ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

SCHOOL OF ELECTRICAL ENGINEERING AND COMPUTING

DEPARTMENT OF ELECTRICAL POWER AND CONTROL ENGINEERING

RELIABILITY ASSESSMENT OF ADAMA I WIND POWER PLANT

BY

ADDISU FEYISSA DEGAGA

JULY 2020

ADAMA, ETHIOPIA

RELIABILITY ASSESSMENT OF ADAMA I WIND POWER PLANT

By

Addisu Feyissa Degaga

ID No: A/PE16410/10

A Thesis submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering & Computing

Presented in Partial Fulfilment of the Requirement for the Degree of Master's in

Electrical Power Engineering

Office of Graduate Studies

Adama Science and Technology University

Adama, Ethiopia

July 2020

RELIABILITY ASSESSMENT OF ADAMA I WIND POWER PLANT

By

Addisu Feyissa Degaga

Advisor: Dr. Molla Biweta

A Thesis submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering & Computing

Presented in Partial Fulfilment of the Requirement for the Degree of Master's in

Electrical Power Engineering

Adama, Ethiopia

July 2020

Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense by Addisu Feyissa Degaga have read and evaluated his thesis entitled "***RELIABILITY ASSESSMENT OF ADAMA I WIND POWER PLANT***" and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfilment of the requirement of the degree of Master of Science in Electrical Power Engineering.

Name	Signature	Date
Addisu Feyissa Name of Student		17-08-2020
Dr. Molla Biweta Advisor		17/08/2020
Dr. Tirehun T External Examiner		17-08-2020
Dr. Tefesse Asrat Internal Examiner		18/08/2020
Dr. Tefera T Chair Person		09/08/2020
Tamirat Permu Alemayehu Garbaba Electrical Power and Control Engineering Department Head ሕንሰርመ አለማየሁ ጋርባባ የኤሌክትሪካል ፓወርና ኮንትሮል ምህንድስና ትምህርት ክፍል ኃላፊ Head of Department		15/8/2020
Dereje Tekilu Aseffa (PhD) Dean, School of Electrical Engineering & Computing School Dean		24/08/20
ለገሠ ለሜቻ ኦብሱ (ዶ/ር) Legesse Lemecha Obsu (Ph.D) Post graduate Dean		24/08/20

Declaration

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

Mr. Addisu Feyissa ____________
Name Signature

Place: Adama Science and Technology University, Adama, Ethiopia

Date of Submission: *July 22, 2020*

This thesis has been submitted for examination with my approval as a university advisor.

Dr. Molla Biweta ________________
Advisor Signature

Acknowledgement

I am sincerely grateful to my advisor, Dr. Molla Biweta for his critical guidance, patience, and inspiration throughout my thesis process. Thank you for imparting your comprehensive knowledge and sharing your wisdom. Completing this thesis with you has certainly been an honor for me. I would like to say thank you to Ms. Aynalem W/Michael (Manager of the Power Plant) for her great cooperation. I would also like to thank the Operation and Maintenance staff of Adama 1 Wind Power Plant. I am grateful to many people and positive circumstances that brought me until this point. Thanks to those whom attentions, moments, comments, criticism, conversations, favors and smiles made my life easier and happier.

Last but not least, I must appreciate my wife who always believes in me and enlightens me to be a good man. The intelligence and fortitude inherited from her make every success of mine.

Table of Contents

List of Tables

List of Figures

Acronyms

AC	Alternating Current
AEP	Annual Energy Production
CE	Capacity Factor
Cdf	Cumulative distribution function
CM	Corrective Maintenance
CMS	Condition Monitoring System
DC	Direct Current
DFIG	Doubly Fed Induction Generator
EEP	Ethiopian Electric Power
Eq.	Equation
GHG	Green House Gasses
MTBF	Mean Time between Failures
MTTR	Mean Time to Repair
MTTF	Mean Time to Failures
O&M	Operation & Maintenance
PMSG	Permanent Magnet Synchronous Generator
Pdf	Probability distribution function
PM	Preventive Maintenance
RBD	Reliability Block Diagram
RPM	Revolution per Minute
SCADA	Supervisory Control and Data Acquisition
T	Time
WPP	Wind Power Plant
WT	Wind Turbine
WTs	Wind Turbine system
WECS	Wind Energy Conversation Systems

Abstract

The importance of renewable energy sources has increased rapidly due to run out of fossil fuels and environmental effects of conventional energy production systems. As one of the renewable energy sources, wind energy has considered to be a leading alternative energy source by reason of vast energy potential of wind. Reliability analysis of wind turbine can help to identify, classify, and investigate several issues and concepts that arise in wind energy systems. Due to random characteristics of wind speed, electric generation reliability of wind energy system is affected in grid connected configurations. Reliability is critical to the design, operation, maintenance, and performance assessment and improvement of wind turbines (WTs). There are a wide variety of wind turbines types. The selection of a wind turbine type, the site of wind turbines fields erection and the maintenance scheme are basic parameters which should be carefully considered for optimum performance and reliable operation and power output. Many techniques had been developed and refined to represent and study the wind turbines complex system in order to make their operation safe, reliable and maintainable. The plant was produce power in good progress in the year 2014 and 2015 G.C. when comparing with year 2017 to 2019. In 2017 the production of the power plant goes down which shows the performance is not good. The objective of this thesis is to analyze and provide reliability information of Adama 1 WPP performance by considering the characteristics of wind at the site, operation of the components and others factors affecting the production of turbines. Wind speed data and failure data are analyzed by using mat lab software. Any data of turbines are collected by excel and fed to mat lab for performance assessment. Additionally, an extensive analysis of historical failure and downtime data of 34 turbines is presented. Quantitative and qualitative terms and measures are employed in order to analyze the reliability of wind turbines in Adama 1 wind farm. Plant Factor and availability are calculated. Finally, it is recommended that the company (EEP) could make ready wind turbine spare parts in stoke to reduce failure downtimes of the components.

Keywords: *Wind Energy, Reliability, Maintainability, Availability, Operation & Maintenance, Failure rate, mat lab, Downtime, Failures*

CHAPTER ONE

INTRODUCTION

1.1. Background

Modern wind turbines are complex aerodynamic, mechanical, electrical and electronic machines incorporating sophisticated control systems. Wind turbines have been erected in increasing numbers in off shore and onshore in many countries like India, Germany and Denmark [1]. The wind turbine energy played a particularly prominent part in production of electricity to support the electric grid.

In the last decade, the design of wind turbines has widely evolved due to increasing the installed capacities of wind turbines rather than other renewable energy sources. By the end of 2016, the world installed capacity of the onshore wind turbines approximately reached 472 GW, by an additional value of 52.4 GW, from almost negligible capacity in early 1990 [2]. This technology evolution for different components needs more knowledge about what priority of these components in industrial operations.

For example, according to the data extracted from the latest wind energy operations and maintenance report 2016, the electrical components are the leading cause of lost days per year as well as the failure in the gearbox is rare but its outage represents the longest outage [3]. So, the evolution should be started from the components that have a greater effect on the power production of WTGs. The RAM analysis will help manufacturers to produce reliable wind turbines. Hence, RAM analysis of renewable energy sources represents a serious challenge in the worldwide development and economy [4].

There are many different types of WTGs. The selection between these configurations is based some issues such as operating and control principles, and the gird connection methods, etc. The selection between different configurations is still the most dominant issue in the reliability study. This is due to the fact that, operators and developers of wind turbines are always trying to pick a turbine which has a higher reliability.

The reliability issues have been identified since three decades. However, the reliability assessment of the whole power production is still under controversy due to the complex nature of these systems. The most literature focuses only on reliability assessment of the system vulnerable components by different methods, whereas literatures that discussed the reliability evaluation of the whole systems are much fewer.

Reliability is the probability of a system, subsystem, or even subassembly performing its function adequately for the period of time intended, under the operating conditions intended.

This intended period is typically the lifetime of the system [5]. From a reliability point of view, there are two different types of systems, repairable system and non-repairable system. The WTGs can be considered as a repairable system [6] and in which the faulty components are repaired or replaced with interrupting the mission of the system.

An increasing number of wind turbines are being incorporated into European electrical networks. In some countries such as Denmark, Germany and Spain they are becoming a key part of networks and as such affect the overall system performance and reliability [7]. The configuration, technology and size of wind turbines have been changing rapidly over the last few years, and larger turbines (≥2MW) incorporating new technology are being installed onshore in different countries. There is potential for more wind turbines to be erected in remote and offshore locations, to achieve a greater wind energy harvest, where the access to turbines for maintenance will be restricted. This is heightening the need for accurate reliability predictions so that wind turbine availability and life can be predicted and reasonable predictions of wind energy harvest over the life of the turbines can be made.

Today, governments over the world set goals to reduce greenhouse gas emission and to increase electricity production from renewable energy sources. The European Commission's targets for 2020 are:

- 20% decrease of greenhouse gas emission from the 1990 levels
- 20% of the EU's total energy comes from renewables
- 20% increase in energy efficiency. [8]

From an examination of the renewable energy sector, hydropower, geothermal power and biogas are all considered developed solutions, whereas wind, solar and nuclear are still under development [9].

Currently, hydro and geothermal power dominate Ethiopian energy production. The addition of wind power within the energy mix is also an interesting option. Wind energy is generally considered predictable over the long-term, whereas hydropower is more predictable over the short-term. A mix of hydro power and wind turbines is generally considered a good decision because of hydropower's ability to level out short term variability in energy production and wind power's long-term reliability [10]. Wind turbines' main power season in Ethiopia is through the winter, when water flow is low. This aspect leads wind power to be used to compensate for hydro power throughout the low season, when the reservoir may be used as energy storage [11].

Today's focus is on the renewables that have demonstrated many opportunities and recent growth, namely solar and wind energy.

