of the huge wind energy potential about 10 GW [4], the use of wind energy is at infant stage. Currently Ashegoda wind farm (phase I and phase II &III), Adama I and Adama II wind farms are active. These wind farms have 120 MW, 51 MW and 153 MW installed capacities respectively. When compared to the total potential it only accounts only about 3.24%.

Agreements have been signed for construction of wind farms at Somalia and Oromia regions. Aysha wind project is expected the largest wind farm in Ethiopia upon its completion with 300 MW capacity. Besides Assela I onshore wind farm is to be constructed 150 Km southeast of Addis Ababa with 100 MW installed capacity. Upon the completion of these two projects the wind energy production of the country will boost to 724MW.

There is a promising wind resource in the central and northern parts of the country. Accordingly, many anemometer stations at different locations were preselected such as, DebreBirhan, Nazareth, Bahir Dar, NefasMeewcha, Sululta, Ashegoda, Harena, Messobo, Bilagg, Yabelo, and Maymekden. The majority of sites lie in altitudes between 2,000 and 2,400 m, with the exception of DebreBirhan.

Though the development of wind energy is at infant stage in Ethiopia compared to the developed countries and some African countries like South Africa and Egypt [13], the increasing demand of energy, the new government policy to allow private investors on energy production, and energy related geopolitical issues (renaissance dam) may change the future energy production mix.

2.3. Basic Principle of Wind Energy Conversion System

The uneven heating of the earth creates pressure zones. Warmer air becomes less dense and moves up; cooler air moves to fill the space. The air in motion is called wind and the energy associated with the motion of air is kinetic energy. A wind turbine transforms the kinetic energy in the wind to mechanical energy in a shaft and finally into electrical energy in a generator. This extraction of wind energy uses two primary physical principles; these are through the creation of either lift or drag force (or through a combination of the two).

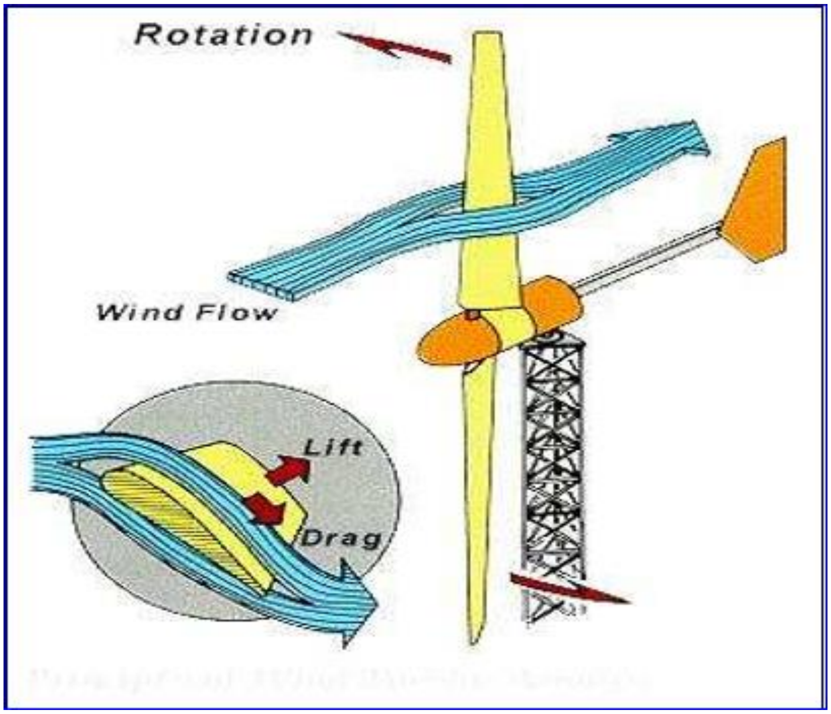

Figure 2.2:Basic principles of wind energy conversion system [3]

2.3.1. Wind Speed and Energy

Since wind is air in motion, the kinetic energy of air with mass m and speed V is given,

$$\boldsymbol{Kinetic\ energy(in\ joules) = \frac{1}{2} * m * V^2} \tag{2.1}$$

The power in moving air is the flow rate of kinetic energy per second in watts.

$$\boldsymbol{P = \frac{1}{2} * \rho * A * V^3} \tag{2.2}$$

Where, P is mechanical power in moving air (watts), ρ is air density (Kg/m^3), A rotor swept area (m^2) and, V velocity of air (m/s) [14].

Sites are compared in terms of specific wind power expressed watts per square meter of rotor swept area. This wind power per swept area is called power density and can be expressed mathematically as follow,

$$\boldsymbol{Power\ density\ of\ site = \frac{1}{2} * \rho * V^3} \tag{2.3}$$

Where, ρ and V are air density of the site and upstream wind speed respectively.

This is the power in the upstream wind, which varies linearly with the air density sweeping the blades and cubic of wind speed (V). Here it is important to keep in mind; the blades cannot extract all of the upstream wind power. Some power is left in the downstream air which that continues to move with reduced speed [14], [15].

2.3.2. Coefficient of Performance (Cp)

Wind turbines can't extract all the kinetic energy on wind into useful mechanical power. The maximum power that can be extracted from wind-by-wind turbine was published by a Germany physicist Albert Betz in 1919. In aerodynamics Betz law indicates the maximum power that can be extracted from wind independent of the design of wind turbine in open flow.

Betz used the principles of conservation of mass and momentum of air stream flowing through idealized actuator disk that extracts energy from wind stream to derive his law. The extracted power by the rotor blades is the difference between upstream and downstream wind powers [14], [15]. Mathematically, the power extracted by the blades is expressed as fraction of the upstream wind power as follows.

$$\boldsymbol{Po = \frac{1}{2} * \rho * A * V^3 * Cp} \qquad (2.4)$$

Where Po is extracted power and Cp is

$$Cp = \frac{1}{2}\left(1 + \frac{vo}{v}\right)[1 - \left(\frac{vo}{v}\right)^2]$$

Here Vo and V are the downstream and upstream wind speeds respectively.

From the above equation Cp is fraction of upstream wind power which is captured by the rotor blades. The remaining power is discharged or wasted in downstream wind. This Cp is known as the power coefficient of rotor or rotor efficiency.

According to [15], the power coefficient value depends on downstream to upstream wind speeds. The maximum value of Cp occurs when the downstream wind speed is equal to one third of upstream wind speed as shown in Figure 2.3 below. Substituting this value to Cp equation, the theoretical maximum value of Cp is found to be 0.59 or 59%. This factor is known as Betz's coefficient or Betz's limit.

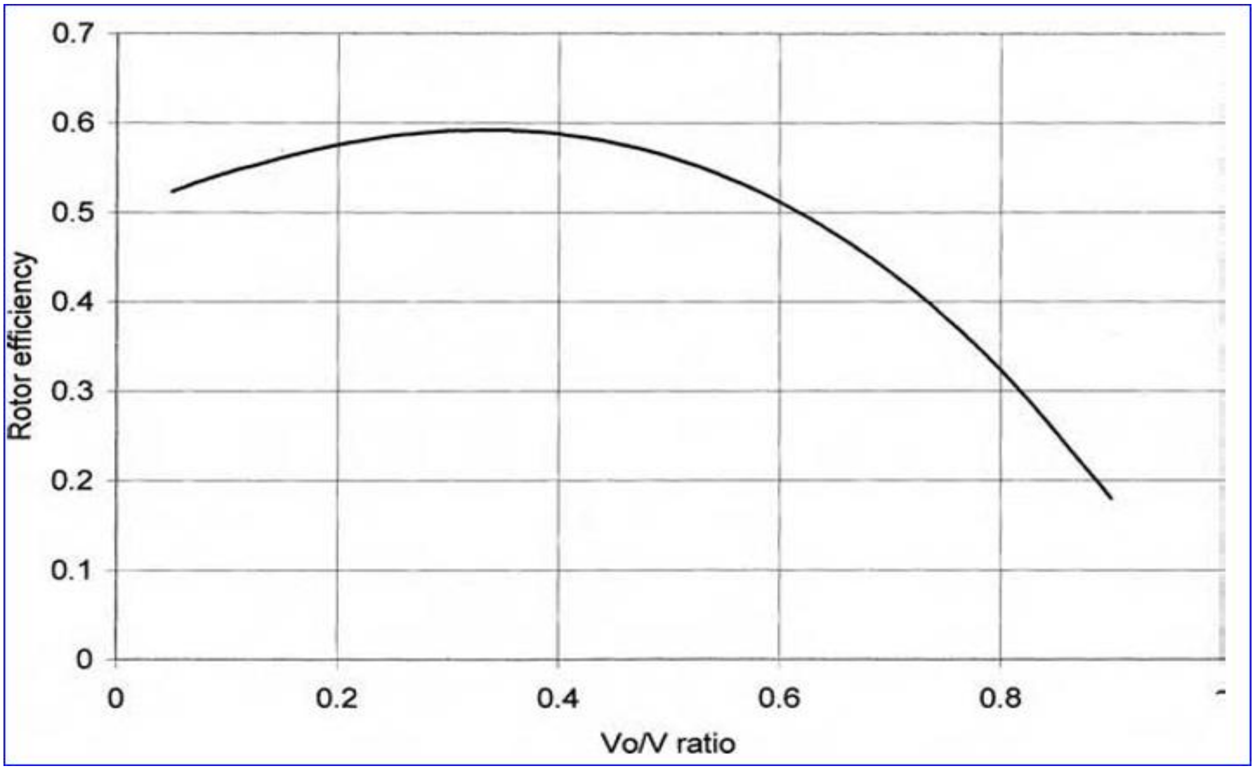

Figure 2.3:Plot of rotor efficiency Vs ratio of downstream to upstream wind speed [14]

In practical designs, the maximum achievable Cp is below 0.5 for high speed, two blade turbines, and between 0.2 and 0.4 for low speed with more blades [15]. Recent papers show that the common turbine efficiencies are 0.35-0.45 even for well-designed turbines [16]. The reason why higher, efficiency is not possible is due to the fluid mechanical nature of wind power, dependent on the continuous flow of air in motion. If, hypothetically speaking, 100% of kinetic energy was extracted, then the flow of air would be reduced to a complete stop and no velocity would remain available to sustain the flow through the energy extraction device, irrespective of the specific wind turbine technology used. The maximum extraction efficiency is achieved at the optimum balance of the largest wind slowdown that still maintains sufficiently fast flow past the turbine [17].

Turbine coefficient of performance is also nonlinear function of tip speed ratio (TSR) which is given by the symbol $\boldsymbol{\lambda}$ and pitch angle (β). Coefficient of performance Vs tip speed ratio allows predicting turbine power characteristics for any wind speed [3].

2.3.3. Wind Turbine Operating Region

The amount of electricity generated by wind turbine generators is largely determined by wind speed. Although high wind speeds generate more power, turbines are designed to operate within specific range of wind speeds. The limits of range are known as the cut in speed and cut out speed. These are determined by the manufacturer to safeguard the turbine from harm.

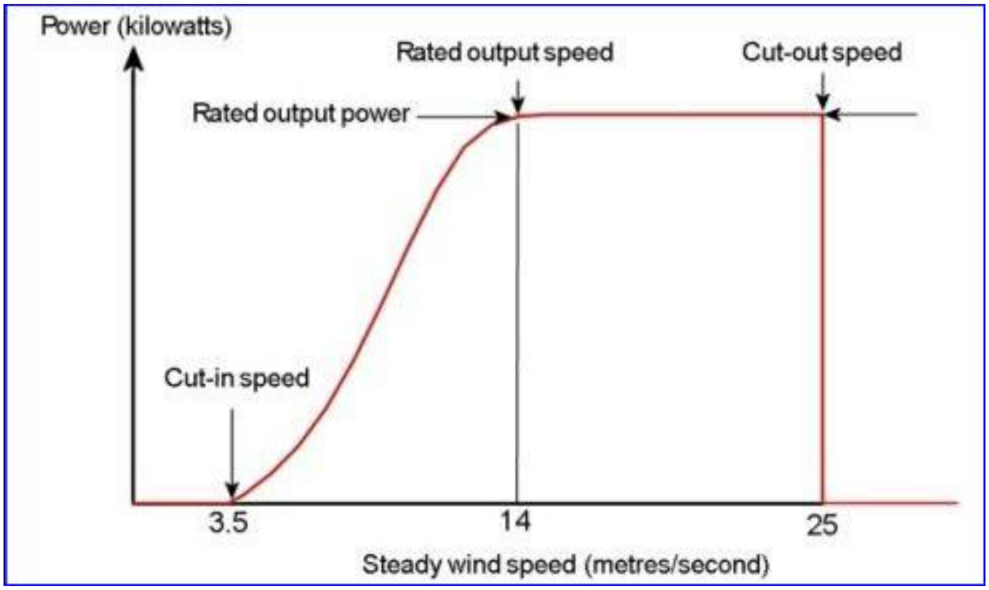

Figure 2.4:Typical wind turbine power output with steady wind speed [18]

The cut in wind speed is the point at which the wind turbine is able to generate power. Alternatively, can be defined as the minimum wind speed at which the blades turn and generate usable power. The cut in wind speed is around 3-4 m/s for most turbines as shown in Figure 2.4 [18], [19].

The minimum wind speed at which the wind turbine generates its designated rated power is called rated speed. Beyond this speed the output power of the turbine is regulated to rated power. The cubic relationship of wind speed with output power doesn't cut out the rated wind speed. Rated speed for most turbines is between 12 m/s and 17 m/s [19].

The upper speed limit for wind turbines is known as cut out wind speed. Beyond this speed most wind turbines cease power generation and shut down. This is a safety feature which protects the turbine from damage. A braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and is usually around 25 m/s [21-23]. As explained above wind turbines operate between the cut in and cut out wind speeds, and this is the operating region of wind turbines.

2.4. Wind Turbine Generator Types

Wind turbines convert the kinetic energy of wind into mechanical energy. These wind turbines can be horizontal axis wind turbines (HAWT) Vertical axis wind turbines (VAWT) depending on the direction of rotation blades. Horizontal axis wind turbines are the most common type nowadays. These turbine types can be divided as upwind and downwind horizontal axis wind turbines. In similar manner, Vertical axis wind turbines can also be classified as drag based and lift based vertical axis wind turbines.

The conversion of mechanical energy into electrical energy is done via generators which are coupled to the shaft of turbine. There are different types of wind turbine generators, the two most commonly used generators are squirrel cage induction generator and wound rotor induction generator also known as double feed induction generator (DFIG). The different wind turbine generators types are discussed below.

2.4.1. Fixed Speed Wind Turbine (Type 1)

In this type squirrel cage induction generator (SCIG) is directly connected to step up transformer. In this type of wind turbine generator, the speed is fixed (nearly fixed) to electrical grid frequency. The speed is determined by gear ratio and frequency of the supply grid, regardless of wind speed [20], [21].

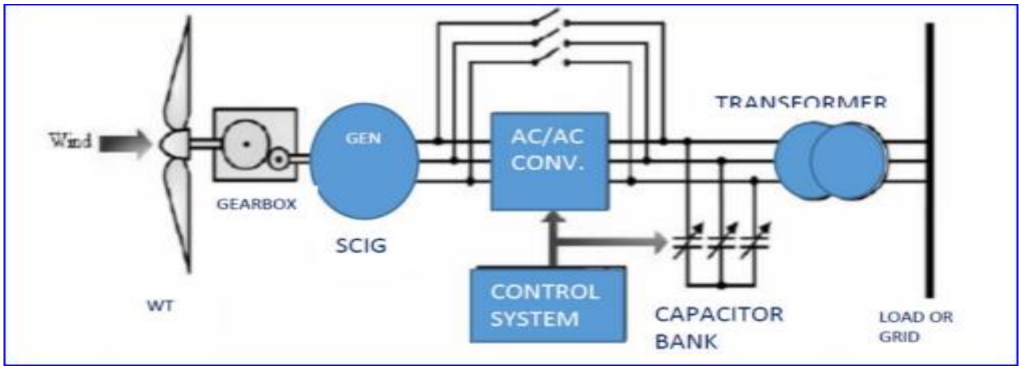

Figure 2.5:Schematic of a SCIG[20]

As shown in figure above SCIG operates completely in a minimum range of wind speeds through a gearbox. Since rotor speed variations are very small which could occur only due to changes in rotor slip, SCIG was widely considered as fixed speed topology [20]. But in some cases, it may be used for a variable speed wind energy generation with a full-scale power electronic converter. In this type of configuration external reactive power compensation and soft starters are used to support the grid [20]–[22].

Extraction of more wind power causes generator overloading, optimal wind power extraction is possible using pitch angle regulation system [20]. Some of the advantages and disadvantages of this type of configuration are;

Advantages [20]–[22]

- Mechanical simplicity and robust construction
- Low cost and maintenance
- Easy control
- Requires no brush for operation
- Rotor bars are well resistant to vibration and dirt
- Avoid short circuit power from grid (control system limits any fault current from grid side converter)

Disadvantages [20]–[22]

- Low efficiency as result of not optimal operation
- Power fluctuation caused by wind and tower pressure
- External reactive power compensation is required
- Weak capability of fault ride through (FRT)
- Two full scale converters are required for operation
- It can’t function as multi-pole direct drive mode (gearless)

2.4.2. Limited variable speed wind turbine (Type 2)

In this type of wind turbine configuration wound rotor induction generators are directly connected to step up transformer as type 1 with regard to the machine stator circuit. But here the variable resistors are softly connected to the rotor. This allows the rotor to control rotor currents to keep constant power during gusting conditions and influence the machines dynamic response during grid disturbance [22]. Soft starter and capacitor banks are used in this configuration to reduce the inrush current during generator excitation and for reactive power compensation respectively.

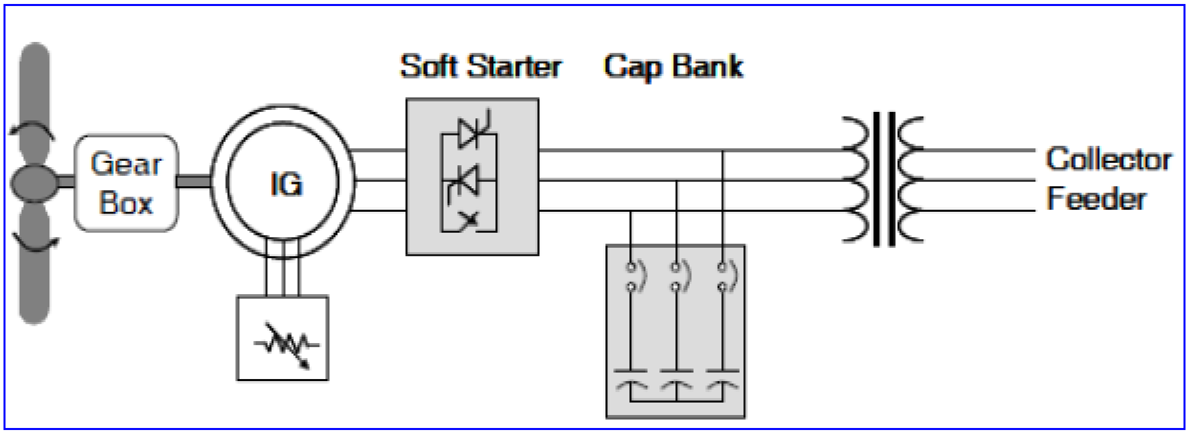

Figure 2.6:Schematic of type 2 wind turbine generator [22]

In similar manner this type of configuration has its own advantages and disadvantages;

Advantages [22]

- Limited speed variation is implemented
- Slip rings can be replaced by optical coupling

Despite the advantages mentioned above, this type wind turbine configuration has the following demerits [22].