The penetration of wind energy conversation systems (WECS) to electric power grids are on the increase. Since then, the reliability aspects of renewable energy sources have growing importance in power systems. Wind energy is becoming a matured technology and is growing dramatically all over the world. The use of wind energy is growing significantly and this clean energy continues to be the technology of choice in many countries. [12]

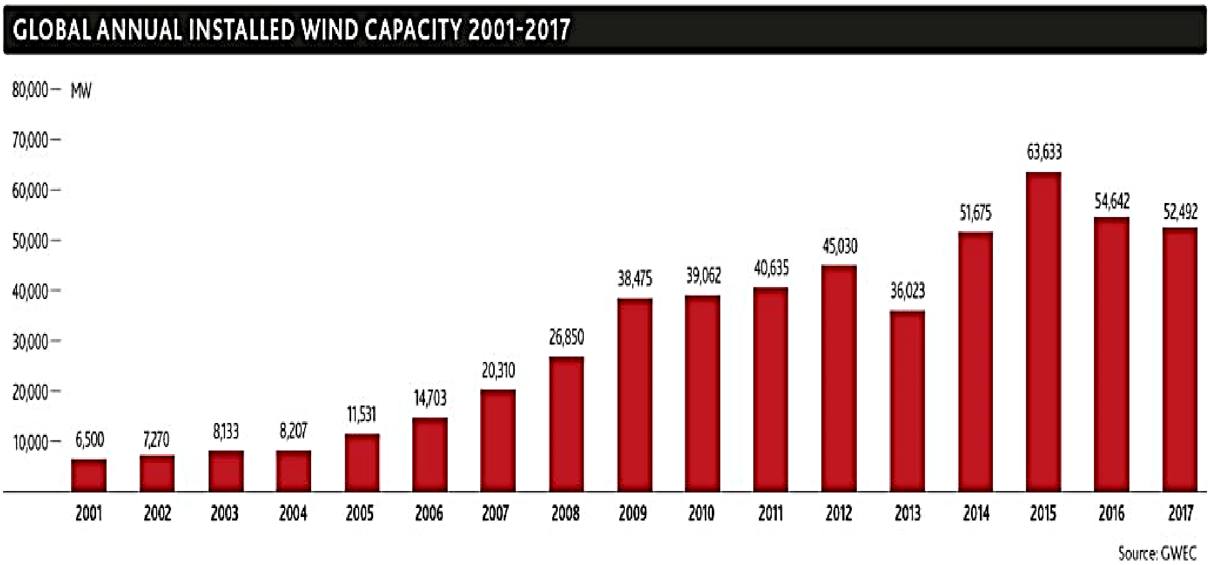


Figure 1.1: Global annual installed capacity of Wind Energy

Thus, it is important to understand the reliability contribution of wind farms and evaluate their actual capability to support wind power connected grid. A wind turbine system normally consists of the blades, the tower, the gear box, the wind generator, the power cables, the power electronics mechanical parts and the unit transformer [13].

In recent years, technological advances have led to the development of small-scale, user friendly, easily installed renewable energy systems. These types of systems enable energy end-users to install renewable generators on-site, connect them to the national network and trade energy on the electricity market [14]. The functionality of these systems is dependent on the functions provided by different components of WTG, whose reliability must be properly designed and availability carefully maintained.

Wind is a resource that can be used in excess without threatening to reduce its natural stock. In fact, wind can be found almost anywhere on earth. Even though wind power systems are only used within a certain range of wind speeds, this type of energy production is quite efficient.

The power curve models the power output for a specific wind turbine as a function of wind speed [15]. This curve is not linear with wind speed and the shape varies between different types of wind turbines

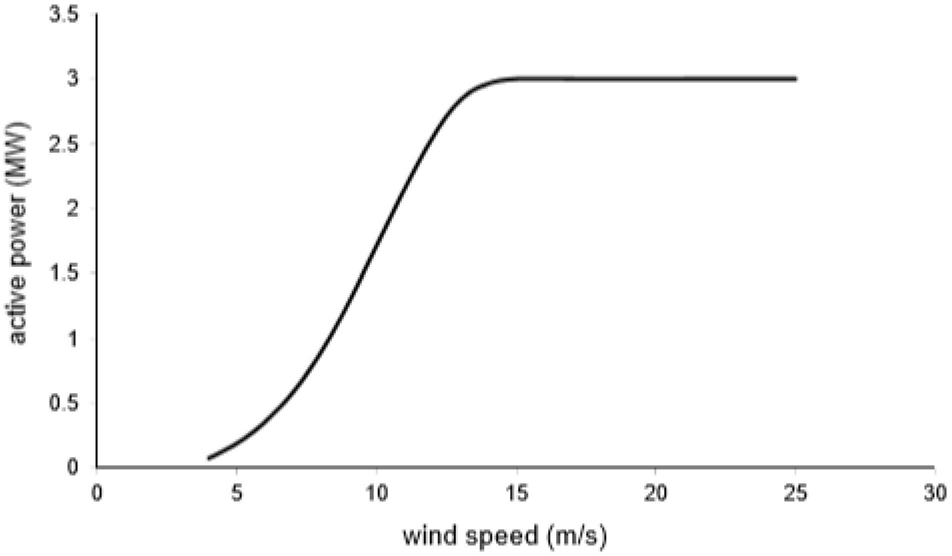


Figure: 2. Power curve characteristic of the analysed Wind Turbine [15].

Although the power outputs depend on wind speed, a wind turbine on land can often generate a certain percentage of its theoretical maximum energy output, e.g. 20% to 30%. Wind turbine operation and maintenance represent an important part of the cost of wind power production. In fact, the share of operation and maintenance costs represents 20% to 25% in the lifetime of a wind turbine. Actually, these costs are limited to 10% to 15% when the wind turbine is fairly new, but they increase to at least 20% to 35% by the end of its lifetime. Operational assessment can help reduce these costs, as it provides information for the development of maintenance and repair strategies. [16]

Reliability assessment is an important part in the design of any system and it can even be considered as a design parameter. Quantitative and qualitative terms and measures may be employed in order to obtain high reliability in wind turbines. [16] One of the initial steps to realizing an improvement in reliability would be to understand the components in the systems which are prone to failures. In order to have a good restoration procedure, study of statistical data for wind turbine failures is important.

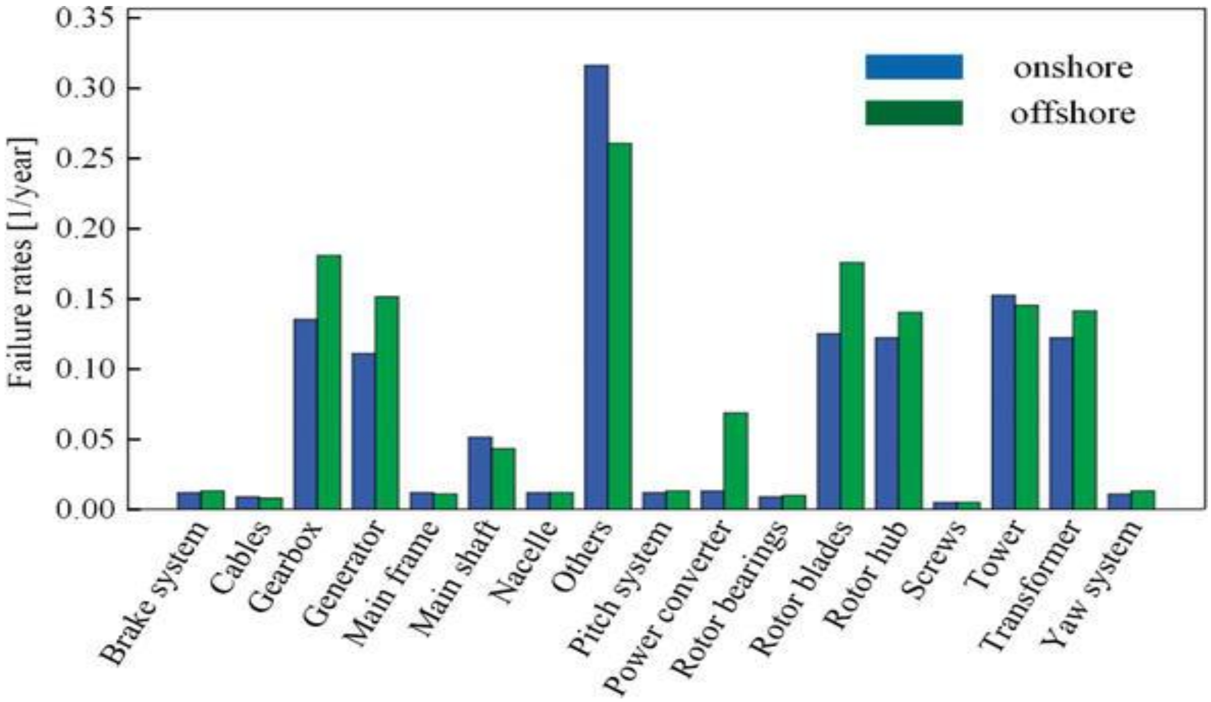


Figure 1.2: Failure rates for wind turbine subassemblies working onshore and offshore. [16]

There is a recognized need for improved reliability in the design, manufacturing quality, operation, and maintenance of wind turbines. Industry and others have acknowledged the importance of reliability in the continued growth and expansion of markets for wind turbine technology. Reliable operations are critical for the hostile environments where turbines are sited and the impacts of reliability (or unreliability) are broad, ranging from economics to advancement of designs.

Modern onshore wind turbines (WTs) achieve a quite high availability of about 95% to 99%. Nevertheless, quite a number of faults cause unscheduled down times, for specific wind turbine types. Reliability achieved is therefore not satisfying, and needs to be decisively improved. Subassemblies of the electrical and control system of WTs failed every two or two and a half year on average. Damage to the general drive train of a WT, in a purely statistical comparison, occurs only every 19 years. [17]

Reliability is a critical issue for the growing wind energy industry since it affects other areas such as safety, availability, maintenance, logistics and cost [18]. Furthermore, reliability is dealt with during all phases of lifetime, from design via testing, to construction and operation until decommissioning. To improve the reliability of wind assets, a detailed understanding of reliability characteristics of systems, components and subassemblies is required. This must be complemented by qualitative assessments and statistical analyses of operational and maintenance information sources. Currently, the wind industry lacks a common understanding and a uniform way of collecting and analyzing data from operation and maintenance for reliability analyses. Thus, databases of existing initiatives are often inconsistent and too small for sound statistical analyses and results are not comparable. However, a variety of respective guidelines already exists, and they should be the basis for harmonization, recommendations and standardization.