- Speed variation range is dependent size of variable rotor resistance
- Power dissipation interms of heat in the resistor
- The need of reactive power compensation to support grid.

Both type 1 and type 2 configurations are considered as fixed speed electric machine drive system. But currently they are being replaced by the variable speed counter parts, due to their low wind energy conversion efficiencies, inflexibilities in supporting grid voltage adjustments, inevitable power flicker, and mechanical stress caused by wind gusts [21].

2.4.3. Variable Speed with Partial Power Electronics Conversion (Type 3)

This type 3 wind turbine generator configuration commonly uses double feed induction generators (DFIG). In this case the variable rotor resistance in type 2 is replaced by variable frequency AC excitation. The stator terminals are connected directly to the grid and the rotor across partially rated converter. These converters are usually variable frequency and back-to-back AC/DC/AC type. Grid side converter and rotor side converter have a DC link connection and are made of two IGBT converters. Decoupling of electrical grid frequency and mechanical rotor frequency is possible through this converter. Besides it also enables variable speed operation [20].

The rotor voltage is applied from the power converters. Control of generator parameters such as, control of active and reactive powers and harmonics is achieved through rotor side converter (RSC). The grid side converter (GSC) controls the power factor and ensures that it is high enough [20], [21].

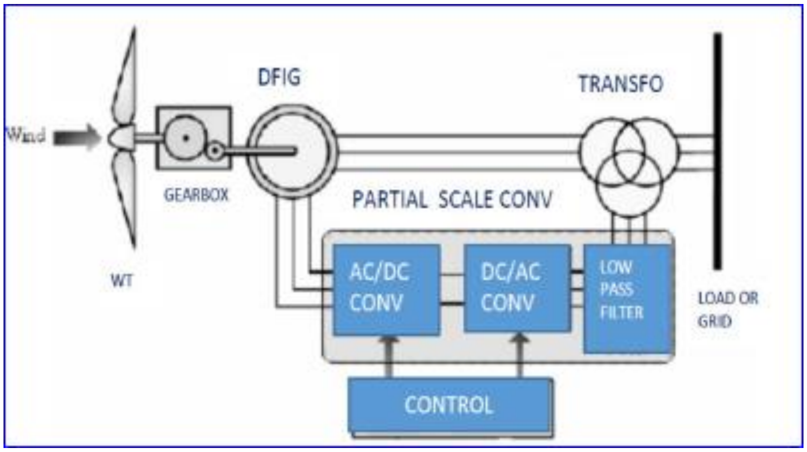

Figure 2.7:Schematic of type 3 wind turbine generator [20]

Like the other wind turbine configuration this type of configuration has also advantages and drawbacks; some of the advantages of this type includes,

- It is simpler than the other type of generators both mechanically and electrically [20].
- Converter rating is 25%-30% in DFIG as compared to 100% nominal power of generator [20], [22]
- Rugged and brushless [20]

- Has a wide range of speed variation (can reach 30% of synchronous speed) [20], [22]
- Reactive power compensation and smooth grid integration via converters [20], [22]
- High efficiency and energy yield [20], [22].

With all the above advantages this type of wind turbine generator configuration has the following limitations. Since multiple poles DFIG with low speed is not technically available, gear boxes are necessary. Difficulties associated with grid fault ride through, medium reliability, and reduced longevity due to bearings and gear faults are some of the disadvantages of this type [20].

2.4.4. Variable Speed with Full Power Electronics Conversion

In type 4 wind turbine system synchronous generator with either an electric or permanent magnet is often used. In some type 4 systems induction machines can be used, but in either cases gear box is removed. As gear box is the most expensive element and vulnerable to failure than other key components, this configuration provide major benefit. However, the elimination of gear box necessities generators with large number of poles to reduce the synchronous speed. This leads the diameter of generator to be larger than the other types making the nacelle wider in diameter [23].

Since the wind speed is variable, the frequency of the power output is also variable. As variable frequency generator can't be connected to fixed frequency grid, converter is installed between the generator and the grid to solve this problem. The converter receives variable frequency power of generator and converts it into fixed frequency needed by the grid. In this type of system, the converter is designed to handle the full power of the turbine. Thus, it is called full converter [23].

This type of design offers a great deal of flexibility in design and operation [24], it effectively decouples the generator from the grid, improving fault response, it allows the turbine to operate over wide range speed, leading to improved power extraction from the grid, since the converter handles the entire output of the generator, it provides more headroom to supply reactive power the grid, and the absence of slip rings reduces maintenance requirements. Having these advantages, handling of the entire generator output by the converter, leads to high cost of converter and more power losses are some of the disadvantages [25].

2.5. Challenges and Opportunities with Wind Energy

2.5.1. Challenges to development of wind energy

Wind is a renewable source of energy and available freely. It is obvious that it is also one of the fastest growing renewable energy sources. However, the rapid development of wind energy faces many challenges. Different literatures are available on wind energy development challenges. But the challenges can be generally categorized as social, environmental and techno-economic challenges.

In July 2017, Apunda and Nyangoye [26] have published research article on challenges and opportunities of wind energy technology. The authors reviewed and critically analyzed the studies from different authors and identified the environmental impact (damage to birds and bats and loss of habitat) and intermittent nature of wind as challenges. In the same year authors, [27] in South Africa identified the slowing down implementation of renewable energy technologies were due to technical, socio-economic and environmental challenges. In this paper the ratio between technology size and power output, the improvement of Betz criterion which limit wind energy extraction to 59%, provision of accurate measurements to predict wind condition, production and availability of spare parts for effective maintenance and lower life time of wind energy technologies than that of other renewable energy and fuel fired technologies are pointed out as the technical challenges. Besides the need of extensive and suitable lands for turbine erection can also be considered as environmental and social challenge.

In 2017, Shyam.B and Kanakasabapathy P. [28] presented conference paper in IEEE International Conference on Technological Advancements in Power and Energy (TAP Energy) and categorized renewable energy development challenges in to four categories.

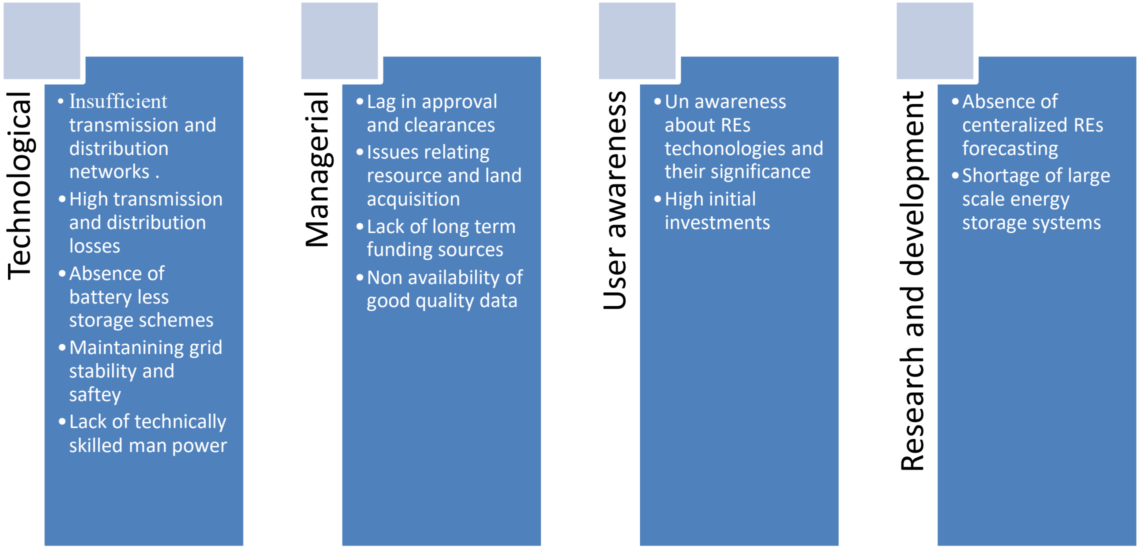

Figure 2.8:Challenges of REs developments

In 2016, Agarwal and Verma [29] have examined regulatory challenges and issues faced in promoting wind energy power plants which includes social, environmental and techno-economic. In this paper design issue, location issues (require large area), grid connection issue which are related technical issues have been critically reviewed. Proper design of wind turbines with respect to blade loading and aerodynamic stability is one of the most important challenges. Since wind farms are located in rural area generation of wind with respect to grid faced two main problems. Limitation of grid infrastructure and issues related to grid integration of wind energy such as voltage fluctuations, significant power losses, uncontrollable reactive power and low power factor, power fluctuation and voltage distortion are identified as technical challenges. The authors tried to incorporate the environmental issues of wind turbines such as, impacts on wild life (direct and indirect), noise impact (aerodynamic type and mechanical type) and visual impact (mainly influenced by shape, color and layout of wind turbines). Finally, the economic challenges such as high capital investment and high production costs also impose burden to rapid expansion wind energy.

2.5.2. Opportunities of Wind energy

Despite the forementioned challenges, harnessing of wind energy is showing fast growth in the last decades. The expansion and harnessing of wind energy come with new opportunities to local communities, energy producers, utilities and to nations in general. Since wind is clean source of energy, it has no direct gaseous emission into the environment; it helps in mitigation of climate change. In addition to environmental benefits, wind energy increases employment opportunities, economic boost, and cost effectiveness can be considered as economic advantages. Finally, the ability of wind turbines to work in different settings is also another opportunity [26]–[30].

2.6. Weibull Distribution in Wind Energy

One method of determining the power producing ability of wind turbine is to test its operation with standard wind speed distribution. Commonly used distributions are the Weibull and Rayleigh distributions. The Weibull distribution is commonly used to model the probability distribution of wind speeds or wind power densities at a particular location over a period of time. It is a generalized gamma distribution whereas, Rayleigh distribution is a special condition of Weibull distribution. Even though, Weibull is more flexible than Rayleigh distribution due to the fact that it allows more parameter adjustment, but the price is more complicated. It is often suggested for use when estimating the cost of energy. For generic wind study, where the variance is directly tied to mean, it is more practical to use Rayleigh distribution. Thus, Rayleigh distribution makes a reasonable estimation of actual wind distributions [31].

Designing, installation and operation of wind energy depends on the availability of resources. Therefore, careful assessment and estimation of wind potential become essential for any wind power operation. Therefore, several wind power density determination models have been developed such as the Rayleigh model, Normal, Log Normal, Truncated Normal, Logistic, Log Logistic, Generalized Extreme Value, Nakagami, Inverse Gaussian, Inverse Weibull and Weibull [32]. According to the authors of the paper among these models, Weibull distribution has been found the most appropriate and widely acceptable to statistically assess wind behavior and potential in any site.

Weibull distribution is characterized by two parameters namely, shape factor (k) and scale factor (c). These parameters are used to describe the variation of wind data over time and location. Weibull probability distribution function (pdf) is used to depict the fluctuation in wind speed during any time interval using these two parameters [33].

$$\boldsymbol{f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right), k > 0, v > 0, c > 1} \tag{2.5}$$

where c represents the scale parameter (m/s) and k represents the shape parameter.

In the context of wind energy, the shape factor (k) determines the shape of probability density function of wind speeds. It indicates whether the wind speed distribution is more skewed towards lower speeds (k< 1), more uniform (k ≈ 1), or skewed towards higher speeds (k > 1). A higher value of k suggest that the location has more frequent occurrence of high wind speeds, which is important for assessing the potential of wind energy yield of wind turbines [32], [33]. Most sites have typical wind distribution at k=2 [33].

Another important function is cumulative distribution function, which is obtained by integration of the Weibull probability distribution function (pdf). It is the cumulative of relative frequency of each speed interval. The corresponding cumulative distribution function of the Weibull distribution is given by [33],

$$\boldsymbol{F(v) = \int_{0}^{V} f(V)dv = 1 - exp - \left(\frac{v}{c}\right)^{k}} \tag{2.6}$$

2.7. SPSS Statistics Software

SPSS stands for statistical package for social sciences, is a comprehensive system for data analysis. The SPSS package includes a number of software programs for data entry, management, statistical analysis, and presentation. SPSS combines complex data and file administration with statistical analysis and reporting tasks. SPSS can produce tabular reports, charts and maps of distributions and trends, descriptive statistics, and sophisticated statistical analyses [34], [35]. In this paper SSPS software and Excel are used to organize and analyze wind speed data, downtime, annual energy production and other datasets that need analysis.

2.8. Review of Related Literature

Different researches have been conducted on performance analysis, assessment and evaluation of wind farms. In this part the most relevant and related previous works are reviewed and research gaps are identified.

Levelised cost of energy (LCOE) which can be defined as the net present value of the cost to produce a unit of energy, is a common metric used to describe wind farm performance. Hence, researchers Dao C. et al [36] have systematically reviewed reliability data of both onshore and offshore wind turbines and investigated its impact on cost of energy. Failure rates and down times of over 18,000 wind turbines were considered for a comprehensive analysis to investigate WT subassembly reliability data variations, identify critical subassemblies', compare offshore and onshore WT reliability, and understand possible sources of uncertainty. Based on the model presented by the authors to evaluate the levelised cost of energy as function of failure rates and downtimes there is a strong nonlinear relationship between wind turbine reliability and operation and maintenance expenditure as well as annual energy production.

Pfaffel S. et al [37] have systematically reviewed performance and reliability of wind turbines. Performance (availability and yield) and reliability of wind turbines make a difference between success and failure of wind farm projects. In this paper performance and reliability data of onshore and offshore wind farm have been collected from different Journals and conference papers. Taking the results of various initiatives, the results have been harmonized. Different reliability and key performance indicators are reviewed. Capacity factor, time-based availability, technical availability, energetic availability, failure rate, mean down time are used to compare the performance and reliability of different initiatives. Here subassembly and component wise reliability comparisons have been made. Accordingly, electrical components are found to cause more failures but lower down times whereas, the drive train has the largest share of down time despite its lower failure rate.

He Y. and Kusiak A. [38] have also presented a two phase approach for performance evaluation of wind turbines for past and future time intervals. In this approach of data derived quantitative metrics historical wind turbine data is used to determine the past performance of the wind turbine. While the performance of wind turbines at future time horizon needs a call for power prediction. In the first phase (phase I) of this approach wind power is predicted using an ensemble of extreme learning machines (ELM). To do this the parameters wind speed, wind temperature and rotor speed are considered. In the second phase (Phase II) Copula model is constructed using the predicted power. To evaluate the effectiveness of the proposed approach five parametric models have been tested and the Frank Copula model performs best for performance evaluation of wind turbines.

The performance of wind turbines can be estimated from annual energy generation and annual average power which varies with wind speed and distribution. In 2017, Kumar R. and Rao K.V.S [39] have analyzed the performance of 2.1 MW wind turbine at Jaisalmer district of Rajasthan. The authors considered a wind farm with 49 turbines each rated 2.1 MW. Based on one-year available data of wind turbine machine availability, grid availability, system availability and energy production were obtained. Then the annual capacity factor of the wind turbine is calculated and total energy production is estimated. In this paper the authors found the grid availability to be higher than machine availability. In the same year the authors [40] also analyzed 7.2 MW wind farm consisting of 12 wind turbines each 600 KW in Sikar town of Rajasthan. They analyzed two years (2014-2016) data of monthly energy production, wind turbine downtime hours and external/internal grid non-availability in hours. Based on the analysis they were able to calculate machine availability, grid availability, system availability, annual usage time and capacity factor. Finally, it was noticed that the energy production of machines can be improved by increasing system availability. In a similar manner, authors [41] have also studied 2.25 MW wind farm at other district of Rajasthan in 2013. On this paper published on IEEE energy production, capacity factor, machine availability and system availability were considered for analysis. They used 2011-2012 data of the three wind turbines installed at the site for calculation. Based on the study the grid availability was found lower than machine availability except for few months. They conclude that, performance of wind farm can be further enhanced by improving grid and machine availability of wind turbines.

Spinato F. et al [42] have investigated the reliability of over 6000 modern onshore wind turbines and their subassemblies in Germany and Denmark. The investigation started by considering the average failure rate of turbine populations. Next, failure rate of turbine subassemblies was considered. Variation of failure intensity function of three subassemblies; generator, gearbox and converter are also considered using power law process. Analysis results show that gearboxes possess reliabilities similar to gearbox outside of wind industry however, wind turbine generators and converters achieve reliability below that of other industries. Hence, early focus should be on generators and converter. Authors in [43] have also made survey of failures in wind power plants. In their paper, they presented results from investigation of failure statistics from four sources. When the reliability of different wind turbine components was compared gearbox were found to be more critical due to high downtime per failure.

Performance of operating wind farms have been evaluated via the use of SCADA and modeled data. The potential annual energy was calculated per individual turbine considering underperforming or loss events to have their power output in accordance with a representative derived operational power curve. Underperformance events have been calculated and categorized. Finally a number of optimization measures are suggested in order to enhance the performance, which can lead to a boost in the financial output of a wind farm [44].

Some researchers have also conducted researches since the development of wind turbine and wind energy technologies regarding the performance and reliability improvements.

Research has shown the present maintenance of both onshore and offshore installations is not optimized. By optimizing maintenance decisions over the life time large potential cost savings can be made. To improve reliability of wind turbines Fischer K. et al [45] come up with the concept of reliability centered maintenance (RCM) applied two wind turbine models. Here wind turbine owners and operators, maintenance service provider, a provider of condition monitoring services, and wind turbine component supplier as well as researchers at Academica have been involved. The analysis focuses on the most critical subsystems with respect to failure frequency and consequences; the gearbox, generator, electrical system and hydraulic system. Most relevant functional failures, their causes, mechanisms, and remedial measures to prevent the failure itself or critical secondary damage has been provided in this paper. Based on the study both the frequency and quality of service maintenance have found significant impact on technical condition failure rate of wind turbines.

As part of Operation and maintenance (O&M) cost minimization and improving downtime Byon E. and Ding Y. [46] developed models for devising optimal maintenance strategies. The strategy called season dependent condition-based maintenance was developed using partially observed Markov decision process (POMDP) with heterogenous parameters. The model is solved using backward dynamic programming, producing dynamic strategy. When compared with fixed, scheduled maintenance and static strategy this model achieves considerable improvements in both reliability and cost. Another attempt by Nilsson J. and Bertling L. [47] introduced condition monitoring system (CMS) to resolve the growing wind turbine need for better maintenance management and increased reliability.