It is clear that the more seldom failures of the drive train usually result in long periods of downtime, and the more frequent failures of the electrical and control system cause only short downtimes. Nevertheless, the high number of minor failures results in high maintenance efforts, production losses and costs, requiring sophisticated condition monitoring system and sufficient reliability characteristics for optimizing design.

Electrical power generation from the wind is established in Ethiopia in 2012, and has significantly increased in the last few years. Adama 1 wind farm is the first Ethiopian wind power generation station. The goal of the work presented here is to evaluate the current situation of the wind power plant by assessing its reliability.

1.2. Statement of the Problem

To better address the intermittency of wind energy from individual wind turbine systems and wind farms, the reliability analysis in regard of the generation output of wind turbine systems and wind farms are of essential need. The system operators and planners will require the clear picture of what a wind farm or individual wind turbine systems would generate in different scenarios, and how these generation outputs transition to each other in a probabilistic manner.

The failure of electrical and mechanical components of wind turbine made the wind farm not to meet its annual target. This is due to continuous component failure, very long repair time shortage of spare parts. In the case study area, the very common problem is lack of maintenance knowledge and shortage of spare parts are observed. So the following factors widen the gap of wind power reliability of case study area. These are:

- Damage of wind turbine components(transformers, power cables, Sensors, convertors, controllers, some others)
- Lack of appropriate maintenance (due to lack of vehicles, access road, skill,)
- Insufficient stocking of spare parts (electrical and mechanical spare parts)
- Continuous failure of components
- Duration of repair time
- Lack of spare parts
- Lack of maintenance experts
- External voltage block

The suggestion that some components are not fully running and that the maintenance is not appropriate is interesting, and motivated this work. So to predict the next generated output of the plant, it is important to know how output power is affected by these factors. The effect of these different systems is not yet thoroughly researched and this thesis is an effort to clarify some of the issues of output power within Adama 1 wind power turbines systems.

If the most critical components for the system can be identified, it will show in what areas to focus when planning the maintenance for the system. By doing an in depth study of the failures one can find out which components fail, how often they fail and if it is possible to measure the wear of the component and from this measurement decide when to perform the maintenance. The wind power systems usually have a high rate of availability but this is because of frequent maintenance. Frequent maintenance however, is obviously not a good and optimal solution. Preventive maintenance at the right moment will save money for the owner of the wind power plant. Especially since some wind power plants are situated at remote sites.

The problem discussion can be narrowed down into major questions that will be clarified and given an answer in this thesis work. These questions are:

1. What component or components are most critical in the wind turbine when it comes to number of failures and the resulting downtime caused by these failures?

2. Is the availability of the plant affected by the failures of turbine components?

3. Is the generated output power affected by failures of turbine components?

1.3. Objectives

1.3.1. General objectives

The general objective of this thesis is to assess the reliability performance of a wind power plant.

1.3.2. Specific objectives

The specific objectives of this thesis work are to:

- Collect the reliability data
- Discuss the value of reliability
- Analyze the output power of the wind farm
- Calculate the plant factor and availability
- Evaluate the reliability of wind turbines
- Recommend a method of improving wind turbine reliability

1.4. Significance of the Study

Unpredicted interruption in the power production from wind farm will lead to disturbances of the grid. A reliability study of wind farms provides results which can give an appropriate benchmark for assessing the system performance and identifying the weak points of the system. With increased knowledge of weak points within the system, informed investment decisions can be made during the design and installation phase. This action can reduce further costs due to supply interruptions and also decrease the need for maintenance. Thus there is of great importance to identify the weak spots and reinforcing them in order to achieve higher reliability and decrease the probability of interruptions.

A wind farm has an inborn stochastic characteristic and it is difficult to guarantee continuous supply but the probability or duration of interruptions can be reduced during its planning stage. This is though always a balance between the reliability assessment and investment cost.

This thesis demonstrates the importance of reliability data and the value of choosing a suitable O&M strategy to operate a complex system such as wind farm. Through the use of key metrics such as reliability, availability, maintainability and maintenance cost can be analyzed. The analysis of these metrics is useful to develop an O&M strategy and to evaluate different wind farm service agreements.

It is critical to execute the correct maintenance strategy for project feasibility and through the use of the simulation, it is possible to compare different strategies and optimize them.

The results provided by a reliability study will not tell us exactly what to do, but in what direction to look. For example, a reliability study can be useful in areas of risk analysis, optimization of operations and maintenance. The risk analysis is a way of identifying causes and consequences of failure events, and the optimization is a way of telling how failures can be prevented and how to improve the availability of a system. One can see reliability theory as a tool for analyzing and improving the availability of the system.

Generally Ethiopian Electric Power, will be benefitted from the current wind farm information to plan different strategies which helps to improve the performance of currently generating wind farms and upcoming wind power plants.

1.5. Thesis Outline

There are six chapters in this thesis, and a brief description of all the chapters is presented below.

Chapter One: This chapter is the introductory part of the thesis. It consists of the background of the study, statement of the problem, general and specific objectives, and significance of the study. It aimed to give the general information of the thesis.

Chapter Two: This chapter mainly presents a brief literature review on different types of wind power system reliability issue, focusing on the specific goal of this work and an elaborate description is presented on the following concepts.

- Wind turbine subsystem and components
- Previous wind turbine reliability research
- Importance of reliability data, concepts and methods
- Main probability distributions used in reliability engineering
- Wind turbine standards

Chapter Three: This chapter deals with the methodology used for the assessment and discusses the analysis of the data. This chapters aim to satisfy research objective.

Chapter Four: In this chapter the site description and the collected data are is presented. The general information about Adama 1 wind farm are stated in this chapter.

Chapter Five: Data analysis, result and discussion are presented in this chapter. Failures of the turbines and downtimes explained here.

Chapter Six: Here the overall conclusion of the thesis and recommendations are discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1. Review of other works

There have been a number of studies conducted within the area of reliability analysis on power systems and wind farms.

In different literatures, many studies conducted on the reliability of wind turbines. P. J. Tavner et. al. realized the prediction of reliability of large wind turbines by using grouped wind data [11]. O. Ozgener and L. Ozgener have performed reliability analysis of a 1,5kW wind turbine on Izmir, Turkey [12]. B. Hahn et al. presented the reliability of wind turbines in Germany [13]. Haitao Guo et. al. achieved reliability analysis of wind turbines with incomplete data collection by using three parameter Weibull function [14].

Johan Ribrant and Lina Margareta Bertling studied reliability performance of the different components within the wind turbine statically [15]. F. Spinato et. al. analyzed the reliability of wind turbine parts [16].

The effects of wind speed on wind turbines availability are investigated by S. Faulstich et.al [17]. All of these studies shows the significance of reliability of wind energy conversation systems.

Other example of studies evaluating the reliability of offshore wind farms is [18] which performs a reliability study with an analysis of electrical system within offshore wind parks, [19] which performs a reliability and investment analysis of different layouts on the selected wind farm and [20] which performs a reliability analysis of collection grids for large Offshore wind farms.

A common factor for all these reports is that reliability analysis is performed without considering possible overflow in cables due to re-routing of the power. When evaluating topologies with increased reliability due to implementing redundancy, it is important to consider the increase in power transferred within the remaining cables in case of failure. Without considering this factor, a proper reliability benefit of redundancy with respect to cable size cannot be performed.

Another aspect to consider is that the wind turbines are not producing energy continuously at their average capacity factor (i.e. 40% of rated capacity) but their production varies continuously.

This implies that it may not be necessary to dimension the cables used for redundancy to handle full production, since the full production condition occurs only for a low percentage of the time. The design should be a balance between several factors such as: probability of wind speed, probability of failure, cost of material, increase in energy supplied and life time of wind farm. As a result of the identified weaknesses in previous studies, it was decided to perform a reliability analysis considering both possible cable overload and impact of wind regimes.

To sum up, there has been ongoing peer research that deals with the reliability modeling of wind turbine systems and wind farms, but some problems exist. The major existing deficiencies of the peer research are as follows:

- To sum up, there has been ongoing peer research that deals with the reliability modeling of wind turbine systems and wind farms, but some problems exist. The major existing deficiencies of the peer research are as follows:
- There is lack of specific component analysis of a wind turbine system. Wind turbine systems are mostly treated as whole unique systems with no specific component analysis.
- Wind probabilistic modeling comes mostly from regressed models. Wind angle is seldom considered especially when quantifying wake effect.
- There is lack of probabilistic modeling of energy storage elements. They are mostly considered as constant output elements without failure.
- The reliability analysis results of wind farms are mostly presented in terms of reliability indices such as Expected Generated Wind Energy (EGWE) of an entire farm.

The distribution of generation states and the transitions among them are not presented. The research presented in this dissertation contributes accordingly to the above deficiencies as follows:

- Wind turbine systems in a wind farm have their each specific generation model when doing reliability analysis of the wind farm.
- The reliability modeling of wind turbine systems is component-based, which takes into account the Markov models of all their components.

- Wind state-space is generated based upon historical or forecasted wind data, which include both wind speed and wind directions. Wake effect is formulated and quantified for wind turbine systems.
- The reliability analysis of wind farms results in the generation state-space which provides the generation states, their probability, their duration and their transitions.

2.2. Theoretical background of wind turbine reliability

Wind is a clean, free and abundant energy source that is used to generate electricity, as wind turbines capture the kinetic energy created by airflows to power a generator supplying an electric current. Several wind turbines are typically configured into windfarms that can cover several square kilometers of land or sea to harness both onshore and offshore wind.

Continued improvements in manufacturing and turbine design, as well as improved capacity factors, have driven down the costs of wind power and confirmed its position as a key driver of the clean energy transition.

a. **Onshore**: -Onshore wind power refers to turbines that are located on land and use wind to generate electricity.
b. **Offshore: -**Offshore wind power is when wind over open water (typically the ocean) is used to generate electricity.[21]

2.2.1. Reliability definitions and functions

Reliability is defined as the probability that a system performs its duty over a defined amount of time when it is operated correctly in a defined operating environment. The definition of reliability can be broken down to four main parts.

- Time
- Probability
- Operating environment
- Performance

Unreliability is the probability of a system failure over a defined amount of time when operated correctly in a defined operating environment. Unreliability is the inverse of reliability.

Maintainability is the ease at which a system is maintained and how quickly broken item are replaced or repaired after failure in order to restore the system to its functional operating state.

Maintainability also includes the prevention of unexpected breakdowns, and the correction of wrong operations to maximize the system's availability.

Availability depends on both reliability and maintainability. One should not confuse availability with reliability. Several specific definitions for availability do exist, and therefore it is important to identify what definition is used. This thesis mainly uses operational availability. Operational availability is the percentage of time that a system is operational, which can best be described by the Equation 2.1. The reliability definition is the probability that subassembly will meet its required function under a stated condition for a specified period of time. For an unrepairable system, the rating scale is reliability; for a repairable system, the rating scale is availability. Wind turbines consist of both unrepairable systems and repairable systems like gears, bearings, bolts and electronic components. So, both reliability and availability should be considered to assess the wind turbines.

$$Availability = \frac{Uptime}{Uptime+Downtime} \qquad (2.1)$$

The sum of uptime and downtime is equal to the system's lifetime, whereby the uptime is the system's operating time and the downtime is the time that the system is not in operation.

Unavailability is the opposite of availability and provides information about how much time the system is not operational. [21]

Table 2.1 demonstrates the relationship between reliability, maintainability and availability. In the table one can see how availability is dependent on both reliability and maintainability and to increase availability either reliability, maintainability or both factors need to be increased.

Table2.1: Relationship between reliability, maintainability and availability

Reliability	**Maintainability**	**Availability**
Constant	Decreases	Decreases
Constant	Increases	Increases
Increases	Constant	Increases
Decreases	Constant	Decreases

The other important definitions in reliability engineering are as follows:

- Failure
- Mean time to failure (MTTF)
- Mean time between failure (MTBF)
- Repair
- Mean time to repair (MTTR)
- Repairable system
- Non-Repairable system

The following sections explore these definitions.

Failure is an event in which the component or system fails to perform its duty under certain conditions.

Mean time to failure (MTTF) is defined as the mean time to failure in a system that is normally non-repairable.

Mean time between failures (MTBF) describes the mean time between failures in a system during operation and can be found by dividing operating time by the number of failures. MTBF is given by:

$$MTBF = \frac{Operating\ hours}{Number\ of\ failures} \quad (2.2)$$

MTBF is used to maintain a repairable system, and cases in which the system is non-repairable, MTBF equals MTTF. [21]

A Repairable System is defined as system that can be repaired after failure and consequently restored to operation conditions.

A Non-Repairable System is a system that cannot be repaired after failure and restored to its operable conditions. These systems need to be replaced with a new working system.

Repair is the process of a restoring system that has failed to operate. A Minor Repair is normally due to smaller failures, such as a failure from the sensors or a replacement of smaller parts within a short period of repair time. A Major Repair is normally a failure from the turbines' mechanical parts, in which repair time is longer [22].

Mean time to Repair (MTTR) is a term used only with repairable systems. It represents the time from the point of the failure until the system is fully operational again.

Along with these definitions of reliability, there are some key reliability functions that are important to identify, that is:

- f(t)Probability distribution function (pdf)

- F(t)Cumulative distribution function (cdf)
- U(t) Unavailability at time t
- λ(t) Failure rate function

The probability distribution function f(t) represents the failure distribution when working with reliability data and the cumulative distribution function F(t) represents unreliability at time t. [23] The probability of failure has occurred at time t, which is known as unreliability, is calculated by finding the cdf, given by:

$F(t) = \int_0^t f(t)dt$……………………………………......……………………….………. (2.3)

The relationship between the unreliability and reliability is given by:

R(t)+F(t)= 1……………………………..………………..……..…………………..…….(2.4)

The relationship between availability and unavailability is given by:

A(t)+U(t)= 1………………………....…..…………………...…….……………………….(2.5)

The hazard or failure rate function provides the number of failures over a period of time, and is given by:

$\lambda(t) = \frac{nf(t)}{R(t)}$…………………………….…….…….…………...……………………………. (2.6)

2.2.2. Wind turbine subsystems

i. **Rotor Blades & Hub**

The rotor blades are the wind turbine's mechanism that captures the kinetic energy of the wind and transforms it into mechanical energy used to power the generator. The rotor blades are bolted to the rotor hub, which is connected to the main shaft.

ii. **Pitch System**

The pitch system provides the blades with the ability to change the tilt and can be used to optimize the extraction of kinetic energy from the wind or brake in the case of storms. The presence of pitch control reduces stress in the mechanical parts of the drive train. However, to add a pitch system does greater the chances of failures.

iii. **Nacelle**

The nacelle is the housing that protects the generator, gearbox and electrical equipment. The nacelle connects to the top of the tower through bearings, which are able to turn as the wind changes direction.

iv. Drive Train

The drivetrain is the connection of the necessary components required to generate electricity. In many cases, it is comprised of the following components:

- The main shaft
- Gearbox
- Brakes
- Generator

v. Gearbox

The gearbox converts the slow rotation 30-60 rpm of the main shaft to a high rotation of around 1000-1800 rpm, which fits the generator's requirements. A crane is required to replace the gearbox in cases of a failure, which consequently leads to a long down time and high costs. For this reason, some manufactures have developed direct drive turbines that have lees moving parts.[26]

vi. Mechanical brake

The mechanical brake is used when the turbine undergoes maintenance or is in a hazardous situation of high wind in which the aerodynamic brakes can fail. The mechanical brakes may be hydraulically or electrically driven disk brakes. The brakes need to be heavy duty in order to absorb the kinetic energy of the wind in emergencies. [27]

vii. Generator

The generator converts mechanical energy to electrical energy through a rotating magnetic field. Generally, there are two types of generators used in wind turbines: synchronous generators and induction generators, which are also known as asynchronous generators.

a. Induction generators are robust, low maintenance and produce power when the rotor rpm is higher than the synchronous speed. These generators self-starting and can be quite easily connected with the grid.

b. Synchronous generators operate in synchronization to the power system frequency, as their name indicates. They are not self-starting, but do have other positive attributes such as their higher efficiency and power quality. They can be connected to the grid through an inverter, which allows the synchronous generator to operate at variable speed. For example, the Enercon low speed angular generator is synchronous generator that has no direct grid coupling. Its voltage and frequency vary in relation to the rpm, and its connection to the grid is established through a DC link and inverter.[27]

viii. **Electrical Control**

The electrical control system is used to control a variety of elements in the turbine, such as the nacelle yaw angle and rotor blade pitch angle, which affects the spin of the rotor shaft and may be used to achieve a smoother power curve. Additionally, voltage, current frequency and other variables need to be controlled and monitored.[28]

ix. Sensors

Wind turbines have a variety of sensors to track their performance. The wind anemometer and the wind vane are two evident sensors that and send data to the control system to configure the yaw and pitch system. Other sensors, for example, may be electrical, vibration and temperature sensors.[28]

x. **Hydraulic System**

The hydraulic system is used to change the position of the yaw system and the pitch system. Electrical motors can also be used instead of the hydraulic system.[29]

xi. Yaw System

The turbine yaw system is located between the nacelle and the tower and enables the turbine to turn according to the direction of the wind.[29]

xii. **Tower & Foundation**

The tower is normally made of steel and holds up the nacelle and the rotor blades. The tower must be strong enough to withstand the forces that work on the wind turbine. The tower sits on a solid foundation made of concrete and iron.[29]

xiii. SCADA

SCADA (supervisory control and data acquisition) is a computer system that gathers and logs data from the wind turbine’s sensors and sends this data to a remote central location in order to track the wind turbines performance. SCADA system can be equipped with multiple alarms and special modifications in order to fulfill its purpose. The SCADA system is useful with respect to condition monitoring. The system is frequently used in order to inform operators about which part of the turbine requires maintenance or a replacement. In this way, it is condition-based and preventive maintenance proves to be very valuable.

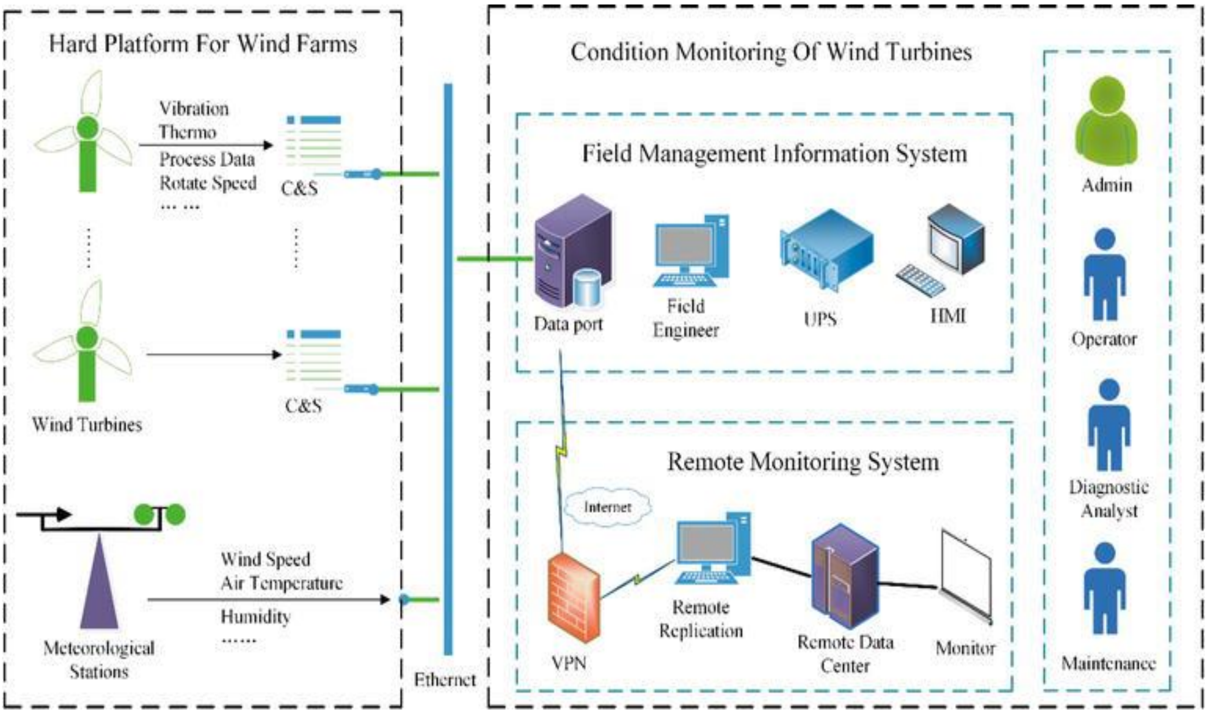


Figure 2.1: Flowchart of the condition monitoring and assessment process.[29]

The reliability of wind turbine system is becoming more and more important with the continued growth and expansion of markets for wind turbine technology. In addition, wind turbines with reduced repair and maintenance (R&M) requirements and higher reliability are needed emergently.