All the above related literatures are done on different countries and case studies. There are also some literatures on Ashegoda wind farm integration impacts. Erlich L. et al [48] dealt with impact of integration of Ashegoda wind farm on transient stability and other operational indices of the power system. Initially, generic wind turbine model used to study the impact of large-scale wind penetration. Using this model voltage and power at point of common coupling as well as the swing curve of conventional synchronous generators following a major grid fault were computed. The next step was to determine critical fault clearing times and to compare with one another involving different levels of wind integration. Based on the study, the wind farm in remote part of the Ethiopia grid has positive effects. The voltage profile of the network due to its remoteness from the grid achieves voltage control capability without installation of active voltage control device.

Numerous studies have been conducted globally on wind turbine performance and reliability evaluation. These works have largely focused on assessing the reliability of individual components, identifying critical failure points, and suggesting potential reliability improvement measures. While some authors have combined performance and reliability assessments, most research has been limited to specific geographic contexts primarily in countries with large-scale wind integration and advanced grid systems.

In contrast, mitigation strategies addressing performance issues have often been discussed separately and without direct linkage to real-time operational assessments. Furthermore, the majority of studies emphasize methodologies and metrics for performance evaluation, with only limited attention to holistic or site-specific mitigation measures, especially in developing regions.

In the Ethiopian context, several studies have examined the integration of the Ashegoda wind farm into the national grid. These works primarily focus on the grid's steady-state and dynamic stability following wind farm integration. While these studies contribute valuable insights into grid performance and reliability challenges, they do not assess the operational performance of the wind farm itself, nor do they propose targeted mitigation strategies for underperformance or failure modes.

This thesis aims to bridge these gaps by conducting a comprehensive performance assessment of the Ashegoda wind farm, identifying critical operational limitations, and proposing practical and site-specific mitigation measures. Given the unique challenges of Ethiopia's northern weak grid, the findings will contribute to more effective wind power operation and reliability enhancement strategies in similar developing power systems.

CHAPTER THREE

3. PERFORMANCE EVALUATION OF ASHEGODA WIND FARM

3.1. Data collection

On this stage important information are collected from wind farm office and other offices as needed for detail assessment and investigation to come up with clear solution to the problem at hand.

After site visit and observation, all the data which are necessary for the case under study are collected first based on the scientific data collection techniques/tools. Following a careful observation and understanding of the wind farm layout and structure; quarter hourly wind speed, daily availability data, daily generation, tripping events, line parameter, transformer parameter and turbine status data are collected on daily basis. The data collected are from July 2015 to first week of May 2019, after which the SCADA system of the wind farm failed to operate. The SCADA system of the wind farm, maintenance log books, wind farm office documents and literatures on the wind farm are used to gather the necessary data. In general turbine power curves, quarter hourly wind speed of four years, turbine stop daily downtime hours due failure, maintenance and low wind speed, site condition and grid related issues which are necessary for the purpose of this study are collected and reviewed carefully. The years considered start from July moth to June in each year of study.

3.2. Description of Study Site and Key Parameters

Ashegoda wind power plant is one of the operational wind power plants in Ethiopian which is located 720 Km far from Addis Ababa and 20 Km away from Mekelle. It is located at 13° 25' 16.8" N and 39° 34' 20.7" E latitude and longitude respectively. The area where the wind turbines are suited is covered with small bushes and grasses. It is mainly used for animal farming and agricultural purpose. The wind farm consists of three phases. Phase I 30 GEV HP type squirrel cage induction generators each 1 MW and phase II & III also have 54 ECO-74 double fed induction generator wind turbine type each rated 1.67 MW. The total installed capacity of the wind farm is 120 MW. The detail of wind turbine generator and site parameters are summarized in table below.

Table 3.1:Site and wind turbine generator parameters

	Phase I	Phase II & III
Total installed capacity	30 MW	90 MW
Number of WECs	30	54
Wind turbine type	GEV HP – 62/1000	ECO-74
Generator type	SCIG	DFIG
Rotor diameter	62 m	74 m
Number of blades	2	3
Hub height	70 m	80 m
Cut-in/Cut-out wind speed	3/25 m/s	4/25 m/s
Rated wind speed	15 m/s	14 m/s
Rotor speed	9.2-22.5 RPM	10-19 RPM
Gear ratio	67	94
Air density of the site	0.922 Kg/m3	0.925 Kg/m3
Temperature of the site	15.5°C	15.5°C

In phase I the generator terminal voltage is 690 V, and each wind turbine generator is connected to 1.25 MVA unit transformer that steps up the generator terminal voltage to medium voltage level of 33 KV and are collected in 4 sub-clusters. Each feeder containing from 5 to 13 wind turbine generators, the turbines within a cluster are connected to one another through underground cables. Each cluster is connected central substation using 3 Km, 33 KV ACSR overhead transmission line. In similar manner, in phase II & III the output voltage is stepped-up using unit transformer and collected via underground cables and transmitted to main substation. After transmitted using overhead lines to the central substation, it is stepped-up by two 65 MVA, 33 KV/230 KV power transformers. The wind farm is connected to grid via two outgoing 230 KV overhead lines at two locations, one at Mekelle substation at distance of 20 Km and another at Alamata substation, which is 120 Km away from the wind farm.

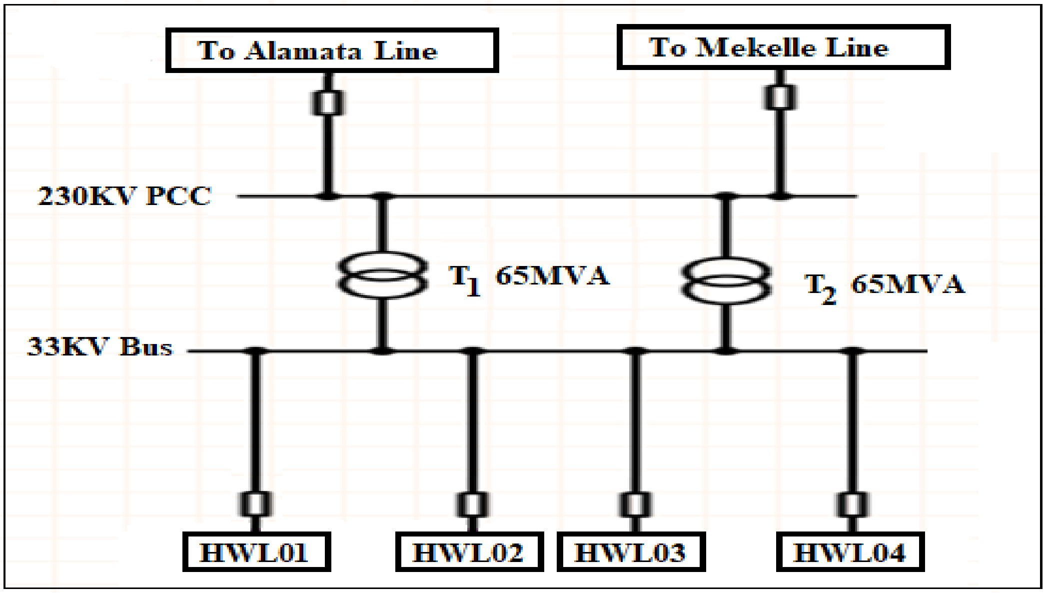

Figure 3.1:Single line diagram of Ashegoda wind farm

3.3. Wind Resource Data Analysis

The output energy of wind farms is highly affected by wind speed as it has cubic relationships. Hence, appropriate resource assessment techniques should be used accurately to minimize the uncertainty. Wind resources data from SCADA system of the wind farm measured at respective hub height with anemometers is collected from wind farm office. Even though most of the wind speed data of four fiscal years are collected from SCADA of the wind farm, some missing data's need to be determined. The missing values calculated using statistical techniques are indicated * (asterisk) symbol in Appendix tables (Table A.1 -A.4).

3.3.1. Model Identification and Parameter Estimation

Wind speed data collection faces several problems such as failure of data observing device. Therefore, wind speed data naturally contains missing values. Finding missing values in wind speed data requires an imputation technique that accurately estimates the missing values while preserving the statistical properties of the dataset. The best method depends on nature of the data (whether it has trends, seasonality, or randomness).

Forecasting is the prediction of the future value based on the observed past data with the model developed. Generally, physical and statistical time series analysis are the two commonly used techniques in wind power forecasting [2]. Physical model considers numerical weather prediction, detailed condition of wind farm and surrounding terrain. In statistical time series analysis data observed over a period of time are used for analysis. In this thesis to fill the missing values of wind speed observed over a period of years, statistical time series analysis is used.

Statistical time series analysis includes Auto-Regressive Moving Average (ARMA), Artificial Neural Network (ANN), Fuzzy Logic, Kalman Filter and so on. The best statistical technique for predicting the next wind speed, given previous values depend on characteristics of data and specific goals of analysis. The most commonly used techniques are [49]–[56]:

3.3.1.1. Linear Interpolation

This is the simplest method that is used for estimating the value of function between any two known values. Basically, the interpolation method is used for finding new values for any function using the set of values. If Y_1, Y_2, $Y_3 \ldots Y_n$ are observed data over a period of time X_1, X_2, $X_3 \ldots X_n$ respectively. Any variable Y between the observed values let Y_1 and Y_2 is given by;

$$\mathbf{Y = Y1 + (X - X1) * \left(\frac{Y2 - Y1}{X2 - X1}\right)} \tag{3.1}$$

Linear interpolation estimates missing values by linearly interpolating between known data points. It is simple and fast, works well for small gaps and data with no significant variability or seasonality. Hence this is good for datasets with short, scattered missing intervals. But this method fails if the data has non-linear trends or seasonality.

3.3.1.2. Polynomial Interpolation

Fits a higher-order polynomial or spline curve to the data and estimates missing values. This a method of finding a polynomial function that fits a set of data points exactly. There are several methods for finding this polynomial such as, Lagrange polynomial, Newton interpolation and Cubic splines. The general expression of polynomial interpolation is given by;

$$\boldsymbol{Y = a0 + a1X1 + a2X2 + \cdots + anX^n} \tag{3.2}$$

Where,

n is the degree of polynomial

a_0, a_1, a_2…, and a_n are constants/coefficients to be determined from the observed datasets.

The advantage of polynomial interpolation is the ability to capture non-linear patterns than linear interpolation. This model best suits when wind speed data exhibits smooth but non-linear trends.

3.3.1.3. Moving Average (MA)

The concept in MA model is replacing missing values with the average of neighboring data points. One way of modifying the influence of all past data is to specify how many past values will be included in the mean. The central idea behind this is the future is affected by only recent past i.e. the mean is calculated using only k latest observations from the total n observations. If the value to be forecasted at time t+1 is F_{t+1} the expression in moving average of order K, MA(K) is given by;

$$\boldsymbol{Ft+1=\frac{1}{k}\sum_{i=t-k+1}^{t}Yi} \qquad (3.3)$$

In this approach as new data are becoming available, the oldest observation is dropped and the latest is included. Generally, the greater the value of k, the greater the smoothing effect. This method is simple and effective for short term gaps in stable data. Therefore, it is used when the data is relatively stable and lacks significant volatility. But this method losses accuracy if large gaps or sharp changes are present.

3.3.1.4. Time Series Modeling (ARIMA/SARIMA)

These time series models are used to predict missing/future values using patterns in previous and future data points. The ARIMA (Autoregressive Integrated Moving Average) model is a popular statistical method for time series forecasting. It is characterized by three parameters: **p**, **d**, and **q**, which define the structure of the model.

p (Autoregressive order): refers to the number of lag observations (past values) included in the model. It captures the relationship between the current and its past values. Another parameter is d (differencing order) refer to the number of times the data needs to be differenced to make it stationary (removing trends or seasonality). The moving average order (q) refers to the number of lagged forecast errors used to model the time series. Generally, it is expressed as ARIMA (p, d, q). This model can be used for stationary data with no seasonality but requires careful parameter tuning and may struggle with large gaps.

SARIMA is seasonal ARIMA model is a time series forecasting method that accounts for seasonality. This model contains non-seasonal (p, d, q) and seasonal (P, D, Q, s) parameters. The non-seasonal parameters are the same as ARIMA parameters but the seasonal parameters represent:

P: seasonal autoregressive order, D: seasonal differencing order, Q: seasonal moving average order and s: seasonal period. Though this model is good for accounting seasonal patterns it difficult in handling large gaps. It is expressed as SARIMA (p, d, q, P, D, Q, s).

3.3.1.5. Kalman Filter

It is a recursive algorithm that uses a series of measurements (with noise) to estimate the state of a system, filling missing data points. It is used for dynamic datasets with white noise or abrupt changes. It is good since dynamically adapts to changing patterns in data and incorporates uncertainty into estimation process. But it is very complex to implement.

3.3.1.6. Machine Learning Models

Nowadays machine learning models are becoming common. In this modeling procedure, non-missing data points are used to train a model to predict missing values based on other features. This type of modeling used for multidimensional datasets with correlated variables. It handles complex, non-linear relationships and can use other variables for imputation. The main limitation for use of machine learning models like Random Forests, K-Nearest Neighbors (K-NN) and Neural networks is, it requires sufficient training data and computational power.

3.3.1.7. Fourier Transform or Spectral Interpolation

Fourier transform or Spectral interpolation uses the frequency domain to model periodic components and estimating missing values. This method is effective for data with strong periodicity. For wind speed data with seasonal or cyclic patterns it is good but requires clear periodic signals.

Generally, depending the nature and extent of missing data the following strategies can be used to address the issue.

1. **For short missing data (small gaps)**
   a. Linear interpolation:
   b. Spline interpolation:
   c. Moving average: Use average of the previous and subsequent days (or wider window, ±3 days) to fill the gap.
   d. Seasonal adjustment: If the data exhibits daily, monthly or seasonal pattern, using averages for the corresponding period (e.g., average wind speed for the same day across multiple years).
2. **Large missing data (Large gaps)**

When entire months of data are missing, more advanced methods may be required:

a. Use of data from similar periods: If the wind speed has a seasonal trend, estimate missing values using data from the same months in the other years.
b. Regression models:
c. Machine learning models
d. Leave it as missing: If the missing data represents small proportion of total dataset and its imputation may introduce bias, leaving it as missing and use algorithms or analysis that can handle missing data directly.

Based on the forementioned reasons in this paper Moving Average order K, MA (K) is used for filling small gaps. Since, the non-missing datasets collected from the farm office show a seasonal trend missing values of larger gaps greater than three days are filled using average data from similar periods.

3.3.2. Forecast/ model accuracy

Forecast accuracy is the measure how close forecasts are to actual outcomes. Accuracy is the overriding criterion for selecting a particular forecast model. If Yt is the observed value at time t and Ft is the forecast value for the period t, the error is defined by:

$$\boldsymbol{et = Yt - Ft} \qquad (3.4)$$

The accuracy of method is evaluated using some standard statistical measures such as, Mean Error (ME), Mean Absolute Error (MAE), Mean Squared Error (MSE), Percentage Error (PE), Mean Percentage Error (MPE), and Mean Absolute Percentage Error (MAPE).

Mean Error: is the average of the differences between predicted and actual values. Even though the positive and negative errors can cancel out masking the true error magnitude small, this type of error can be helpful for understanding bias i.e. whether the predictions tend to overestimate or underestimate.

$$\mathrm{ME} = \frac{1}{\mathrm{n}} \sum_{\mathrm{t}=1}^{\mathrm{n}} \mathrm{et} \qquad (3.4.1)$$

Mean Absolute Error: The average of the absolute differences between predicted and actual values. This measures the average magnitude of errors without considering their direction. But this does not highlight larger deviations as much as squared errors, since it treats all errors equally.

$$\mathrm{MAE} = \frac{1}{\mathrm{n}} \sum_{\mathrm{t}=1}^{\mathrm{n}} |\mathrm{et}| \qquad (3.4.2)$$

Mean Squared Error: It is defined as the average of squared differences between predicted and actual values. Penalizing large errors more heavily, useful when large errors are particularly undesirable.

$$\mathrm{MSE} = \frac{1}{\mathrm{n}} \sum_{\mathrm{t}=1}^{\mathrm{n}} \mathrm{et}^2 \qquad (3.4.3)$$

Percentage Error: This error is defined as the percentage difference between predicted and actual values for each data point. It is best for understanding relative error on an individual bias. If actual values are small, it can be misleading by resulting very high percentages.

$$PEt = \left(\frac{Yt-Ft}{Yt}\right) * 100\% \qquad (3.4.4)$$

Mean Percentage Error: It is the average of percentage errors. It is helpful for understanding overall trend in percentage terms, but like mean errors positive and negative values can cancel each other out.

$$\mathrm{MPE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{t}=1}^{\mathrm{n}} \mathrm{PEt} \tag{3.4.5}$$

Mean Absolute Percentage Error: It is the average of absolute percentage errors. Can be good for comparing prediction accuracy across different scales of data.

$$\mathrm{MAPE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{t}=1}^{\mathrm{n}} |\mathrm{PEt}| \tag{3.4.6}$$

In general, MAE and MAPE are commonly used for interpretability, while MSE is preferred in machine learning optimization when larger errors need more weight. In this thesis MAE is used to check the accuracy of the model used to predict the missing values.

3.3.3. Weibull Distribution

Weibull distribution is important for estimating the annual energy output of wind farms. As discusses in section 2.6, Weibull distribution is characterized by two parameters namely, shape factor (K) and scale factor (C). These parameters regulate the wind speed distribution for optimum performance of wind energy conversion system. Therefore, it is very essential to accurately estimate the parameters. The methods used for estimating the Weibull parameters can be categorized as graphical and analytical methods. Graphical methods (Weibull probability plotting and Hazard plotting techniques) are easy and fast but involve great probability error.

Analytical methods are preferred due to high probability of error in graphical methods. Maximum Likelihood Method (MLM), Least Square Method (LSM), Standard Deviation Method (SDM), Energy Pattern Factor Method (EPFM), Moment Method (MM), Power Density Method (PDM) are some of the analytical methods used for Weibull parameter estimation. Out of these methods Maximum Likelihood Method (MLM), is the most widely used technique as it has many large sample properties that make it attractive for use [57], [58].

Mathematically, the simplified expression of Weibull shape factor (K) can be written using Maximum Likelihood method-iterative method as follows.

$$\boldsymbol{K} = \left(\frac{\sum_{i=1}^{n} Vi^{k} * \ln(Vi)}{\sum_{i=1}^{n} Vi^{k}} - \frac{\sum_{i=1}^{n} \ln(Vi)}{n}\right)^{-1} \tag{3.5}$$

Here, n is random sample size and Vi is the wind speed at instant(time) i. The value of the shape parameter can be obtained by solving this equation iteratively.

Once (K) is determined, the scale parameter C can be estimated using equation (3.6) as follows.

$$C = \left(\frac{\sum_{i=1}^{n} Vi^{k}}{n}\right)^{1/K} \tag{3.6}$$

Now, the Weibull probability distribution function (pdf) is used to depict the fluctuation in wind speed during any time interval using these two parameters [33].

$$\mathbf{f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right), k > 0, v > 0, c > 1} \tag{3.7}$$

3.4. Annual Energy Production

A wind turbine's AEP is the total amount of its electrical energy expected to be produced over one year, expressed in MWh or GWh. Adding the AEP of all individual wind turbines results in the total AEP of a wind farm. To estimate annual energy production of wind farm, wind resource data (wind speed distribution and air density), wind turbine characteristics (power curve, rated wind speed, cut-in and cut-out wind speeds), wind farm layout (number of turbines, turbine spacing and orientation), turbine availability and losses are required. Here are the steps used for annual energy estimation:

Step 1: Compute the probability distribution

Weibull parameters can used to determine Annual Energy Production (AEP) of a wind farm. However, it is not necessary to compute Weibull parameters if high resolution daily wind speed data are available. Hence, in this thesis direct method of determining probability distribution are used. The daily wind speed data are analyzed using excel to determine the frequency of occurrence a certain wind speed (V_i) and the probability of wind speed $f(V_i)$.