However, wind turbines produced by different companies have different reliability. There is no unified evaluation criterion. The current reliability analysis methods mainly focus on wind speed and failures of wind turbines and ignore the influences of other systems. The effects of the reliability model are limited if the system is simplified and seen as a series or parallel connection. Due to high costs of repair and maintenance, it is essential to study the health management systems of wind turbines and develop maintenance strategies in order to improve reliability and reduce unexpected repair and maintenance. The high-reliability systems can be achieved from three aspects, as shown in Figure 2.2.

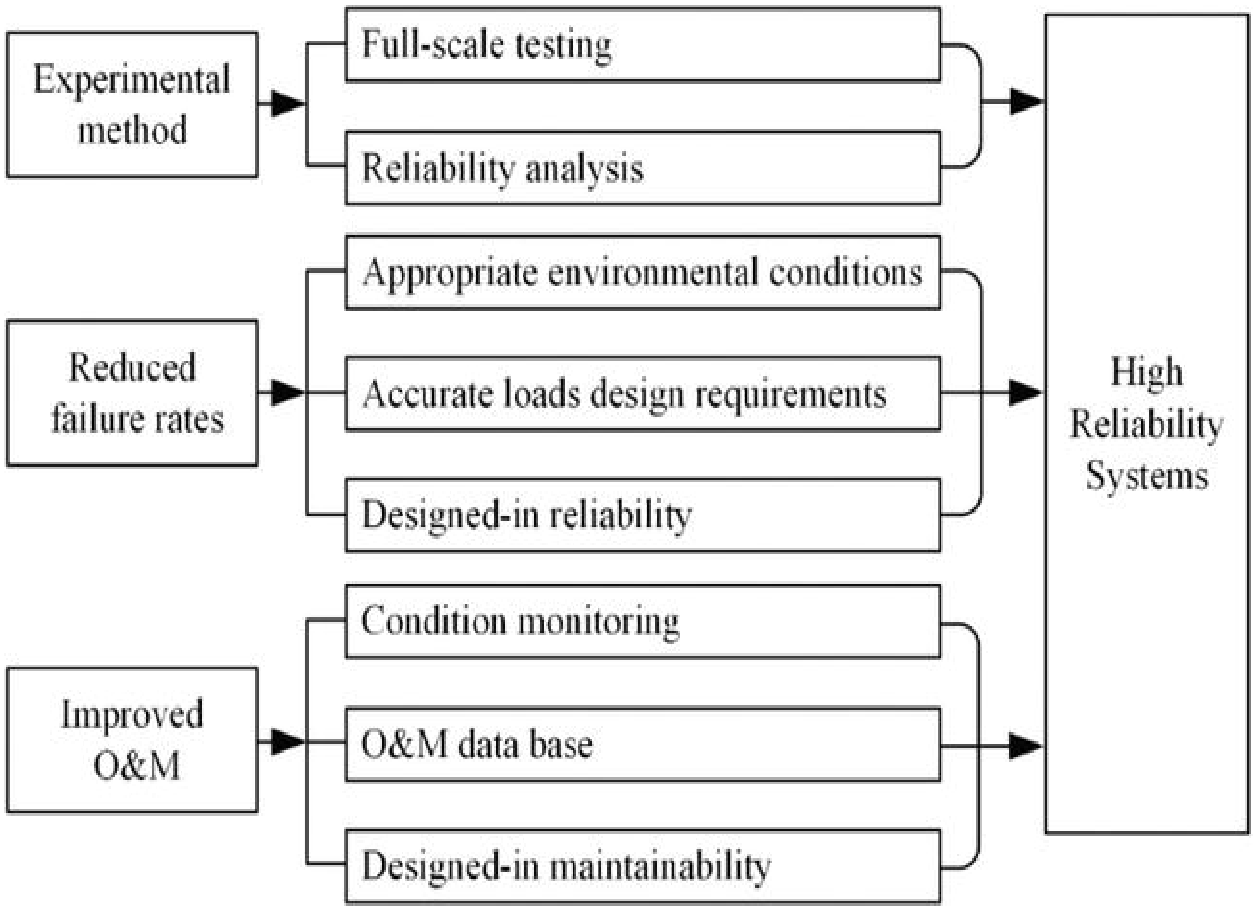


Figure 2.2: The requirements for developing the high-reliability systems. [30]

2.2.3. Probability distributions and their applications

To model the lifetime of components probability distributions may be used. There are several different types of distributions suitable for different kind of applications. In this thesis only the Weibull and the exponential distribution are considered.[31]

i. The Weibull distribution and the exponential distribution

The Weibull distribution is a widely used life distribution in reliability analysis. The distribution is very flexible and can through an appropriate choice of parameters model many types of failure rate behaviors. The Bathtub-curve can be modelled easily with three different sets of parameters respectively for the three different phases.

The distribution for the useful life period is a special case of the Weibull distribution. This special case of Weibull distribution is equal to an exponential distribution. Hence for the useful life period, the exponential distribution is used.

The use of exponential distribution for lifetimes comes with a number of important side effects.

- The failure rate is constant which means that it is independent of time.

- The exponential distribution has no memory, so an item is always viewed as good as new as long as it is functioning.
- When estimating the reliability function, the mean time to failure and so on, it is sufficient to collect data on the number of hours of observed time operation and the number of failures. The age of the component is of no interest in this context.[32]

ii. Bathtub curve and other shapes of curves

Normal mechanical failure modes degrade at a speed directly proportional to their severity. Thus, if the problem is detected early, major repairs can be prevented in most instances. One needs to find the right time for the failure to prevent major repairs, but before trying to find the time for a failure one needs to examine and learn more about the lifetime of the component.

The failure rate of a component is often high in the initial phase of its lifetime. This can be explained by the fact that there may be undiscovered defects in the components. When the component has survived the initial period; the failure rate stabilizes at a level where it remains for a certain time until it starts to increase again as the component begin to wear out. The shape of the curve depicting the failure rate of the component, is similar to that of a bathtub, hence the expression bathtub-curve.

The figure 2.3 shows the bathtub curve with the three typical phases. The initial phase is called burn in period, the stable phase is called useful life period and the end phase is called wear out period. Other examples of names for these three periods are break in, operations and breakdown. This terminology varies in literature but the main concept of three different stages in the life of the component or system are still the same?

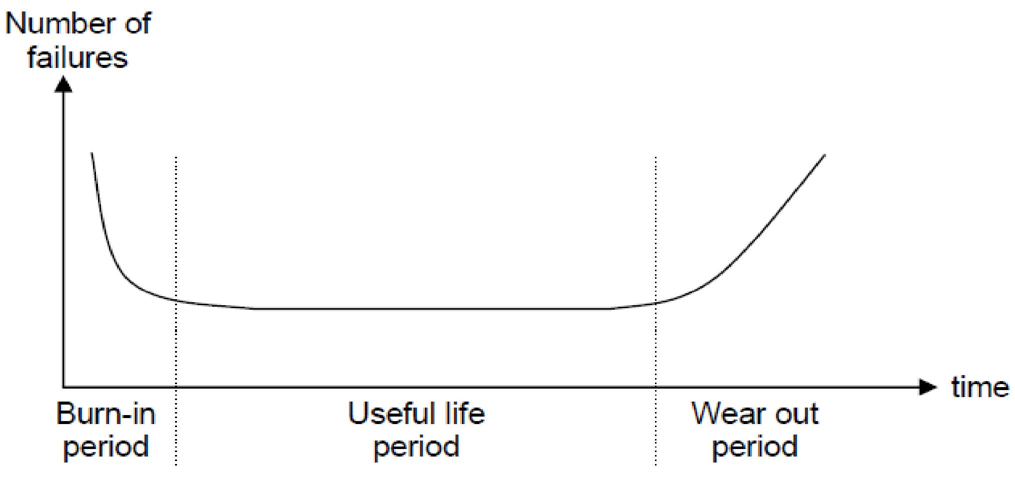


Figure 2.3: The Bathtub curve [33]

Figure 2.3 gives one example of a possible shape for the failure function. There are other failure functions with other shapes, but the bathtub curve appears as a good choice for mechanical components such as gearboxes. For the majority of mechanical items, the failure rate function will usually show a slightly increasing tendency during the useful life period, because of the wear on the mechanical components.

The Alternating Renewal Process: When a component fails, immediate repair is undertaken and when the repair is done, the component is put back into the system and is considered as good as new, hence the expression renewal.

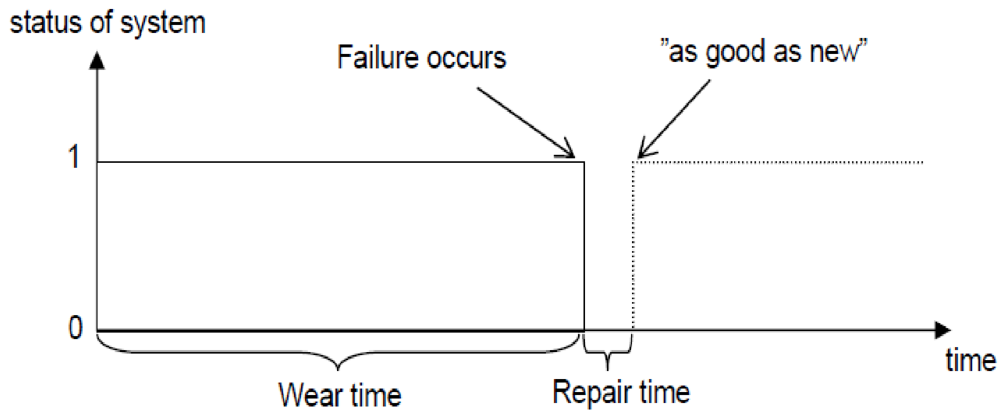


Figure 2.4: Alternating Renewal process [34]

iii. Wear model

To be able to understand and to apply theoretical tools to a physical component model are used. One way of modelling the system is by setting it to one of two states: up or down, failure or no failure, as given in Figure 2.4 We can picture the state of the system as a binary process. The statistical data used in this thesis is only based on the stages; up or down, hence only a model with two states will be used.

iv. Improved wear model

It is also possible to look at models with intermediate states between completely new and completely failed. In this type of model, failure is a damage accumulation process [8], as given by Figure.2.5. A good example is mechanical deterioration, where there are several states between brand new and failed.

Wear is defined as the progressive loss of substance resulting from mechanical interaction between two contacting surfaces. A model with several states appears suitable for systems with monitoring equipment. The wear model with different stages of deterioration is applicable when analyzing specific components where the different stages of wear have been well defined.

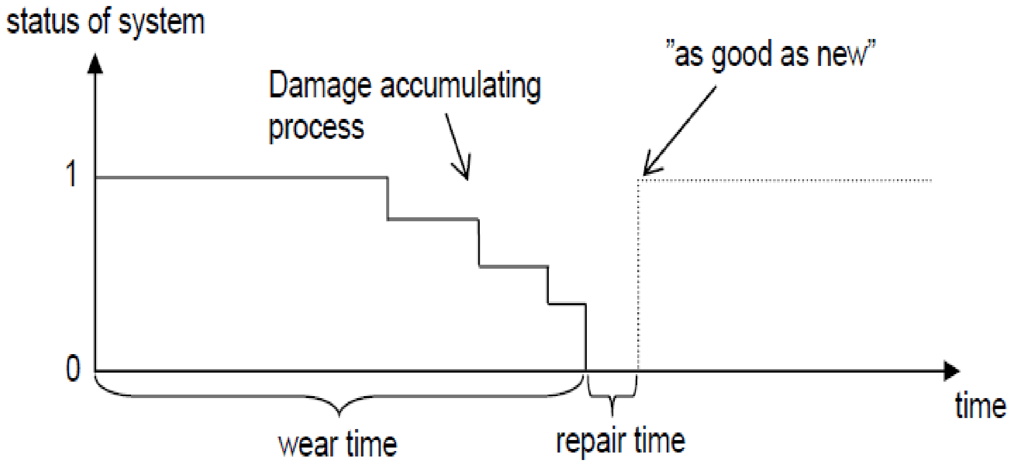


Figure 2.5: Damage accumulating process [34]

v. Repair time

The repair time can be modelled similarly to the lifetime of operations. There is a suitable distribution for repair time, the lognormal distribution, which for example takes into account that some repairs can be made quickly while other repairs rely on spare parts that are not available at the moment. It is also common to use the exponential distribution for repair time.

The repair time is of course important when detailed models of the maintenance are considered but as we will later find out it is difficult to find data concerning repair of wind power turbines and yet more difficult to find out the exact amount of time spent on repair. The information that may be available is the amount of time that the system was unavailable, but this time may consist of scheduled maintenance and stoppages caused by other events not connected to any failure. In this thesis a model of exponential distribution for repair time will be considered.

2.3. The basics of a wind power plant

The function of a wind power system is to transform the kinetic energy in the wind into electric energy. This is accomplished by letting the wind energy force an aerodynamic rotor to turn. The wind energy is thus transformed into mechanical energy. The mechanical energy in the form of a slow turning rotor shaft is geared up to a high-speed shaft which is connected to a generator, that means based on generator revolution per minute (RPM). Inside the generator the rotational mechanical energy is transformed into electrical energy. The electric power output is then connected to the grid.

Wind power output has a direct relationship with the area swept by the rotor. Since area is proportional to diameter squared, this means that doubling the rotor diameter will quadruple the energy output. When all other factors have been taken into consideration. A bigger rotor certainly generates more power. Although it may cost more, in the long run, whenever you are getting a wind turbine erected, go for a big a rotor as possible.

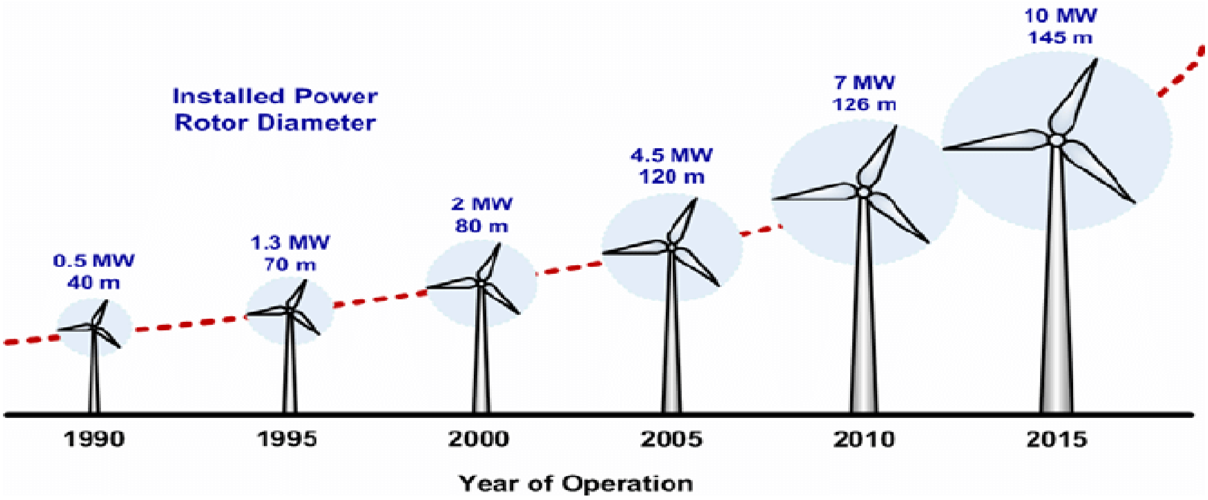


Figure 2.6: Development of wind turbine rotor size [35]

One of the deciding forces so far for increasing capacity factors has been an increase in the size of the rotors used on wind turbines. Turbine rotors are affected by two different forces: torque, which turns the rotors and creates energy, and thrust, which pushes against the turbine. Dealing with thrust can be difficult when designing a rotor.

2.3.1. Wind speed and consistency

Higher wind speeds generate more power because they allow the blades to rotate faster. This rotation translates to more mechanical power and more electrical power from the generator. Location of the installation is very important and should have average wind speeds. Since different regions have different wind speeds, study of any proposed site is done extensively to ensure good returns on investment. Typically wind speeds are measured for a year at the site before any decision is taken. The amount of wind power generated depends on the density of air, wind turbine rotor area, and the wind speed.[35]

$P = ½ \rho A V^3$ ……………………………………………………………………………. (2.7)

Where, P = Wind power generated in w (watts)

ρ = Density of dry air in [kg/m^3]

A = Rotor swept area in [m^2]

V= Wind speed in [m/s][35]

Wind power generation is proportional to the cube of the wind speed. It indicates that accurate wind speed modeling is essential for studying wind power effect on system reliability. The basic function of the wind power system may look easy but the system is still very complex. The development within wind power has been extensive in recent years and different concepts and construction designs have evolved. There has been a constant drive for higher performance and a higher power output. In addition to the complexity of the business, each manufacturer has basically chosen their own way of designing a wind turbine system. The evolution process within the wind power business has changed the features of some of the components, but the basic idea of turning wind energy into electrical energy via a generator is still the same.

Many developments and improvements have taken place since the commercialization of wind technology in the early 1980s, but the basic architecture of the mainstream design is little changed. Most of the wind turbines have upwind rotors and are actively yawed to preserve alignment with wind direction. [25]

2.3.2. Modeling of the wind power system

The wind power system is a complex system and to do a better analysis a certain level of modeling has to be made. When modeling a complicated system, a good approach is to divide the system into smaller parts such as subsystems or components. In this case the whole plant including structure and all electrical parts up to the grid connection will be viewed as the system. The system consists of several complex parts that ought to be modeled as subsystems, but as a first approach all the subsystems are modeled as components of the main system.[35]

2.3.3. Choice of components

The selection of components for the description of the main system is not just an arbitrary choice but a choice of what is useful in practice and where available data can be found.

The choice of which component should be used for modeling the whole system is based on function and available information.

i. A choice based on function

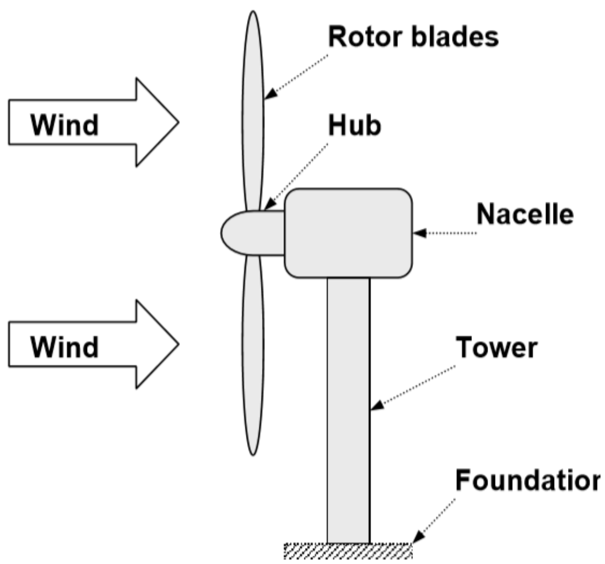
When describing a wind power system, a common way is to explain the main function by dividing the system into a set of different components with different features, for example brakes, tower, rotor blades etc. The different components are manufactured differently and are easy to replace as modules in the system, hence it is convenient to view them as separate components in the system.

ii. A choice based on information

The second choice for which components to be used in the modeling of the system is based on what information that is available. When statistics of failures are reported, it is inconvenient to have reports sheets with every component down to the smallest bolt, instead they are grouped according to a set of components based on their function. Failure reports from Adama 1 wind farm are divided into the set of components and they are basically based on their function within the system.[35]

2.3.4. The components of the wind power system

The names of the components are general and apply to almost all designs of wind turbines. The terminology used for the components comply with the same terminology used within the wind power industry. The system components described here are for a common system with the basic features.