Step 2: Combine wind speed and wind turbine power curve

Each wind speed is mapped to corresponding power output of the wind turbine from the power curve. In this case study i.e. Ashegoda wind farm, there are two types of wind turbines as discussed in earlier sections. The power curve (table) of GEV HP-62/1000 and ECO-74 of the wind turbines are taken from the contractor unpublished documents in Ashegoda wind farm office. The power curve tables are for nominal power of 1000 KW, 1.225 Kg/m^3, class III and 62 m rotor diameter in phase I of the wind farm and nominal power of 1670 KW, 1.225 Kg/m^3, class II and 74 m rotor diameter in phase II and III of the wind farm [59]. See Table B.1 and Table B.2

Step 3: Calculating Annual Energy Production (AEP)

The annual energy production of a wind turbine can be computed using equation (3.8)

$$\mathbf{AEP} = \sum (\mathbf{P(Vi)} * \mathbf{f(Vi)} * \mathbf{8760}) \qquad (3.8)$$

Where,

P(V_i) is the power at wind speed V_i, f(V_i) is the probability of wind speed V_i and 8760 is the total number of hours in a year.

Step 4: Account for Air density

Correct the power curve for actual air density at the site using:

$$\boldsymbol{AEPcorrected} = \boldsymbol{AEP}\left(\frac{\boldsymbol{\rho\ site}}{\boldsymbol{\rho\ standard}}\right) \qquad (3.9)$$

Where, ρ site is the actual air density in the site and ρ standard is the standard air density at sea level which is 1.225 Kg/m^3.

Step 5: Determine the net annual energy production by accounting the losses

The net annual production is obtained by subtracting the energy loss from the gross annual production. The energy loss could be due unavailabilities, electrical losses, maintenance stops, grid failures, uncertainties, and any other effects leading to production losses. Since it is not possible to predict wind right, energy yield assessment studies are performed by wind experts to provide net energy yield and exceedance probability figures to mitigate that risk. The net yield figure derives from gross yield, after taking into consideration the losses. According to the latest forecasting trends and best practice the following losses could be considered. Wake loss, turbine availability and maintenance losses, grid and balance of plant (BOP) availability, electrical losses, site conditions, blade degradation and curtailment plans are some of the losses.

To consider the uncertainty and losses P50, P75 and P90 probabilistic figures can be used. These are probabilistic estimates used in wind energy production forecast to account for uncertainty. P50, is the median estimate which state's there is a 50% probability that the actual energy production will above this value and 50% probability it will be below that value. P75 is also another probabilistic figure, there is a 75% probability that the actual production will exceed this value. The third common figure is P90, there is a 90% probability that the actual production will exceed this value. P90 or P75 figures are recommended depending on the quality of energy yield assessment but are more conservatives. Z-score is used to measure how many standard deviations ($\boldsymbol{\sigma}$) a value is from the mean in a normal distribution. The Z-score values used for P75 and P90 in net annual energy estimation are -0.67 and -1.28 respectively.

$$\boldsymbol{Net\ P50 = GEP(1 - Loss)} \qquad (3.10)$$

Where, GEP is gross energy production, Loss is percentage of loss and $\boldsymbol{\sigma}$ is standard deviation.

After computing P50, then P75 and P90 can be computed using equation below.

$$\boldsymbol{P75 = P50 + (z * \sigma)} \qquad (3.11)$$

The same equation is used to compute P90 as P75 but the Z-score value different from the value used in P75.

3.5. Key Performance Indicators (KPIs) wind farms

Performance of wind farms are evaluated using some indicators. Performance indicators of wind farms are crucial for evaluating their efficiency, reliability and overall contribution to the energy grid. To evaluate the overall performance of wind farm, some key performance indicators (KPIs) are used, some of the commonly used key performance indicators are:

3.5.1. Capacity Factor (CF)

Capacity factor can be defined as the ratio of actual energy produced to the maximum possible energy that could have been produced if the wind farm operated at full capacity all the time.

Alternatively, it can also be defined the energy generated during a period of time divide by the wind farm rated power multiplied by the number of hours in the same period [60].

$$\boldsymbol{CF}(\%) = \frac{\boldsymbol{Actual\ output}}{\boldsymbol{Maximum\ Possible\ Output}} * \mathbf{100} \qquad (3.12)$$

3.5.2. Time-based Availability (TBA)

Time-based availability is defined as the accumulated time that the wind turbine is operational divide by total time in the period. It is the percentage of time the wind farm is operational and capable of generating electricity. This indicator is specific, since the observed value is clearly defined and is the time that a WT is operational; measurable and easy to understand, it is relatively easy to distinguish periods of power production from periods of inactivity. Despite existing technical specifications for its calculation, no international standard exists [44].

$$\boldsymbol{TBA}(\%) = \frac{\boldsymbol{Operational\ time}}{\boldsymbol{Total\ time}} * \mathbf{100} \qquad (3.13)$$

3.5.3. Technical Availability (TA)

Technical availability refers to the percentage of time that the wind turbines are capable of operating and generating power, excluding downtime due to external factors like grid curtailment or lack of wind. Simply it reflects the reliability and performance of turbines from technical standpoint [60].

$$\boldsymbol{TA}(\%) = \frac{(\boldsymbol{Total\ time} - \boldsymbol{Downtime\ due\ to\ technical\ issue}) * \mathbf{100}}{\boldsymbol{Total\ time}} \qquad (3.14)$$

Where:

Total time =time period under evaluation

Downtime due to technical issues=time turbines were unavailable due to internal faults, maintenance, or repair needs but, external downtimes (grid outages, wind below cut-in speed curtailment) are excluded.

3.5.4. Energy-Based Availability (EBA)

Defined as the ratio between the real energy production and the actual energy available. This illustrates the real efficiency a WT or WF since it reveals the percentage captured from the available energy [61].

$$EBA = \frac{\text{Real energy production}}{\text{Actual energy available}} \qquad (3.15)$$

Although it is very easy to measure the produced energy over certain period of time, it is quite difficult to precisely define the actual available energy of the same period. Therefore, it is very challenging to define a standard procedure. Current approaches rely on theoretical production calculation from an operational power curve based on SCADA data.

3.5.5. Mean Downtime (MDT)

Mean downtime (MDT) in wind energy system refers to the average time a wind turbine or a wind farm is non-operational due to failures, maintenance, or external issues (grid outage or extreme weather). This key reliability metric is used in performance evaluation and planning. It is usually defined using equation (3.16) as follow [60];

$$MDT = \frac{\text{Total Downtime}}{\text{Number of failures}} \qquad (3.16)$$

Where:

Total downtime is the cumulative time (in hours or minutes) that a system or component is unavailable.

Number of failures is the total count of separate downtime events.

Since wind farm is an aggregate of wind turbines, the MDT for entire wind farm can be determined using either turbine level approach or farm level aggregation depending on data.

A. **Turbine-Level Approach:** calculate MDT for each turbine, then average.

$$\text{Wind Farm MDT} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\text{Total Downtimei}}{\text{Number of Failuresi}}\right) \qquad (3.17)$$

Where: N is the number of turbines.

B. **Farm-Level Aggregation:** aggregate the downtime and failure data across the whole farm.

$$\boldsymbol{Wind\ Farm\ MDT = \frac{\sum Down\ time\ of\ all\ turbines}{\sum Failures\ of\ all\ turbines}} \tag{3.18}$$

3.5.6. Mean Time Between Failures (MTBF)

MTBF of wind farm is the average time the system operates before a failure occurs. It is expressed as the total operational hours divide by the number of failures for a specific component or the whole WT. The term MTBF is frequently used to describe reliability, as well as its reciprocal value, the failure rate [60].

$$\boldsymbol{MTBF = \frac{Total\ Operating\ Time}{Number\ of\ failures}} \tag{3.19}$$

Steps to determine MTBF of a wind farm

1. Determine the total operating time for all turbines over a period
2. Count the total number of failures in that period
3. Divide the operating time by the number of failures

3.5.7. Mean Time to Repair (MTTR)

Another important performance indicator is mean time to repair, which is defined as the average time it takes to repair and restore a failed component or turbine. It is the average time to return wind turbine to functional state. This can imply either a repair or replacement of faulty component, leading to term of restoration. The reciprocal of MTTR is repair rate [60].

$$\boldsymbol{MTTR = \frac{Total\ Downtime}{Number\ of\ Failures}} \tag{3.20}$$

Steps to determine MTTR of a wind farm

1. Sum up the down time caused by all failures (in hours)
2. Divide by the number of failures.

3.5.8. Curtailment Losses (CL)

Curtailment loss in a wind farm refers to the reduction in production due to external and internal constraints that force the turbines to operate below their full potential even when wind conditions are favorable. This is the amount of potential energy production lost due to grid limitations or other factors requiring the wind farm to reduce its output.

$$\boldsymbol{Curtailment\ Loss = Available\ Energy - Actual\ Energy} \qquad (3.21)$$

3.6. Causes of Underperformance Wind Farms

Reasons for performance deviations can be split into several categories based on what found different literatures. While some studies present underperformance as the difference between actual produced power and potential producible power, other studies stated that erroneous pre-construction estimates cause for underperformance [44].

Pre-construction uncertainties include data quality, data availability, long term corrections and models used. Incorrect data, method, measurements and so on could result in incorrect plannings. Hence, the output of the wind farm may not be as expected. The wind conditions such as wind speed, air density, vertical wind shear, turbulence intensity, directional distribution and inflow angles greatly affects the output.

The second category for causes of underperformance of wind farm is the operating condition of the wind farm. In this category downtime of machines /the whole farm due to different reasons can be considered as major cause of underperformance. Planned and unplanned outages such as component failures, maintenance stops, low wind speeds and grid failures can be some of the reasons for long downtimes. Three major keys can be used to assess the downtime based on the data provided in the SCADA system. Number of downtime events, duration of events and duration between events are the keys for downtime analysis. Based on these keys the underperforming wind turbines can be detected and further analysis could be done using the detailed operational alarm in the SCADA system.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1. Wind Speed Analysis Results

Model has been developed to determine missing values of wind speeds. Values of wind speeds between 1 and 3 days (short gaps) estimated using moving average method from order 3 to 7 whereas gaps greater than three days are filled using average wind speeds from similar months of other years. In the case of MA model with the lowest mean absolute error (MAE) is selected from the developed model to fill the gaps. In most cases is MA (3) is found with low error to represent the model. But, MA (7) is found suitable to predict July 8, 2018 wind speed data with MAE of 0.413 m/s. The values from MA models of order K are summarized in the Appendix-E. The wind speed is found to be 6.356 m/s with total absolute error (TAE) of 1.24 m/s and MAE of 0.413. As it can be seen from the Table E.1 increasing the order of the moving average smooths the error.

For another day the wind speed is found to be 6.04 m/s with MAE of 0.895 as it can be seen in Table E.2. Here it can be observed that the predicted wind speed depends on the three most recent values. In similar manner from Table E.3 and

Table E.**4** the value of wind speed for the respective days are determined using MA (3) with 1.026 m/s and 0.813 m/s MAE respectively.

Even though there is no single standard permissible error for wind speed forecasting using moving average, as acceptable error levels depend on the application, industry and specific requirements. But generally, for day ahead forecasting MAE around 1.83 m/s is cited in aviation related wind field [62]. When the obtained values are compared with this value, acceptable. Hence, it is reasonable to predict the short-term wind speed values using MA model.

The wind resource data are analyzed in Microsoft office Excel after the missing values have been replaced. The average monthly wind speed data for each fiscal year are plotted using graphs.

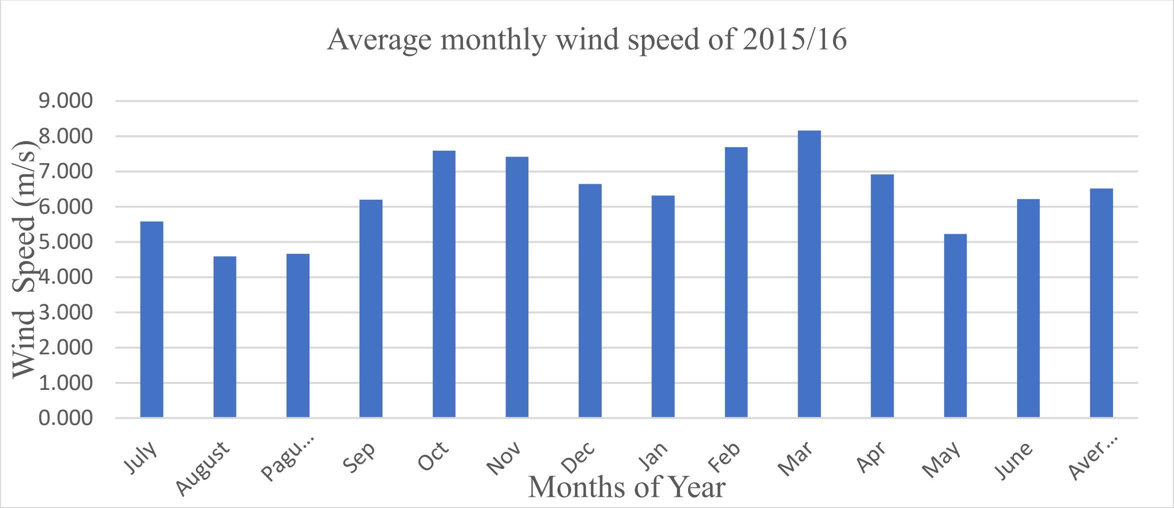

Figure 4.1:Average monthly wind speed of 2015/16

The average monthly wind speed varies between 4.6 m/s and 8.2 m/s which are recorded in August and March respectively. Relatively low wind speeds are recorded in summer season (July, August, Pagumen). The annual mean wind speed is found to be 6.52 m/s and the variation of the wind speed from mean (standard deviation) is 1.65 m/s.

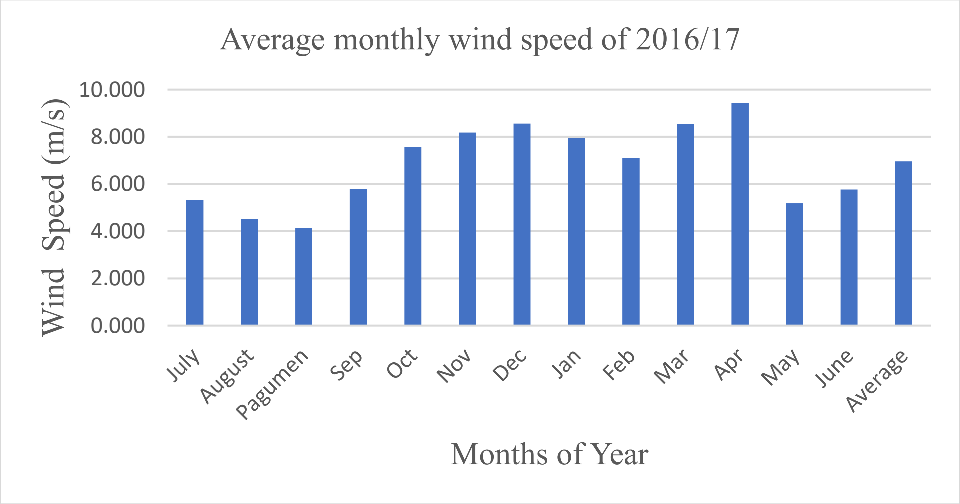

Figure 4.2:Average monthly wind speed of 2016/17

In this fiscal year (2016/17) above 6 m/s wind speed is recorded for 7 months as it can be seen from the above figure. The highest monthly wind speed recorded is 9.44 m/s in April month. The months from October to April shows increasing pattern however, in the remaining 5 months (May-September) wind speed varies between 4.1 m/s and 5.8 m/s. The variation is quantized with standard deviation 2.13m/s from the mean which is 6.96m/s. In similar manner as the previous year low wind speeds are recorded in summer season.

Fiscal year 2017/18, also show similar pattern as the previous year. Above 7 m/s wind speeds are recorded for seven months starting from October to April as it can be seen in Figure 4.3. The mean annual wind speed is 7.45 m/s with standard deviation of 1.88 m/s.

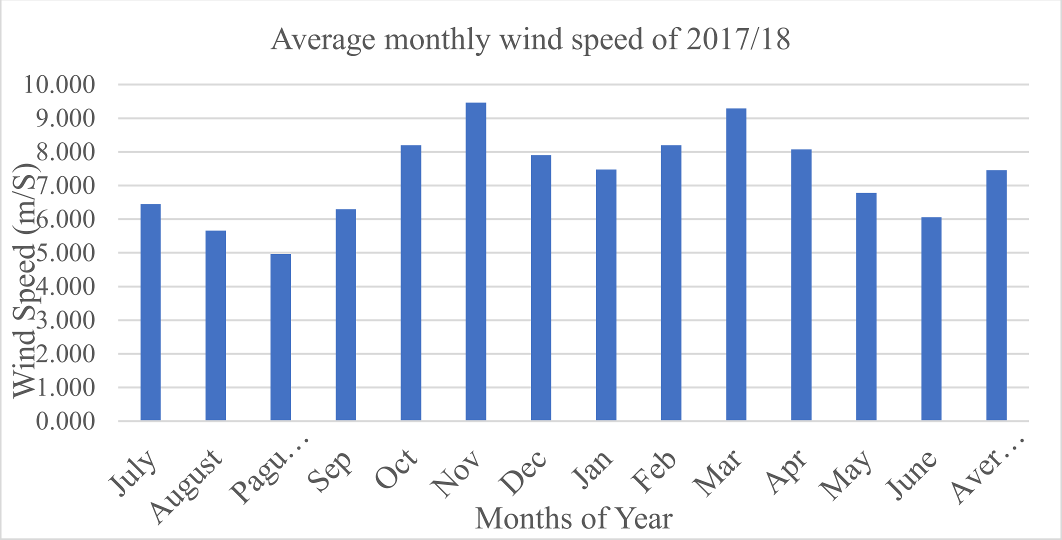

Figure 4.3:Average monthly wind speed of 2017/18

Periods of low wind speed remain the same as the previous year's i.e. summer season (August and Pagumen) with 5.661 m/s and 4.966 m/s respectively.

Wind speeds are lower in the earlier months (July to Pagumen) in the last fiscal year considered in this study (2018/19). But there is an increasing trend from September, peaking around November to February. Wind speeds remain high through April and slightly decrease towards the end of the year (May to June) as it can be observed in Figure 4.4.