- *Rotor blades and Pitch system*
- *Hub*
- *Structure – Tower, Foundation and Nacelle*
- *Drive train*
- *Generator*
- *Electrical system, Control system, Sensors*
- *Mechanical brakes, Hydraulic system, Yaw system*

Figure 2.7: Components of Wind Turbine [35]

2.4. Measurements

To be able to acquire useful information about the performance of a system or component, some measurements of the reliability and availability have to be used. Later in the analysis of data from the wind power turbines these measurements will be used in order to compare different components and different systems.

2.4.1. Measurements of reliability performance

The reliability can be measured in many ways depending on the particular situation, for example as: Mean time to failure or number of failures per time unit or failure rate. The mean time to failure, MTTF, is defined as the mean time between initial operation and the first occurrence of a failure or malfunction, as the number of measurements of such time on many pieces of identical equipment approaches infinity. When a failure has occurred, the item is repaired and put back into operation and the item is then considered as fully functioning.

The mean down time, MDT, is defined as the average time that the system is not functioning when a component is being repaired, and is basically the time it takes to repair a failure. The mean time between failures, MTBF, takes into account the mean time to failure and the mean down time. The down time is usually much shorter than the time of operations and then the two measurements can be viewed as: MTTF ≈ MTBF, as shown by Figure 2.8.

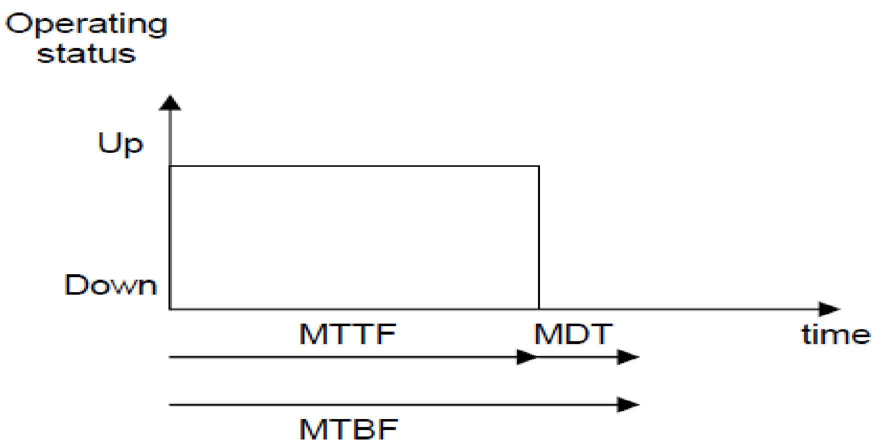


Figure 2.8: Measurements of reliability [36]

2.4.2. Measurements of availability performance

The availability performance is defined as: the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided.

By using the measurements of reliability performance, i.e. MTBF and MTTF, the availability for the system can be described as the portion of operational time, MTTF, over a nominal period of time, in this case MBTF, given that the time *t* approaches infinity. In the next equation a measurement of availability is shown by:

$$Availability = \frac{MTTF}{MTTF+MDT} = \frac{MTTF}{MBTF}\ , when\ t \rightarrow \infty \qquad (2.8)$$

The measurement of availability differs within wind power. A commonly used measurement of availability is the amount of operational time divided by the nominal time, as given by equation 2.9.

The nominal time is usually a period of one year and then the availability is presented as percentage of operational time per year.

$$Availability = \frac{Nom.time - Downtime}{Nom.time} \qquad (2.9)$$

Another way of expressing the availability is to eliminate downtimes not caused by the wind power plant, such as external failures of the grid, as given by equation 2.10.

$$Availability = \frac{Nom.time - (Downtime - Downtime\ caused\ by\ grid\ failures)}{Nom.time} \qquad (2.10)$$

These two different definitions of the availability have been used in the sources for the statistical data. The effect these differences have on the result is not investigated, but assumptions say that the two different definitions will not influence the result.

A third option to use for availability is to not use the nominal time of one year but the actual available operational time. Example the available operational time is only when the wind is blowing and not when the plant has stopped due to low winds or to high winds.

Unavailability is the period which the plant is not functioning. This can be scheduled downtime (maintenance) or unscheduled downtime (malfunction or failure).

2.5. Maintenance methods

Maintenance is required for almost all types of machinery and applies also to the wind power system. The type of maintenance that is performed can be defined as either preventive or corrective maintenance. Preventive maintenance is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of a failure. Corrective maintenance is carried out after a failure and is intended to repair the system. [36] In other words, preventive maintenance is performed before a failure and the corrective is preformed after the failure occurs. An ideal maintenance strategy meets the requirements of machine availability and operational safety, at minimum cost. Consequently, the challenge in planning the maintenance is to decide on when to perform preventive maintenance. [36]

Here in figure 2.9 an explanation of three different methods for maintenance is presented; corrective maintenance and two types of preventive maintenance; scheduled maintenance and condition-based maintenance.

2.5.1. Corrective maintenance

Corrective maintenance is defined as: - Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function. This type of maintenance is often called repair and is carried out after the failure of a component. The purpose of the corrective maintenance is to bring the component back in to a functioning state as soon as possible, either by repairing or replacing the failed component. To only use corrective maintenance is seldom a good solution. This means that the system will run until a breakdown occurs and, in some literature, this is referred to as a breakdown strategy.

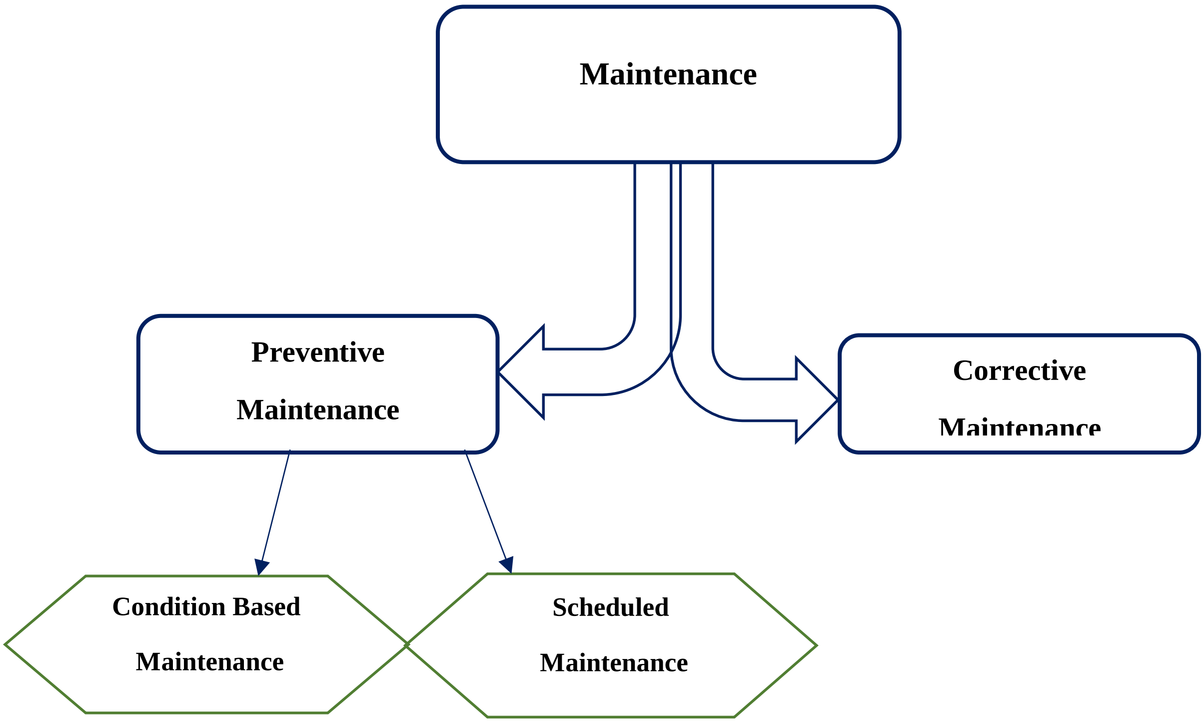


Figure 2.9: Classification of maintenance types [36]

With a breakdown strategy the preventive maintenance is reduced to a minimum and the system will be operated until a major failure of a component occurs which will result in a shutdown of the wind turbine. This strategy is risky, since failures of relatively small and dispensable components can lead to severe consequential damages.

Another aspect of such a strategy is that most component failures are likely to be related to the actual load condition of the wind turbine and is also likely to happen during high load conditions. This means that the shutdown of the turbine is related to high wind periods. Downtime in such periods will lead to higher production loss. If the wind turbine is situated offshore, the accessibility is likely to be bad during high wind periods.

Another drawback of this strategy is that when repair is needed the downtime can be extensive since logistics gets more complicated and delivery periods for spare parts can be long. A breakdown strategy minimizes the cost for repair and maintenance during operation. With no knowledge of the consequence of a failure until it occurs makes it impossible to calculate the costs of replacements. The lifetime of the component is unpredictable and only once the component has failed can an assessment of the cost and lifetime be made.