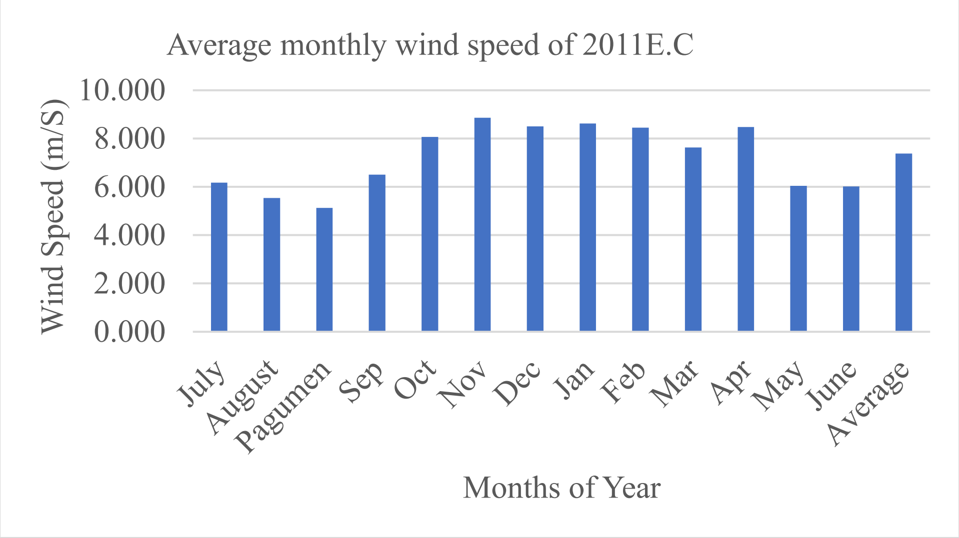

Figure 4.4:Average monthly wind speed of 2018/19

The highest wind speeds occur between November and February, with a peak around November. The lowest wind speeds are observed in August and Pagumen. Seasonal effects could be influencing wind speed, such as monsoon winds or climatic patterns specific to the location. Higher wind speeds in the middle of the year may indicate stronger seasonal winds.

Generally, the four fiscal year annual average wind speeds are plotted using bar chart as shown below. The average annual wind speed of the site varies between 6.52 m/s and 7.45 m/s in the four years operation period of the wind farm.

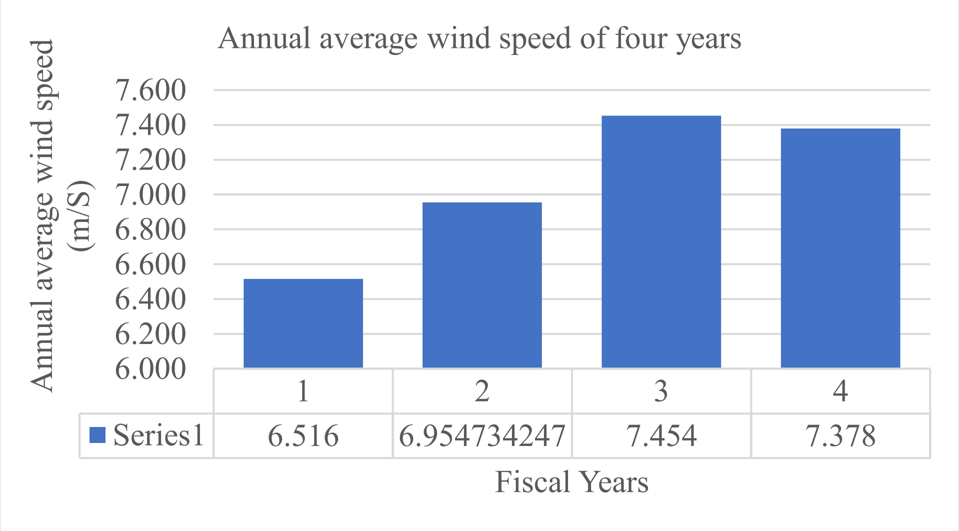

Figure 4.5:Four years average annual wind speed of Ashegoda wind farm

The annual average wind speeds of the site were 6.52 m/s, 6.96 m/s, 7.45 m/s and 7.38 m/s in 2015/16, 2016/17, 2017/18 and 2018/19 respectively. The difference in the annual wind speed is less than 1m/s. This small variation in the annual wind speed indicates the site experiences relatively consistent wind speeds year to year. This low interannual variability is helpful in reducing uncertainty in energy yield predictions.

4.2. Frequency Distribution and Annual Energy Production of the wind farm

Analyzing the daily wind speed in excel, the frequency and probability distribution of each wind speed throughout a year is obtained. The frequency and probability of the wind speed for each year is analyzed separately for the four operation fiscal years which counted from July to June. As it can be seen the frequency and probability of occurrence wind speed below cut in wind speed is low. In all the operation periods the frequency and probability of wind shows an increasing pattern up to the mean and declines gradually.

The frequency distribution in Table C.1 shows most of the distribution is between 4 m/s and 9.5 m/s. The highest frequency and probability of occurrence a wind speed lies between 5.5 m/s and 6.5 m/s in the first fiscal year. In the meantime, 15% of the days in the year have 5.5 m/s wind speed which is equivalent to 55 days in a year. The frequency and probability towards higher wind speeds decreases progressively. Even though, the rated wind speed is 15 m/s and 14 m/s for phase 1 and phase 2&3 respectively but in actual the wind speed never reached the rated speed.

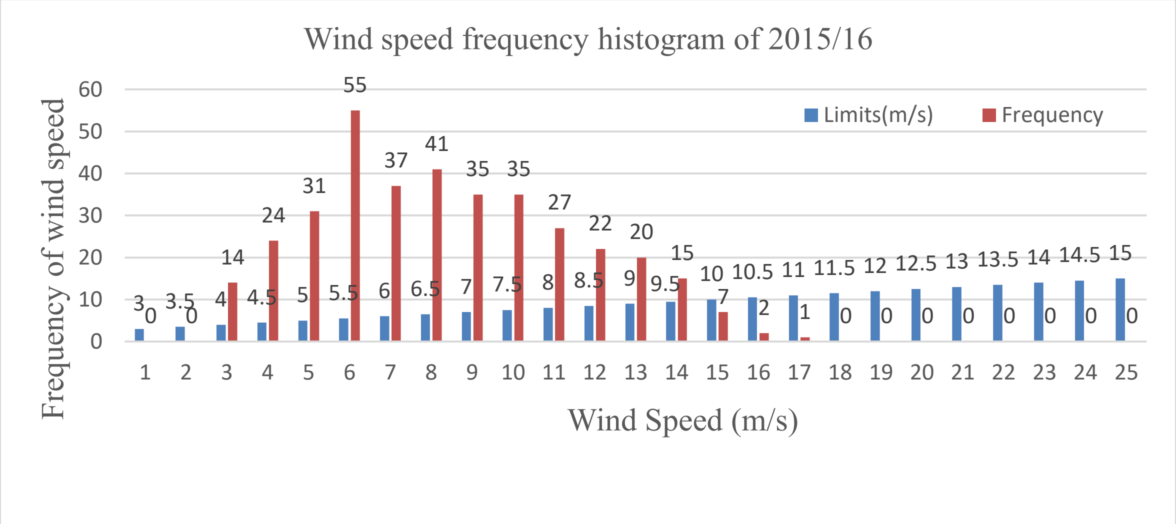

Figure 4.6:Wind speed frequency distribution of 2015/16

The annual average wind speed is 6.52 m/s, the distribution seems even to right and the left of the mean wind speed.

Similarly, the frequency distribution of wind speed in each year is plotted in the figures below.

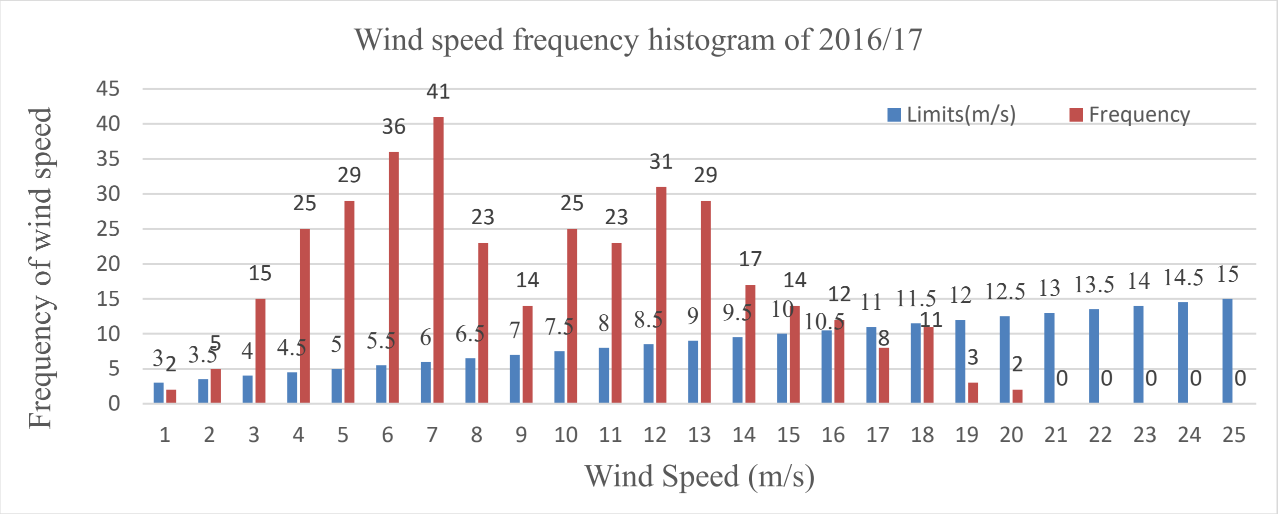

Figure 4.7:Wind speed frequency distribution of 2016/17

Low wind speeds below cut-in wind speed is observed in 2016/17 fiscal year for seven days which is equivalent to 168 hours. The mean annual wind speed is 6.96 m/s and the highest frequency occurs at 6 m/s. The most frequent wind speeds appear between 5.5-6 m/s, with the highest peak reaching 41 occurrences at 6 m/s. Generally, wind speeds between 5-9 m/s show consistent high frequencies. Wind speeds above 12 m/s are very rare, with 0 occurrences from 13 m/s and beyond. There is a gradual increase in frequency from lower speeds up to around 6 m/s, followed by some fluctuations before declining. This distribution suggests that moderate wind speeds (5-11.5 m/s) are the most common, which could be useful for applications like wind energy generation. The peak at 6 m/s suggests that this is the most typical wind speed in the recorded year.

Though the annual average wind speed is 7.45 m/s, the most typical peak wind speed recorded in 2017/18 fiscal year is 8 m/s. The highest frequency of occurrence is 43 days in a year which is 11.8 % of the total days in a year. Wind speeds between 5 m/s and 11 m/s are common but, rarely above 11.5 m/s wind speed occurs. The probability of occurrence of above 14 m/s is zero.

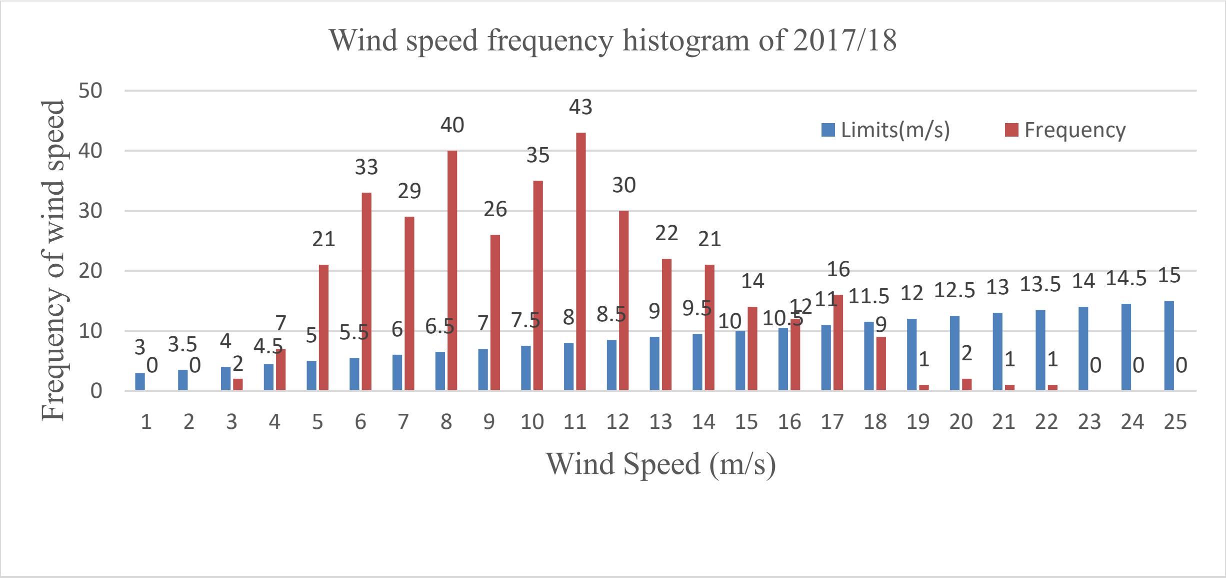

Figure 4.8: Wind Speed frequency distribution of 2017/18

Similar to the other years most wind speeds lie between 5 m/s and 10 m/s with the most peak occurring at 8 m/s. This almost the same as the annual average wind speed 7.38 m/s of the year (2018/19). Most of the distributions are around the mean, with probability of occurrence of the wind speed between 5 m/s and 11 m/s around 93.7%. This implies wind speeds above 11 m/s and below 5 m/s accounts only 6.3% of the total days in a year.

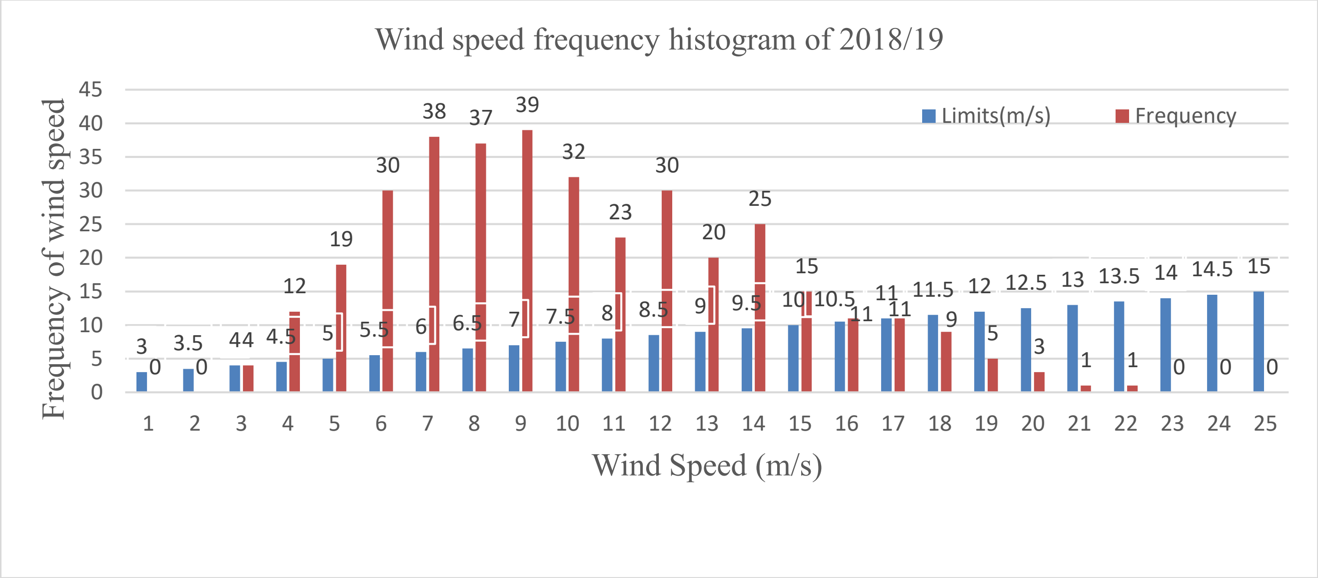

Figure 4.9:Wind speed frequency distribution of 2018/19

Generally, the plot of frequency histograms shows most of wind speed lies between 5 m/s and 9.5 m/s in the first two fiscal years. The peak distribution of wind speed is found at 5.5 m/s and 6 m/s respectively. However, in the latter two years have the same peak distribution and distribution ranges. Most of the wind speed lies between 5 m/s and 11 m/s with the peak distribution in 8 m/s.

After analyzing the wind speed data, the gross annual energy production of wind turbines in each phase is computed. The energy output wind turbines at phase 1 and phase 2&3 are computed separately since they have different power curve, rating, air density, hub height and rotor diameters.

Table 4.1:Phase 1 Gross Annual Energy Production

Year	AEP(GWh)	AEP at 0.922Kg/m3	Total AEP
2015/16	2.03	1.53	45.80
2016/17	2.59	1.95	58.44
2017/18	2.93	2.21	66.22
2018/19	2.87	2.16	64.91

The results of analysis indicate the gross annual energy production of 1 MW, 30 wind turbines in the first fiscal year considered is found 45.8 GWh. After showing increase in the energy output of the turbines in the next two years almost 1.3 GWh decrease in the output energy is observed in the last year. However, there is 20.4 GWh difference in the output energy in the lowest and highest production periods. This difference is observed due to variation of wind speed in different years.

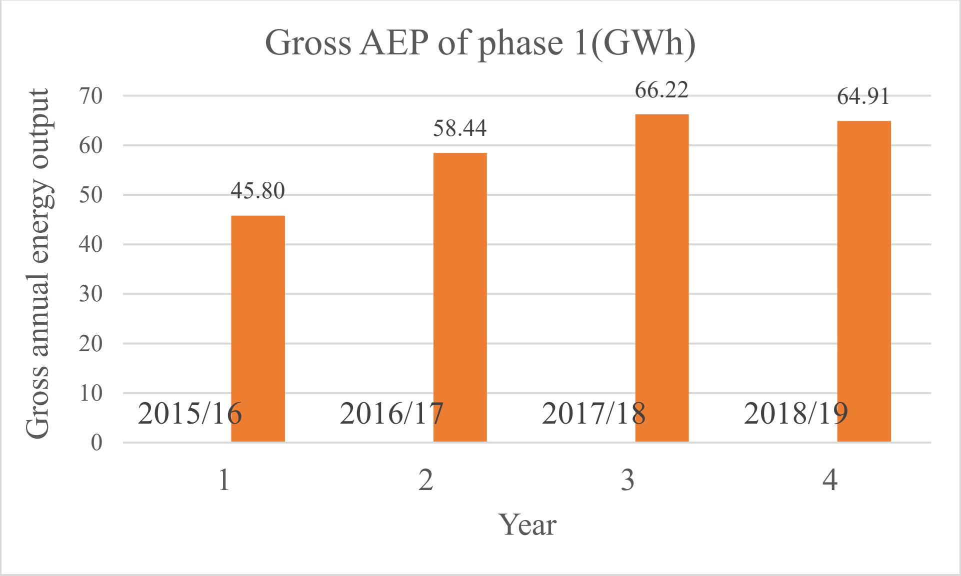

Figure 4.10: Gross annual energy production of phase 1 (GWh)

The gross annual energy production of ECO-74 wind turbines at phase 2&3 Ashegoda wind farm is also estimated in the same manner.

Table 4.2: Phase 2&3 Gross Annual Energy Production

Year	AEP(GWh)	AEP at 0.925Kg/m3	Total AEP
2015/16	3.22	2.43	131.29
2016/17	4.18	3.15	170.31
2017/18	4.73	3.57	192.95
2018/19	4.64	3.50	188.98

The gross annual output of each wind turbine and total annual energy production of the 54 wind turbines in phase 2&3 is summarized in the table above. The gross output of the wind farm follows the wind speed in respective year. Hence, the gross annual out is 131.3 GWh at air density of the site in the first operation period and increases till the third year reaching around 192.95 GWh. At the end of the period considered in this study the gross AEP is found to be around 189 GWh. The figure below shows the gross annual energy production in the years operation period.

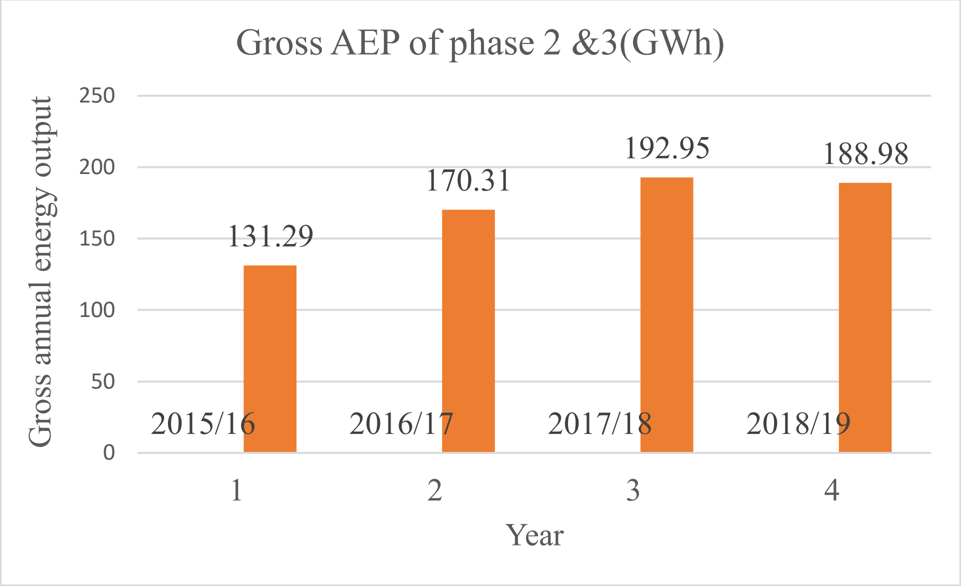

Figure 4.11: Gross annual energy production of phase 2&3 (GWh)

As it can be seen from this figure there is almost 61.7 GWh difference in the annual energy production between the maximum production period (2017/18) and the minimum production period (2015/16).

The total gross annual energy production (GEP) the wind farm is determined by summing up the energy production of each phase over the year.

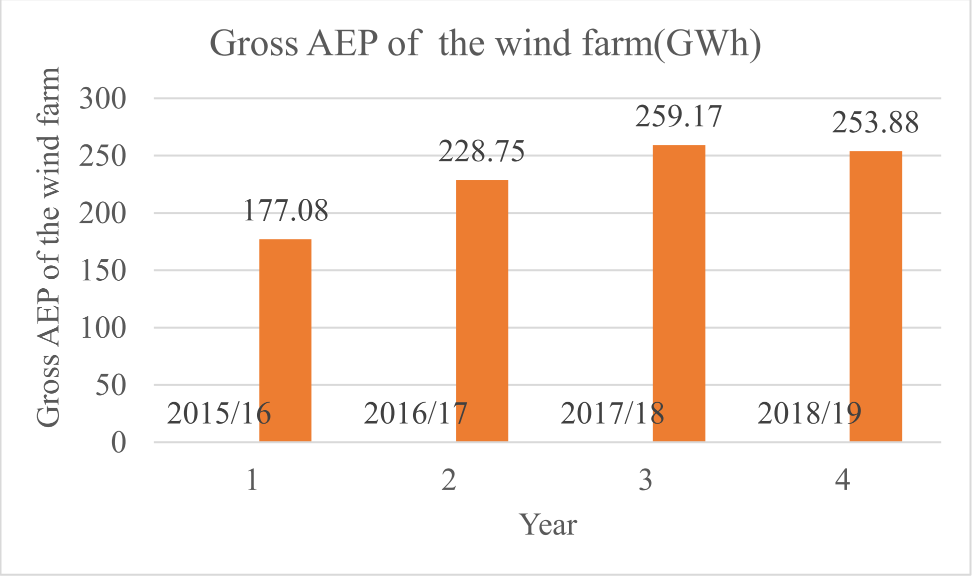

Figure 4.12: Gross annual energy production of the wind farm

This histogram shows the gross annual energy production of the whole wind farm. The contribution of the 84 wind turbines is taken into account. However, gross annual energy represents the theoretical energy yield before losses. This can be compared to net production to evaluate efficiency. Accordingly, the gross energy production (GEP) of wind farm at different operation years is different. In the initial year of the study considered for this thesis, the annual GEP is found 177 GWh which is the lowest compared to the other years. The production increases up to the third year (2017/18) and reaches the highest output 259.2 GWh and falls back to 254 GWh in the last year.

When the results are compared to the planned annual energy output of the contractors, there is significant difference. The planned gross annual energy production (wake effect included) was 99.858 GWh from phase 1 and 304.641 GWh from phase 2&3 with total sum of 404 GWh. But based on the actual data collected from the farm office, the analysis result shows the annual energy production is much lower. The maximum gross output obtained in one fiscal year is 259.2GWh, which is 64.2% of the initial plan. Since the comparison is between the gross energy production i.e. before considering any losses the major reason for low production is wind speed. The long-term average wind speed expected during the planning phase was 8.38 m/s in phase 1 and 8.61 m/s in phase 2&3. But, the annual average wind speeds of the site were 6.52 m/s, 6.96 m/s, 7.45 m/s and 7.38 m/s in 2015/16, 2016/17, 2017/18 and 2018/19 respectively similar for all phases. However, this doesn’t mean that low speed is the only reason for under performance of the farm since the net production is not computed yet.

The net annual energy production can be estimated by subtracting the sum of all the losses from the gross annual production. Considering IEC 61400-15 (assessment of wind resource, energy yield and losses), IEC 61400-12 (power performance measurements) and IEEE 1547 (interconnection and performance requirements) the maximum overall loss is typically around 10% to 20% of the total available energy. Taking 10% which was assumed during the planning phase [5] and using the probability exceedances the net annual energy output is summarized in table below.

Table 4.3:Net annual energy output of Ashegoda wind farm

Year	GEP(GWh)	Loss (%)	σ (%)	σ(GWh)	P50	P75	P90
2015/16	177.1	10	14.1	24.9711	159.39	142.659	127.427
2016/17	228.8	10	14.1	32.2608	205.92	184.305	164.626
2017/18	259.2	10	14.1	36.5472	233.28	208.793	186.5
2018/19	254	10	14.1	35.814	228.6	204.605	182.758

Based on the above standards, the site conditions and power curve of the manufacturer the estimated net energy output for each year ranges from 142.7 GWh-208 GWh based on P75. Even considering more conservative P90 the net annual output of the wind farm ranges from 127.4 GWh-186.5 GWh. There is 75% chance of exceeding 142.7 GWh, 184.3 GWh, 208.8 GWh and 204.6 GWh in each fiscal year respectively. In similar manner the exceedance probability of 127.4 GWh, 164.6 GWh, 186.5 GWh and 182.8 GWh is 90% in respective years. But, P50 is the mean net energy output with 159.4 GWh, 206 GWh, 233 GWh and 229 GWh in respective fiscal years.

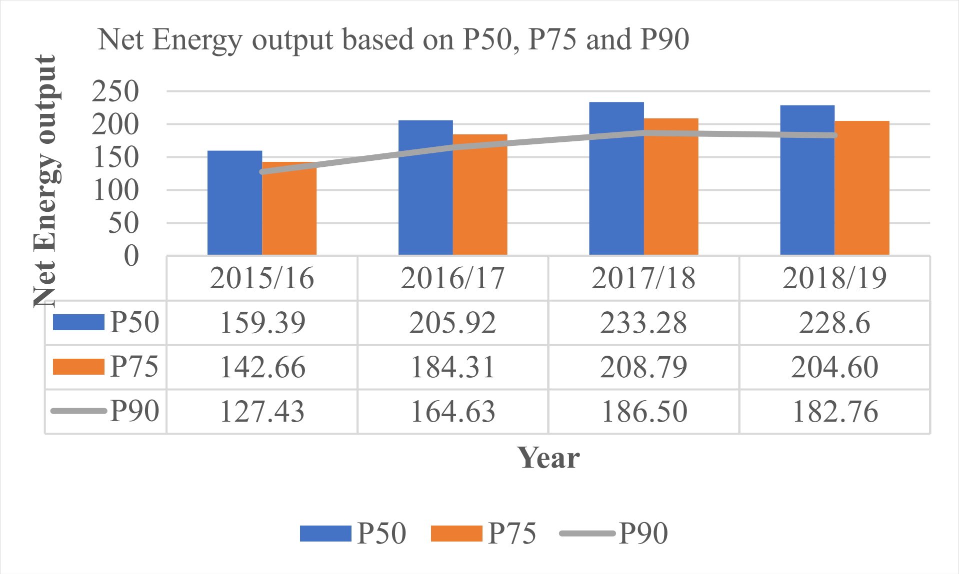

Figure 4.13: Net Energy output based on P50, P75 and P90

The estimated (expected) net energy output results are compared with the actual measured values with energy metering panel and recorded with the SCADA system. The comparison shows there is huge difference between the expected energy output of the wind farm and the actual measured values in the last two years of the period considered.

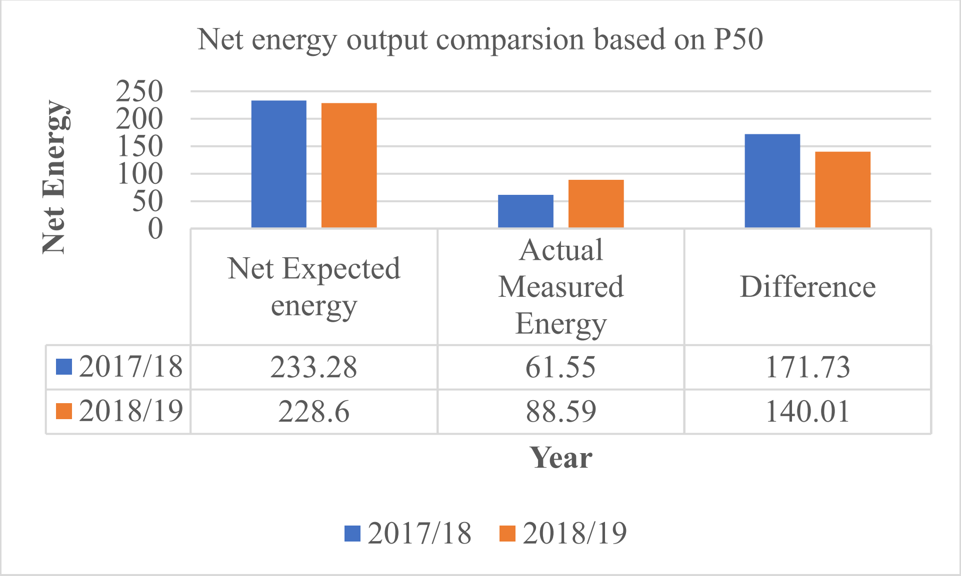

Figure 4.14: Net energy output comparison

The result shows though the difference between net energy output among the two years is small, the actual measured energy is very small in comparison to the potential. The wind farm only produced 61.55 GWh (26.4%) and 88.59 GWh (38.75%) of the net expected energy in each fiscal year. The difference between the expected net energy and measured energy can be considered as the production lost due to different reasons. In the consecutive fiscal years 171.73 GWh (73.6%) and 140 GWh (61.25%) net energy is lost.

4.3. Performance Evaluation Results

Analysis result on capacity factor of the 120 MW wind farm in two years operation period shows, the wind farm operates at 5.86% and 8.43% of the maximum possible output at full capacity during the same period. The maximum possible output of the wind farm is estimated by multiplying 120 MW by number of hours in a year (8760).

Table 4.4: Capacity Factor during the two years

Year	Actual output (GWh)	Maximum possible output (GWh)	CF (%)
2017/18	61.55	1051.2	5.85521
2018/19	88.59	1051.2	8.42751

Capacity factor does not represent the theoretical energy production based on the real on-site wind conditions. There is no single standard value for capacity factor of wind farms as it varies with location, wind resource, turbine technology, and operational practices, with typical values ranging from 20% to 40%. But as it can be seen the capacity factor of the wind farm in two years operation are very small less than 10%. This low value of capacity factor suggests the wind farm is not operating at its full potential for a significant portion of a year, potentially different reasons. This indicates the gap between nominal and realistic power production of the wind farm is large. This raises a question on the consistency and reliability of the wind farm.

Besides the availability of wind resources, the availability of machines is also important for better performance of a wind farm. Generally, the availability of machines in a wind farm can be expressed based energy-based availability and time-based availability. Hence, the energy-based availability (EBA) of Ashegoda wind farm is calculated to evaluate the performance of the wind farm.

Table 4.5**:** Energy-based availability of Ashegoda wind farm of two fiscal years

Year	Real (Measured) Energy Production (GWh)	Actual Energy Available (GWh)	EBA (%)
2017/18	61.55	233.28	26.3846
2018/19	88.59	228.6	38.7533

The energy-based availability of the wind farm in the two years operational period is found to be 26.4 % and 38.75% as it can be seen in the table above. As this performance metric assesses the percentage of potential energy generated compared to the actual energy generated, taking into account periods of downtime and varying wind conditions it is good measure compared to time-based availability which focus on operation hours. The result shows only 26.4% and 38.75% of the potential energy that could have been generated are produced in the fiscal years considered respectively. Even though there is no a single, universally accepted standard value for energy-based availability, a reasonable target for well-maintained wind farm is typically around 97% or higher [61]. When the obtained values are compared with the value in literature it is very small. Downtimes (scheduled maintenance, repairs, and unexpected outages), wind variations, wind turbine performance and site-specific conditions could be the possible reasons for low energy-based availabilities.

Another key performance indicator is time-based availability (TBA) which indicates the proportion of time a turbine is available for operation. Based on the data available and analysis results for 321 days of 2017/18 FY and 363 days of 2018/19 FY, the total operational time of all the wind turbines is found 227,283 and 87,295.5 hours respectively. Hence the TBA (%) of the wind farm is found to be 35.12% and 11.93% of the total time during the respective fiscal year. Though no standard exists for TBA of wind farms, a typical value of 97% is taken as industry standard [61]. When the analysis results are compared with the value in literature, the values are very small. The farm only operates for very small portion of the time i.e. non-operational times are much greater than the working hours.

Technical availability and mean downtimes are also import key performance indicators. Though it is not possible to determine the technical availability as no different record is available for the downtimes due to technical issues only, but the total downtime (due to technical and non-technical issues) of the wind farms are found 419,853 and 644,513 hours in the two fiscal years considered for this thesis respectively. In 2017/18 FY, the total downtime of all wind turbines 404,936 hours are due maintenance and failures and 15,457.5 hours are due to low wind speed.

Table 4.6:Total downtime of Ashegoda wind farm in hours

Year	Downtime due F& M	Downtime due to low wind	Total down time
2017/18	404395.5	15457.5	419853
2018/19	633340	11173	644513

In the second fiscal year considered though the downtime due to low wind speed decreases to 11,173 hours but downtime due to failure and maintenance increases to 633,340 hours. When the total downtime hours divided to the total number of turbines each turbine stops for 4,998.25 and 7,672.8 hours per year, which is equivalent to 15.58 and 21.14 hours per turbine per day in the years considered in this study respectively.

The amount of energy lost (curtailment loss) is important in wind power generation as it represents lost opportunities for clean, renewable power generation. In the fiscal years considered 171.73 GWh (73.6%) and 140 GWh (61.25%) net energy is lost. This is huge amount of energy which could power several small villages.

4.4. Causes of Underperformance of Ashegoda Wind Farm

Underperformance of wind farms can result from a variety of technical, environmental, and operational factors. The underperformance of Ashegoda wind farm is found due to the following reasons:

Resources assessment errors: Inaccurate wind speed predictions during the pre-construction phase leads to overestimation of energy yields. The long-term average wind speed expected during the planning phase was 8.38 m/s in phase 1 and 8.61 m/s in phase 2&3. But, the annual average wind speeds of the site were 6.52 m/s, 6.96 m/s, 7.45 m/s and 7.38 m/s in 2015/16, 2016/17, 2017/18 and 2018/19 respectively similar for all phases.

Grid and curtailment constraints: Analysis result based on data of SCADA system of the wind farm indicates unplanned grid and planned grid outages contribute to downtime of the turbines in the farm. Planned outages by the order of load dispatch center (LDC) and unplanned the WTs/WF such as system voltage loss are some reasons.

Maintenance and downtimes: Based on the analysis results maintenance and downtimes are found the main reasons for underperformance of the wind farm. Unplanned outages due to technical faults (such as failure of components, grid failure etc.) and weather related (low wind speeds) associated with delayed maintenance leads to prolonged turbine inactivity. For 2017/18 and 2018/19 FYs low wind speed accounts 3.68% and 1.73% of the total downtime, whereas, maintenance and failures account 96.32% and 98.27% of the total downtime respectively. Here to be specific failure of the control and communication system (SCADA) takes the largest share of the downtime due failure and maintenance. This is mainly due to failure and locking of SCADA system by the contractors caused by some disagreements with EEP. Delayed maintenance due to absence spare parts in inventory (stock) of the wind farm seconds to failure of control & communication system. Even though component wise failure analysis is not possible data lack of clear failure data, frequent failures are observed on the power electronic converters (insulated gate bipolar transistors) and electrical control units.

Generally, long downtimes caused by component/system failures and delayed maintenance are found the most important factors for underperformance of the farm. But when comparing with initial the planned yield, resource assessment error also leads overestimation of energy yield.

4.5. Proposed Mitigation Measures for Underperformance of The Wind Farm

To mitigate the underperformance of wind farm due to prolonged maintenance downtime caused by absence of spare parts and SCADA system failure, a set of technical, operational, and logistical measures are proposed. These mitigation strategies aim to enhance reliability, reduce downtime, and improve overall energy yield. Some of the proposed mitigation measures includes;

4.5.1. Spare parts availability and Inventory Management

This proposed strategy includes;

Establishing critical spare part list: Identifying and categorizing of critical components whose failure leads to extended downtime.

Implement a Just-In-Case (JIC) inventory strategy: This helps to reduce lead time for replacements by stocking critical spares onsite or at a regional hub.

Predictive Spare Parts Forecasting: In this strategy historical data and predictive maintenance tools should be used to estimate part wear rates and pre-order accordingly.

4.5.2. SCADA System Reliability and Redundancy

Since most of the downtime are due to failure of the SCADA system, it is important to propose a possible strategy which could improve the issue. Some of the proposed strategies are;

Deploying Redundant SCADA systems: This helps to prevent total SCADA failures by using dual-redundant servers and communication networks.

Implementing Edge Monitoring Solutions: This can be implemented by using localized data logging or remote terminal units (RTU) that can temporarily operate independent of central SCADA.

Regular SCADA health checks and Cybersecurity measures: In this approach scheduled periodic testing, software updates, and protecting of SCADA system from potential cyber threats, which are common cause of system failure should be done.

4.5.3. Maintenance Optimization

Since unoptimized maintenance of wind farms result in unnecessary downtimes, implementing optimized maintenance is very important for effective performance of wind turbines. This maintenance optimization can be implemented by using predictive maintenance programs and/or Computerized Maintenance Management System (CMMS). In predictive maintenance programs vibration monitoring, oil analysis and thermal imaging can be used to predict failure before causing major downtime. In the case of CMMS integration, the CMMS itself is linked to SCADA real time maintenance alerts.

CHAPTER FIVE

5. CONCLUSION, RECOMMENDATION AND FUTURE WORKS

5.1. Conclusion

Wind is a clean, environmentally friendly and fast-growing source of energy. Now a days many countries are integrating wind energy in to their grids. Ethiopia is also one of the countries with promising resources and operating wind farms. Though wind turbine technologies are at advanced stage of development, researches and standards regarding the operational performance of wind farms/wind turbines is at infant stage. In this thesis performance evaluation of Ashegoda wind farm, which is one of the wind farms in operation in Ethiopian is conducted and some mitigation measures are proposed. Based on the data from the SCADA and unpublished materials at the farm office the performance of the wind farm is analyzed using Excel and IBM SPSS software.

Wind speed data of four years are analyzed and some missing values are replaced using appropriate wind forecasting models. After evaluating the accuracy, the models using total absolute error and mean absolute error the missing values of wind speeds are replaced. Based on the analysis results of four years operational data, the annual average wind speeds of the site were 6.52 m/s, 6.96 m/s, 7.45 m/s and 7.38 m/s in 2015/16, 2016/17, 2017/18 and 2018/19 respectively similar for all phases. This result shows the actual wind speed of the site is below the long-term average wind speed expected during the planning phase. Based on the results the annual variation in wind speed is small, though seasonal patterns are common.

The probability and frequency distribution of wind speed is analyzed by Excel using the high-resolution daily wind speed of four years data. Combining the probability and frequency distribution with the power curve of the wind turbines, and correcting to the air density of the site the annual energy output of the wind farm is determined. When the results are compared with the actual measured energy output of the wind farm large differences are observed in 2017/18 and 2018/19.

Key performance indicators such as energy-based availability, time-based availability, capacity factor, total downtime and energy curtailments are used to evaluate the performance of the wind farm. Based on the analysis the capacity factor of the wind farm during the two operational years is found 5.86% and 8.43% and the energy-based availability of the wind farm is found to be 26.4 % and 38.75%. Besides, the TBA (%) of the wind farm is also found to be 35.12% and 11.93% of the total time during the respective fiscal year. Though there is no single standard values for the KPI's, when these values are compared with some values in literature, the values are very small. This indicates the wind farm is not performing as it is expected.

This thesis paper also tries to investigate the causes of underperformance of the wind farm. For 2017/18 and 2018/19 EFYs down time due to low wind speed accounts 3.68% and 1.73% of the total downtime, whereas, maintenance and failures account 96.32% and 98.27% of the total downtime respectively. Here to be specific failure of the control and communication system (SCADA) takes the largest share of the downtime due failure and maintenance. This is mainly due to failure and locking of SCADA system by the contractors caused due to some disagreements with EEP. Delayed maintenance due to absence spare parts in inventory (stock) of the wind farm follows to failure of control & communication system for the large downtime. Generally, long downtimes caused by component/system failures and delayed maintenance are found the most important factors for underperformance of the farm. The initial wind resource assessment and long-term forecast also leads overestimation of energy yield. As a result of the downtime and low wind speed, 171.73 GWh (73.6%) and 140 GWh (61.25%) energy is lost in 2017/18 and 2018/19.

Finally, to improve the performance of the wind farm some mitigation measures are proposed. Spare part availability and inventory management, SCADA system reliability and redundancy and maintenance optimizations are some the proposed solutions.

In conclusion, the Ashegoda wind farm is underperforming relative to its design expectations. Implementing the proposed mitigation strategies is essential to enhance its operational efficiency and contribute meaningfully to Ethiopia's renewable energy goals.

5.2. Recommendation

The government of Ethiopia and EEP should evaluate the performance of wind power plants. This will help to find appropriate solutions for improvement. The proposed mitigation measures should be considered and implemented. This will enable quick recovery of investment and decrease of the financial losses.

Based on the performance evaluation results, it is recommended that wind farm operators should implement real-time monitoring systems and predictive maintenance tools to reduce downtime and increase energy output. Data analytics should be leveraged to track turbine performance trends and identify inefficiencies early.

Policymakers should support performance improvements by offering incentives for modernization of older wind farms and setting performance benchmarks. Regulatory frameworks must also evolve to require environmental mitigation plans as part of licensing.

5.3. Future Works

This section outlines possible extensions of this thesis for future research.

In this study, a Moving Average (MA) model was used to estimate missing wind speed data. However, more accurate imputation methods could be explored using modern machine learning techniques.

Currently, electrical and mechanical losses are assumed to follow the contractual agreement of 10%. If detailed parameters of the feeder and collector circuits become available, the thesis could be extended to include a more precise assessment of these losses.

Although the author has attempted to identify the causes of underperformance, a more detailed, component-wise performance evaluation could be conducted. This would help in prioritizing critical components for maintenance or upgrades. In addition, the financial losses due to energy curtailment could be quantified, and the proposed mitigation measures could be evaluated and integrated.

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APPENDIX-A

A. Average daily wind speed of Ashegoda wind farm

Table A.1 Average daily wind speed of 2008E.C fiscal year

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	5.215	4.391	4.176	5.118	8.208	3.843	5.188	5.846	6.026	3.843	7.156	4.252	6.123
2	4.58	3.755	4.667	4.639	7.389	7.077	5.755	7.196	6.732	7.077	7.993	5.139	6.025
3	4.836	3.755	3.949	4.16	7.289	6.8	6	7.329	7.315	6.8	8.335	4.073	5.418
4	4.83	5.106	4.807	4.895	7.017	8.804	4.407	5.386	8.457	8.804	6.423	4.598	6.012
5	5.371	3.899	4.915	3.823	7.8	7.8	6.504	6.205	7.754	7.8	5.956	4.491	5.53
6	6.258	3.686	5.479	4.514	9.3	9.3	8.265	5.056	7.295	9.3	4.675	5.802	6.472
7	5.515	5.259		5.042	10.13	5.167	7.601	4.874	7.722	5.167	7.626	6.754	6.526
8	5.267	5.67		5.031	9.168	6.714	6.135	6.041	9.183	6.714	9.738	6.113	5.339
9	5.314	5.341		5.201	9.436	8.71	9.031	4.466	9.917	8.71	7.646	4.545	5.029
10	6.39	5.076		4.298	9.6	9.6	8.565	4.563	8.375	9.6	4.707	4.375	5.895
11	6.698	5.371		5.06	9.255	9.198	6.893	7.643	8.395	9.198	5.853	5.511	5.727
12	6.177	5.238		5.635	8.642	8.714	8.051	8.102	9.356	8.714	6.064	5.207	4.865
13	5.948	4.273		6.323	8.579	8.72	8.615	5.794	7.481	8.72	9.44	5.797	5.136
14	6.135	4.253		7.183	7.909	5.202	6.527	6.039	5.647	5.202	8.1	6.131	5.864
15	5.785	4.594		5.836	7.078	5.704	7.28	7.025	7.086	5.704	6.143	5.541	5.815
16	5.838	4.783		6.099	6.19	8.918	6.793	6.41	8.405	8.918	7.101	5.805	6.68
17	5.427	4.1		6.345	7.059	8.785	7.556	4.1	5.683	8.793	7.94	5.416	6.409
18	5.994	4.273		6.95	7.965	8.651	7.223	4.52	8.354	4.258	9.51	4.638	5.067
19	6.306	4.466		7.702	6.849	8.596	5.648	4.104	9.324	6.535	6.706	5.784	5.231
20	6.544	4.055		6.641	6.677	7.736	4.266	5.053	10.683	8.029	6.706	4.953	8.154
21	6.069	4.035		6.516	6.342	6.321	5.46	7.451	10.219	7.133	5.147	3.993	7.638
22	4.946	5.704		8.151	6.799	7.099	4.338	6.468	9.605	6.272	5.205	5.115	6.951
23	6.786	5.264		8.055	6.577	8.165	6.572	7.904	7.835	7.994	6.92	4.509	6.596
24	6.476	4.738		8.531	7.535	7.619	6.809	9.104	6.333	8.275	6.385	5.375	6.518
25	5.338	4.755		7.645	5.75	6.409	8.3	7.839	8.047	5.035	6.675	5.365	7.571
26	5.178	5.063		7.476	6.269	6.225	6.111	9.486	7.27	5.152	8.331	4.885	8.097
27	4.741	4.252		7.188	7.34	7.344	7.329	8.966	5.75	5.939	7.282	5.88	7.256

28	3.537	3.656		6.375	7.793	7.492	7.494	5.354	4.695	6.807	4.089	6.045	6.699
29	4.692	3.77		7.479	6.985	6.464	5.396	5.451	4.782	7.675	4.945	5.255	6.277
30	5.323	3.845		8.071	3.846	5.369	5.188	5.705	7.073	7.221	5.056	5.47	5.706

Table A.2 Average daily wind speed of 2009E.C fiscal year

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	6.372	4.662	3.201	4.203	7.309	9.239	8.399	8.77	8.614	8.223	11.477	8.272	6.516
2	4.34	5.633	5.006	3.77	7.11	7.794	7.245	10.68	8.399	8.897	10.783	8.342	5.573
3	5.37	6.655	3.935	4.781	8.386	9.519	8.21	8.517	8.8	11.305	11.61	8.026	4.916
4	5.577	5.875	4.448	4.883	8.243	10.176	7.765	6.928	9.377	11.662	10.468	4.796	5.632
5	5.314	4.182	4.138	4.108	7.784	10.3	7.525	8.367	6.206	11.16	9.259	4.366	5.969
6	4.718	2.815		3.875	8.607	8.867	6.778	6.903	7.319	10.54	8.616	4.452	5.891
7	4.39	3.711		3.306	8.23	9.728	7.715	5.865	8.11	11	11	4.604	4.583
8	4.465	5.205		4.235	8.258	8.343	7.091	8.843	5.968	6.592	7.632	2.828	6.107
9	4.5	4.226		4.929	7.373	8.244	8.607	11.1	5.23	5.789	8.981	4.754	5.883
10	5.953	3.352		5.977	6.303	8.454	11.74	9.059	5.375	5.795	9.156	4.693	7.121
11	5.441	5.17		4.966	6.16	8.282	9.4	7.924	4.953	6.171	8.696	5.006	5.227
12	7.017	5.531		5.339	5.229	8.526	8.982	7.975	8.571	5.245	8.727	4.581	6.135
13	6.141	4.588		4.194	6.141	8.165	9.671	7.277	8.8	6.236	11.071	4.766	4.896
14	5.208	3.784		4.556	7.472	5.69	10.07	8.642	8.253	5.54	10.704	5.263	5.316
15	3.793	4.404		6.123	7.36	3.85	8.532	9.185	5.457	5.37	8.737	4.259	5.565
16	6.215	4.721		5.697	8.049	4.046	9.065	8.642	5.519	5.803	7.946	4.749	4.977
17	5.947	4.975		6.254	8.022	5.785	8.11	10.12	5.854	5.563	9.068	4.883	3.884
18	4.252	4.514		5.609	7.947	6.784	6.486	9.127	5.873	5.722	5.133	5.125	5.551
19	5.142	5.739		5.218	7.999	8.946	8.924	5.073	5.149	7.654	4.548	5.492	5.944
20	7.145	4.44		4.353	6.415	10.178	8.382	5.913	7.122	8.233	5.654	4.793	5.185
21	6.971	4.214		6.065	7.532	9.85	9.574	7.15	8.931	10.117	10.117	3.825	5.315
22	3.866	4.439		9.56	7.661	7.846	10.77	7.511	6.393	9.645	9.645	4.484	5.186
23	5.132	5.033		8.575	7.277	7.554	10.21	7.512	7.026	9.265	9.265	5.046	7.278
24	3.199	3.953		6.927	7.68	9.965	8.696	7.522	7.559	10.159	10.159	5.959	6.558
25	3.647	4.823		7.38	7.568	10.276	9.897	8.846	5.92	11.309	11.309	5.405	6.365
26	7.435	4.101		6.884	6.685	8.103	9.299	7.08	5.923	9.281	9.281	4.952	6.117

27	6.418	3.702		8.102	7.415	8.095	9.831	7.046	6.581	9.913	9.913	5.389	5.863
28	4.256	3.461		7.618	9.061	7.281	8.881	6.074	5.842	11.188	11.188	5.995	5.901
29	5.055	3.924		8.075	9.245	8.094	4.792	6.295	10.602	11.044	11.044	5.309	7.153
30	6.341	3.677		8.067	8.691	7.219	5.959	8.354	9.603	12.023	12.023	5.139	6.534

Table A.3 Average daily wind speed of 2010E.C fiscal year

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	6.356*	7.183	4.3	3.856	6.935	9.57	6.659*	7.307	7.886	10.925	7.734	7.384	6.497
2	6.631	7.096	5.442	5.461	6.049	11.25	7.381*	8.139	8.364*	9.011	9.366	8.666	6.256
3	4.936	6.072	4.728	5.402	6.08	12.633	7.351*	8.552	8.946*	5.968	10.127	7.558	5.365
4	5.786	6.043	5.03	6.456	7.201	11.422	7.817*	8.09	9.420*	6.365	7.993	7.442	5.599
5	6.688	7.021	5.329	5.407	6.065	9.013	8.213*	6.574	7.305*	7.354	9.073	8.308	6.99
6	8.343	6.037		5.472	5.838	9.376	8.062*	7.28	6.715*	9.86	7.531	7.06	7.223
7	5.988	5.358		5.144	6.021	10.025	7.894*	7.556	11.838	8.42	7.856	8.544	6.326
8	6.121	5.195		5.231	7.065	9.165	6.688*	7.434	13.183	8.252	5.705	5.748	4.745
9	5.669	5.195		4.913	7.207	8.586	8.723*	6.077	10.336	9.885	7.662	6.115	4.721
10	6.541	4.183		4.927	9.258	8.217	9.619*	5.411	5.673	11.439	8.989	6.258	4.841
11	8.214	4.423		5.045	8.485	7.202	8.539*	6.041	5.39	10.698	9.402	6.040*	6.025
12	7.185	4.909		4.242	7.68	4.582	8.252*	7.824*	7.188	10.475	11.224	9.223	5.213
13	7.624	4.563		6.415	6.47	5.535	8.622*	6.464*	5.798	10.957	8.567	11.025	6.3
14	7.217	5.958		6.106	9.03	7.005	8.251*	7.103*	8.792	9.819	6.369	8.126	5.992
15	7.339	6.526		6.591	8.814	8.076	7.7*	7.981*	8.461	10.821	6.492	7.065	6.832
16	6.733	7.717		6.539	9.067	10.853	7.595*	7.407*	9.856	10.466	7.365	6.431	7.217
17	7.507	7.194		5.482	10.806	11.457	8.197*	7.507*	7.606	11.248	5.43	4.404	5.955
18	9.291	6.566		5.657	10.544	11.435	5.856*	7.585*	4.974	12.406	5.455	4.978	5.545
19	6.918	3.932		6.646	10.385	10.958	6.790*	5.788*	6.368	12.102	8.032	6.128	4.173
20	5.308	5.475		6.484	10.634	11.269	7.516*	6.496*	7.086	10.004	5.875	5.833	4.595
21	4.763	5.068		7.243	7.588	10.496	7.756*	8.366*	4.837	9.548	8.048	5.082	6.269
22	6.386	4.605		7.805	8.551	10.999	7.972*	8.123*	6.334	10.69	5.231	5.255	6.958
23	5.913	5.3		8.64	8.745	9.787	9.326*	8.140*	6.631	9.668	9.462	5.791	5.671

24	5.574	5.727		8.905	7.76	10.106	7.868*	8.793*	8.835	7.952	7.708	5.842	5.217
25	4.544	6.349		7.691	7.73	10.726	9.077*	8.843*	9.748	10.438	8.714	5.656	5.157
26	4.279	6.512		7.963	7.792	9.616	8.358*	8.353*	7.45	8.406	8.949	5.369	5.384
27	5.794	5.401		6.715	9.293	7.432	9.328*	8.435*	9.883	5.218	10.709	4.73	5.527
28	6.765	4.995		7.281	9.811	6.851	8.583*	7.793*	10.733	6.133	10.986	8.058	8.494
29	6.812	4.719		7.602	9.631	9.403	6.228*	7.727*	10.028	6.259	7.951	7.742	9.044
30	6.34	4.518		7.523	9.382	10.896	6.761*	7.111*	10.15	7.998	8.365	7.653	7.736

Table A.4 Average daily wind speed of 2011E.C fiscal year

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	8.495	5.262	4.244	4.658	8.317	4.824	6.391	11.513	6.446	8.733	7.106	9.097	6.379*
2	9.466	6.44	5.518	4.15	7.65	7.02	9.144	9.962	9.962	6.863	7.267	8.133	5.951*
3	8.566*	7.274	5.82	4.88	6.681	8.978	7.842	10.722	10.722	7.049	7.526	6.552*	5.233*
4	8.842*	5.278	5.878	5.801	6.405	8.602	11.279	10.427	10.427	6.873	8.395	5.612*	5.748*
5	8.958*	3.593	4.172	4.253	6.652	7.241	10.61	7.955	7.955	6.977	5.439	5.722*	6.163*
6	7.272	5.319		3.682	6.002	5.485	9.143	5.53	5.53	9.333	7.885	5.771*	6.529*
7	7.097	5.892		4.984	7.574	5.047	8.367	7.451	7.451	6.205	10.251	6.634*	5.812*
8	6.806	5.165		5.89	6.948	7.414	6.839	7.614	7.614	8.251	6.208	4.896*	5.397*
9	6.917	4.552		4.563	7.107	9.19	8.53	6.814	6.814	8.431	8.35	5.138*	5.211*
10	7.292	4.706		4.672	6.755	10.864	8.555	6.65	6.65	8.371	7.617*	5.109*	5.952*
11	6.231	4.79		5.932	7.981	11.372	9.323	6.819	6.819	8.169	7.984*	3.506*	5.660*
12	6.408	5.378		4.515	8.614	13.272	7.722	7.395	7.395	6.93	8.672*	6.337*	5.404*
13	7.16	5.767		6.507	11.699	12.298	7.581	6.32	6.32	8.173	9.693*	7.196*	5.444*
14	6.239	5.525		5.507	7.785	4.968	8.154	6.628	6.628	9.021	8.391*	6.507*	5.724*
15	4.879	6.37		5.394	9.005	8.85	7.288	7.733	7.733	6.745	7.124*	5.622*	6.071*
16	4.785	7.086		6.124	9.161	9.606	6.928	7.169	7.169	6.018	7.471*	5.662*	6.291*
17	5.815	5.882		7.204	9.049	10.753	8.925	8.303	8.303	6.499	7.479*	4.901*	5.416*
18	5.551	5.824		7.819	8.835	10.564	3.859	9.107	9.107	8.2	6.699*	4.914*	5.388*

19	4.263	5.738		6.878	10.86	11.224	5.799	8.188	8.188	8.286	6.429*	10.6	5.116*
20	5.497	6.871		8.231	10.198	12.369	9.9	8.521	8.521	6.115	6.078*	8.551	5.978*
21	5.456	6.541		8.689	12.206	11.235	8.235	10.496	10.496	7.267	7.771*	4.3*	6.407*
22	6.104	5.579		7.933*	11.123	9.726	8.81	10.389	10.389	5.495	12.567	4.951*	6.365*
23	4.263	5.402		8.284*	9.371	10.634	11.2	9.005	9.005	8.05	10.131	5.115*	6.515*
24	4.468	4.033		9.678	6.451	9.734	8.1	9.752	9.752	7.127	9.775	5.725*	6.098*
25	4.123	5.111		8.941	6.725	6.941	9.033	9.845	9.845	6.481	10.453	5.475*	6.364*
26	5.644	5.076		7.72	5.782	6.208	9.663	8.492	8.492	6.451	11.152	5.069*	6.533*
27	5.619	5.532		8.124	6.399	6.959	10.823	9.292	9.292	7.958	11.829	5.333*	6.215*
28	4.282	5.945		6.886	8.467	7.345	9.373	11.95	11.95	10.277	10.634	6.699*	7.031*
29	4.529	4.964		7.972	6.673	8.139	8.495	11.436	11.436	9.678	8.939	6.102*	7.491*
30	4.379	5.38		9.142	5.626	9.015	9.136	7.273	7.273	9.018	9.082	6.087*	6.659*

APPENDIX-B

B. Power curve table of Ashegoda wind farm turbines

Table B.1 GEV HP-62/1000 wind turbine power curve table at 1.225Kg/m3

Wind Speed (m/s)	Power (KW)
2.5	0
3	7
3.5	23
4	43
4.5	67
5	95
5.5	128
6	168
6.5	215
7	269
7.5	330
8	399
8.5	476
9	560
9.5	646
10	731
10.5	804
11	859
11.5	899
12	929
12.5	952
13	969
13.5	981
14	990
14.5	997
15	1000
15.5-25	1000

Table B.2 ECO-74 wind turbine power curve table at 1.225Kg/m3

Wind Speed (m/s)	Power (KW)
3	0
4	47
5	125
6	228
7	373
8	570
9	834
10	1144
11	1445
12	1619
13	1668
14	1670
15	1670
16	1670
17	1670
18	1670
19	1670
20	1670
21	1670
22	1670
23	1670
24	1670
25	1670

APPENDIX-C

C. Frequency and Probability distribution of wind for Ashegoda wind farm

Table C.1 Four years frequency and probability distribution of wind

Frequency table of 2008E.C			Frequency table of 2009E.C		Frequency table of 2010E.C		Frequency table of 2011E.C	
Limits(m/s)	Frequency	f(Vi)	Frequency	f(Vi)	Frequency	f(Vi)	Frequency	f(Vi)
3	0	0	2	0.005494505	0	0	0	0
3.5	0	0	5	0.013736264	0	0	0	0
4	14	0.0382514	15	0.041208791	2	0.005479452	4	0.010958904
4.5	24	0.0655738	25	0.068681319	7	0.019178082	12	0.032876712
5	31	0.0846995	29	0.07967033	21	0.057534247	19	0.052054795
5.5	55	0.1502732	36	0.098901099	33	0.090410959	30	0.082191781
6	37	0.1010929	41	0.112637363	29	0.079452055	38	0.104109589
6.5	41	0.1120219	23	0.063186813	40	0.109589041	37	0.101369863
7	35	0.0956284	14	0.038461538	26	0.071232877	39	0.106849315
7.5	35	0.0956284	25	0.068681319	35	0.095890411	32	0.087671233
8	27	0.0737705	23	0.063186813	43	0.117808219	23	0.063013699
8.5	22	0.0601093	31	0.085164835	30	0.082191781	30	0.082191781
9	20	0.0546448	29	0.07967033	22	0.060273973	20	0.054794521
9.5	15	0.0409836	17	0.046703297	21	0.057534247	25	0.068493151
10	7	0.0191257	14	0.038461538	14	0.038356164	15	0.04109589
10.5	2	0.0054645	12	0.032967033	12	0.032876712	11	0.030136986
11	1	0.0027322	8	0.021978022	16	0.043835616	11	0.030136986
11.5	0	0	11	0.03021978	9	0.024657534	9	0.024657534
12	0	0	3	0.008241758	1	0.002739726	5	0.01369863
12.5	0	0	2	0.005494505	2	0.005479452	3	0.008219178
13	0	0	0	0	1	0.002739726	1	0.002739726
13.5	0	0	0	0	1	0.002739726	1	0.002739726
14	0	0	0	0	0	0	0	0
14.5	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0

APPENDIX-D

D. Downtime

Table D.1 Downtime due to failure and maintenance of 2010 EFY

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	152.5	391	292	408	1161.5	864		1944	2016	1685	1831	1870.5	1760
2	284	277	282	361.5	144	1684		1944	2016	1680	1832	1754	1920
3	191	299.5	382	652	144	1776		1955	2016	1702	1736.5	1776	1889
4	172.5	310	393.5	280.5	144	1776		1968	2016	1673	1728	1776	1860
5	329	315	471.5	459.5	144	1776		1968	2016	1440	1728	1777.5	1797
6	267.5	308.5		399	224	1760.5		1968	2016	1584	1747.5	1742	1902
7	175.5	299		418	456	1608		1992	2016	1584	1765	1745	1842.5
8	170.5	491		357.5	2016	1693.5		1992	2003.5	1584	1193.5	1346	1756
9	242.5	375		346	1008.5	1720		1992	1980	1584	1760	1800	1933.5
10	239	404.5		306	1039.5	1728		1992	1440	1599.5	1741	1349.5	1905
11	197.5	331		389	975.5	1839.5		1992	1880	1612	1728	1670	1875
12	219	319.5		408.5	784	1867.5		1992	1885.5	1752	1728	1828.5	1738.5
13	263.5	322		412.5	688	1866.5		2016	1791.5	1533	1728	1743	1699.5
14	238.5	286		409	288	1779.5		2016	1825.5	1732.5	1224	1782	1278.5
15	225.5	252.5		382	576	1779.5		2016	1705	1766	1815	1752	1735.5
16	239.5	374.5		434	1404	1517		2016	1672	1752	1713	1529.5	1747
17	576	411		367	1103.5			2016	2016	1752	1773	1288	831.5
18	270	457.5		298	1153.5			2016	2016	1498	1792	1756	1850
19	241	619		327	1179			2016	1948	1741	1847	1776	1727
20	241	403		399.5	2016			2016	1717	1728	1828.5	1825.5	1799
21	209	338.5		361	1496			2016	1795	1729	1968	1675	1754
22	266.5	427		356.5	984			2016	1732.5	1738.5	1186	1768.5	1752
23	290.5	638.5		606.5	984			2016	1744	1348.5	1050	1763	1852
24	257	367		206	984			2016	1743	1838	1884	1728	1944

25	330	385.5		165.5	816			2016	1732	264	1728	1728	1816
26	343	544.5		2016	974			2016	1784	456	1728	1584	1569.5
27	355	553.5		1176	704			2016	1740	280	1728	1713	1752
28	305.5	483		150	1332			2016	1743.5	465	1728	1764.5	1731
29	275.5	410.5		1000	926.5			2016	1717	1803.5	1728	1767	1731
30	362	445.5		800	884.5			2016	1656	1896	1728	1746	1650

Table D.2 Downtime due to failure and maintenance of 2011 EFY

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	1512	1880.5	996	1578.5	1815	1893.5	1851	1890.5	1419.5	1354.5	1455.5	1387.5	2016
2	1837.5	1924	1148.5	373.5	1810		1824	1832.5	1311.5	1631.5	1442.5	1496	2016
3	2016	1810.5	1459.5	1032	1800	1877.5	1824	1825.5	1452	1405.5	1388.5	2016	2016
4	2016	1869.5	1148	1734	1900	1902.5	1846.5	1848	1442	1675.5	1433	2016	2016
5	2016	1880	1649.5	1666.5	1877.5	1862.5	1877.5	1848	1392	1422	1057	2016	2016
6	2016	1870.5		1455	1841.5	1727	2016	1948.5	1393.5	1421.5	1391.5	2016	2016
7	2016	1878.5		1226	1824	1568	2016	1847	1401.5	1404	1814.5	2016	2016
8	1932	1812		1804	1881	1848	1932	1835.5	1437	1432		2016	2016
9	1504.5	1907		1771.5	1889	1204.5	1857.5	1824	1469	1440	1841	2016	2016
10	1492	1844		1523	1824	1852	1607	1824	1560	1430	2016	2016	2016
11	1570	1825		1699	1878	1883	1848	1593.5	1072.5	1451	2016	1680	2016
12	1572.5	1846		1305	1844	1876.5	2016	1551.5	815.5	1422	2016	2016	2016
13	1549	1856		1781.5	1863.5	1824	2016	1648	1556.5	1454.5	2016	2016	2016
14	1333	1836.5		1737	1908	1871	2016	1690	1815	1438.5	2016	2016	2016
15	1993.5	1896		1803.5	1849	2016	2016	1512	1787.5	1367	2016	2016	2016
16	1468.5	1943		1508	1824	2016	1939	1533.5	1785	1508	2016	2016	2016
17	1764.5	1789.5		1873.5	1824	1924	1415.5	1526.5	1794	1661.5	2016	2016	2016
18	1806	1855.5		1819	1943	1890.5	1765	1363	1800	1443.5	2016	2016	2016
19	1724	1848		1800	1900	1845	1837.5	1426	1864	1430	2016	1993	2016

20	1776	1935.5		1804	1850.5	1841.5	1708	1424	1863	1098	2016	1980.5	2016
21	1800.5	1740		1952	1920	1578	1848	1413	1855.5	1436	2016	2016	2016
22	1883	1895.5		2016	1824	2016	1468	1392	1888	1418.5	2016	2016	2016
23	626	1854		2016	1843	2016	768.5	1427	1827.5	1425	2016	2016	2016
24	1698.5	1871.5		1981.5	1811	1933.5	1832.5	1400	1771	1448.5	2016	2016	2016
25	1429.5	1755.5		1403.5	1660.5	1855	1858	1415.5	1771	1399	1669	2016	2016
26	1513.5	1963		1838.5	1808.5	1903.5	1833	1415	1634.5	1303.5	1140	2016	2016
27	1479.5	1979.5		1896	1847	1842	1847	1421	1848	1366.5	1368	2016	2016
28	1393.5	1740		1874.5	1846.5	1824	1936	1482	1949.5	1443	1368	2016	2016
29	1503.5	1161.5		1880	1836.5	1837.5	1968	1412	1908	1440	1371.5	2016	2016
30	1435.5	1518.5		1888	1843.5	1828.5	1968	1350.5	1540.5	1430.5	1392	2016	2016

Table D.3 Downtime due to low wind speed of 2010 EFY

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	0.5	20.5	18	411	0	3		0	0	0	7.5	0	0
2	44	69.5	0	257.5	0	0		0	0	0	0	0	0
3	294	229.5	0	204.5	0	0		0	0	88	0	0	0
4	89.5	44	0	446	0	0		0	0	75	0	0	0
5	119	48.5	126.5	214.5	426	0		0	0	180	0	0	0
6	24.5	30.5		132.5	0	0		0	0	0	0	0	0
7	13.5	82.5		79	0	0		0	0	0	0	0	0
8	55.5	125.5		203.5	0	0		0	0	0	152	30	29
9	61	250.5		427	0	0		0	0	0	0	0	0
10	29.5	192		576.5	11.5	0		0	24	0	0	52	0
11	14	624		249	2.5	0		0	1.5	0	0	0	0
12	24.5	213.5		515	3	9.5		0	0	0	0	0	9
13	20	143.5		112	2	0		0	0.5	0	0	0	84
14	26.5	10		501	24	0		0	0	0	0	0	210

15	26.5	65		15.5	0	0		0	0	0	0	0	15
16	8.5	98.5		141.5	0	0		0	0	0	0	294	15
17	12.5	61.5		241.5	0			0	0	0	119	336	45
18	14	124.5		65.5	0			0	0	0	0	29.5	0
19	148.5	420		18.5	0			0	0	0	0	41.5	75
20	134.5	105.5		288	0			0	0	0	3	3	0
21	159.5	334.5		112	4			0	0	0	0	126	0
22	41.5	303		27.5	6.5			0	30	0	105	0	0
23	38.5	34.5		24	0			0	0	0	0	0	0
24	73	159		27	0			0	0	0	0	0	0
25	278.5	65		13	0			0	0	0	0	0	0
26	154	10.5		0	0			0	68	0	0	168	50
27	42	136		0	0			0	0	72	0	165	0
28	30.5	353.5		0	8			0	0	135	0	0	0
29	105	148.5		0	0			0	0	19	0	0	0
30	49	0		18	0			0	0	0	0	0	0

Table D.4 Downtime due to low wind speed of 2011 EFY

Date	July	August	Pagumen	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
1	0	0	630	336	0	0	0	0	0	0	0	0	0
2	0	0	36	1465	0		0	0	0	0	0	0	0
3	0	1.5	0	882	0	0	0	0	0	0	0	0	0
4	0	0	294	126	0	0	0	0	0	0	0	0	0
5	0	45	214	252	0	0	0	0	0	60	504	0	0
6	0	45		539.5	0	134	0	0	0	0	0	0	0
7	0	0		672	0	0	0	0	0	75	0	0	0
8	0	0		0	0	0	0	0	0	0		0	0
9	30	0		90	0	0	0	0	0	0	0	0	0
10	0	30		390	0	0	0	0	0	0	0	0	0
11	0	0		135	75	0	0	0	630	0	0	0	0
12	0	0		105	0	0	0	0	630	90	0	0	0
13	0	9		0	0	0	0	0	0	0	0	0	0
14	0	30		0	0	0	0	0	0	0	0	0	0
15	0	0		0	0	0	0	0	0	150	0	0	0
16	89	0		0	0	0	0	0	0	0	0	0	0
17	0	30		0	0	0	34	0	0	0	0	0	0
18	0	0		0	0	0	0	0	0	0	0	0	0
19	120	0		0	0	0	0	0	0	0	0	0	0
20	0	0		0	0	0	0	0	0	504	0	0	0
21	0	0		0	0	0	0	0	0	0	0	0	0
22	0	15		0	0	0	0	0	0	0	0	0	0
23	0	0		0	0	0	0	0	30	0	0	0	0
24	1	18		0	87	0	0	0	0	0	0	0	0
25	0	27.5		0	0	60	0	0	0	30	0	0	0
26	0	30		0	65	0	0	0	225	535.5	0	0	0
27	0	0		0	0	0	0	0	0	126	0	0	0

28	126	4		0	0	0	0	0	0	0	0	0	0
29	0	5		0	15	0	0	0	0	0	0	0	0
30	126	75		0	15	0	0	75	0	0	0	0	0

APPENDIX-E

E. Moving Average Wind Speed Results

Table E.1: Wind speed value for July 1, 2010E.C

Date	Observed value (Yt)	MA(3)	Error with MA(3)	MA(5)	Error with MA(5)	MA(7)	Error with MA(7)
21	5.315						
22	5.186						
23	7.278						
24	6.558	5.926	0.632				
25	6.365	6.341	0.024				
26	6.117	6.734	-0.617	6.140	-0.023		
27	5.863	6.347	-0.484	6.301	-0.438		
28	5.901	6.115	-0.214	6.436	-0.535	6.097	-0.196
29	7.153	5.960	1.193	6.161	0.992	6.181	0.972
30	6.534	6.306	0.228	6.280	0.254	6.462	0.072
1		6.529		6.314		6.356	
			TAE=3.391		TAE=2.243		TAE=1.240
			MAE=0.484		MAE=0.449		MAE=0.413

Table E.2:Wind speed value for May 11, 2010E.C

Date	Observed value (Yt)	MA(3)	Error with MA(3)	MA(5)	Error with MA(5)	MA(7)	Error with MA(7)
1	7.384						
2	8.666						
3	7.558						
4	7.442	7.869	-0.427				
5	8.308	7.889	0.419				
6	7.06	7.769	-0.709	7.872	-0.812		
7	8.544	7.603	0.941	7.807	0.737		
8	5.748	7.971	-2.223	7.782	-2.034	7.852	-2.104
9	6.115	7.117	-1.002	7.420	-1.305	7.618	-1.503
10	6.258	6.802	-0.544	7.155	-0.897	7.254	-0.996
11		6.040		6.745		7.068	
			TAE=6.266		TAE=5.786		TAE=4.602
			MAE=0.895		MAE=1.157		MAE=1.534

Table E.3:Wind speed value from July 3 to 5, 2011E.C

Date	Observed value (Yt)	MA(3)	Error with MA(3)	MA(5)	Error with MA(5)	MA(7)	Error with MA(7)
23	5.671						
24	5.217						
25	5.157						
26	5.384	5.348	0.036				
27	5.527	5.253	0.274				
28	8.494	5.356	3.138	5.391	3.103		
29	9.044	6.468	2.576	5.956	3.088		
30	7.736	7.688	0.048	6.721	1.015	6.356	1.380
1	8.495	8.425	0.070	7.237	1.258	6.651	1.844
2	9.466	8.425	1.041	7.859	1.607	7.120	2.346
3		8.566		8.647		7.735	
4		8.842		8.678		8.071	
5		8.958		8.604		8.434	
			TAE=7.183		TAE=10.071		TAE=5.570
			MAE=1.026		MAE=2.014		MAE=1.857

Table E.4:Wind speed values September 22 and 23, 2011E.C

Date	Observed value (Yt)	MA(3)	Error with MA(3)	MA(5)	Error with MA(5)	MA(7)	Error with MA(7)
12	4.515						
13	6.507						
14	5.507						
15	5.394	5.510	-0.116				
16	6.124	5.803	0.321				
17	7.204	5.675	1.529	5.609	1.595		
18	7.819	6.241	1.578	6.147	1.672		
19	6.878	7.049	-0.171	6.410	0.468	6.153	0.725
20	8.231	7.300	0.931	6.684	1.547	6.490	1.741
21	8.689	7.643	1.046	7.251	1.438	6.737	1.952
22		7.933		7.764		7.191	
23		8.284		7.876		7.448	
			TAE=5.692		TAE=6.720		TAE=4.418
			MAE=0.813		MAE=1.344		MAE=1.473