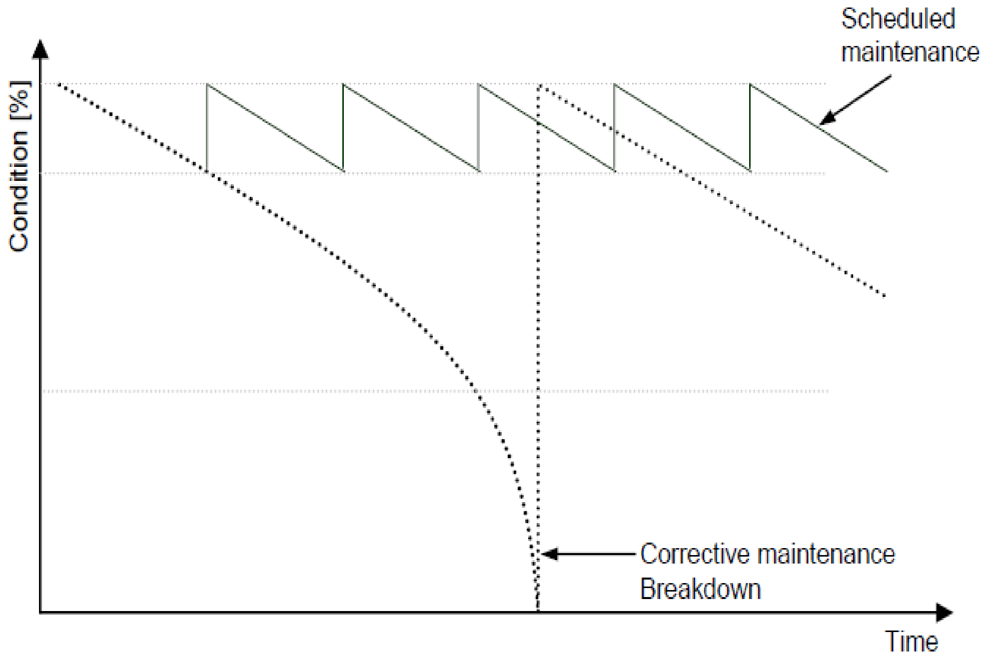


Figure 2.10: Corrective Maintenance compared to Scheduled Preventive Maintenance [36]

2.5.2. Preventive maintenance

Preventive maintenance is defined as: – Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of functioning of an item. [36]

The preventive maintenance is performed regularly to postpone failures or to prevent failures from occurring. There are two different types of preventive maintenance; the scheduled maintenance and the condition-based maintenance. What differs between these two are the way of deciding when to perform the preventive maintenance?

i. Scheduled maintenance

Scheduled maintenance is defined as: - Preventive maintenance carried out in accordance with an established time schedule or established number of units of use. [36]

Scheduled maintenance means that preventive maintenance is carried out in accordance with an established time schedule. The time-schedule for the preventive maintenance can be either clock-based or age-based maintenance. Clock-based maintenance means that the preventive maintenance is carried out at specified calendar times and age-based maintenance means that the maintenance is carried out when a component reaches a certain age. The age does not need to be calendar time, but measured in for example revolutions or operational time etc.

Preventive maintenance performed at scheduled intervals should be designed to reduce the probability of failures. Maintenance cycle times will be matched to the requirements of the system. The system will be inspected and maintained periodically, see Figure 8. The components that first show sign of wear and fatigue will be maintained and replaced. This type of maintenance strategy means that components exposed to wear will be replaced regularly even if they are not at the end of their lifetime. Scheduled maintenance requires regular access to the system and a big share of the costs for the maintenance will stem from the supply for cranes and maintenance personnel. Transport of personnel and spare parts to the wind farm can also be cost intensive with this preventive maintenance strategy. The advantage of preventive maintenance is that it can be scheduled ahead of time and the coordination of logistics can be made easy.

ii. Condition based maintenance

Condition based maintenance is defined as: – Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. Performance and parameter monitoring may be scheduled on request or continuous.

Condition based maintenance is a type of preventive maintenance that is based on the performance and monitoring of parameters from the system. With this type of preventive maintenance, monitoring equipment collects machine data. The condition monitoring may be scheduled, on request or continuous. The collected machine data can indicate required maintenance prior to predicted failure. Maintenance is initiated when a condition variable approaches or passes a threshold value. The system components will be operated to a defined condition of wear and fatigue. When this condition is reached, the component needs be maintained or replaced. Examples of condition variables that the system monitors are vibration, temperature, number of particles in the lube oil etc.

The ability to monitor the condition of components facilitates planning of maintenance prior to failure and will minimize downtime and repair costs. The components will be used closer to their lifetimes and the coordination of spare parts will be easy. Another benefit of implementing a condition-based system is that trends and statistical data such as mean time to failure can be provided. The statistical data from monitoring system is important for getting reliable data for remaining lifetime of components in the system. With site specific data the prediction of remaining time for the components can be more precise. Figure 2.11 shows an example of condition-based maintenance along with corrective and scheduled maintenance.

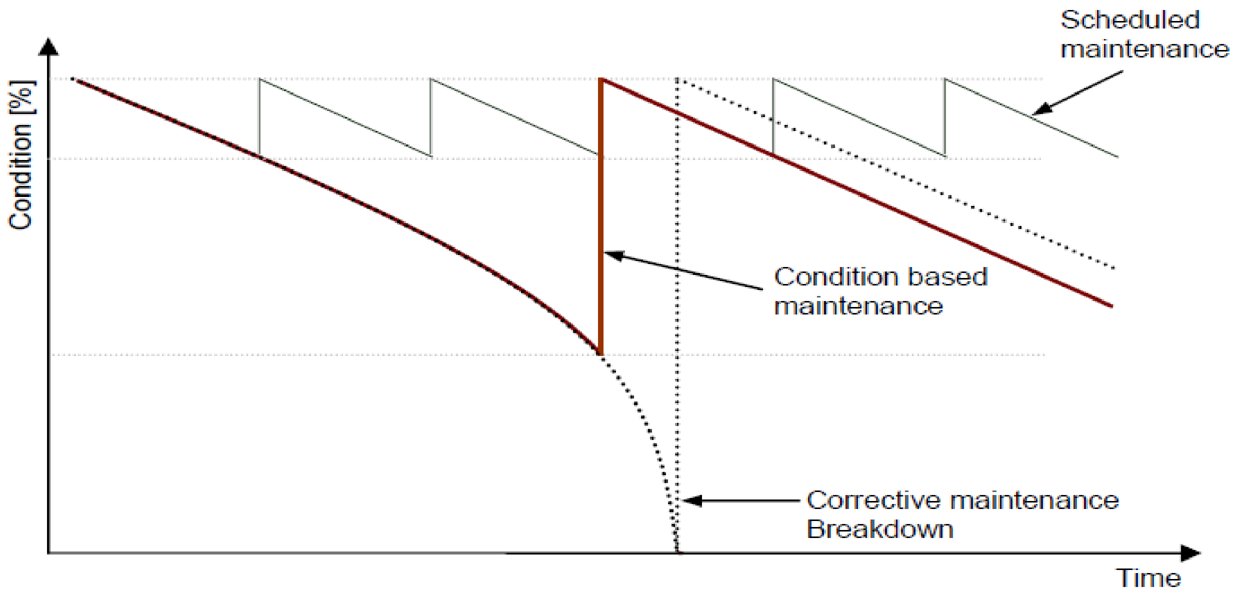


Figure 2.11: Condition based maintenance compared to scheduled and corrective maintenance [36]

2.5.3. Comparison of maintenance methods

Figure 2.11 shows a graphical example of possible scenarios for maintenance. The comparison shows that scheduled maintenance is performed more often than condition-based maintenance. The example also shows that the lifetime of the component is not fully used in the scheduled maintenance compared to the use of corrective- or condition-based maintenance. Table 2.1 shows some advantages and disadvantages found for the different maintenance methods when applied to wind power.

Table 2.2: Comparison of maintenance methods.

Method	Advantage	Disadvantage
Corrective Maintenance	• Low maintenance costs during operation. • Components will be used for a maximum lifetime.	• High risk in consequential damages resulting in extensive downtimes. • No maintenance scheduling is possible. • Spare parts logistics is complicated. • Long delivery periods for parts are likely.
Preventive Maintenance - Scheduled	• Expected downtime is low • Maintenance can be scheduled. • Spare logistics is easy	•Components will not be used for maximum lifetime. • Maintenance costs are higher compared to corrective maintenance.
Preventive Maintenance - Condition based	• Components will be used up to almost their full lifetimes. • Expected downtime is low. • Maintenance activities can be scheduled. • Spare part logistics is easy given that a failure can be detected early in time.	• Reliable information about the remaining lifetime of the components are required. • High effort for condition monitoring hardware and software is required. • Cost of another layer in the system. • Not a mature market for monitoring systems within wind power. • Identification of appropriate condition threshold-values is difficult.

Sources: [36]

2.6. Maintenance strategy

Figure 2.11 shows a graphical example of possible scenarios for maintenance. The comparison shows that scheduled maintenance is performed more often than condition-based maintenance. The example also shows that the lifetime of the component is not fully used in the scheduled maintenance compared to the use of corrective- or condition-based maintenance.

Table 2.1 shows some advantages and disadvantages found for the different maintenance methods when applied to wind power. With the three methods presented a maintenance strategy can be implemented. The strategy will be a combination of preventive and corrective maintenance.

The use of condition monitoring equipment makes the condition-based maintenance a good option as to reduce cost related to maintenance. Logistics can be planned ahead and the lifetime of the components can be almost completely utilized.

A condition monitoring program can minimize unscheduled breakdowns of all mechanical equipment in the plant, and ensure that repaired equipment is in an acceptable mechanical condition. The program can also identify machine train problems before they become serious.

CHAPTER THREE

METHODOLOGY

3.1. Thesis Approach

The choice of research approach depends on the degree of precision by which the original research question can be formulated, and how much knowledge exists in the area of the chosen subject.

This study had used both exploratory and descriptive approaches.

a) **Exploratory approach**: when information is insufficient, the study is exploratory. The main purpose with exploratory studies is to collect as much knowledge about a study problem area as possible. This means that the problem is analyzed from a number of different points of view. A wealth of ideas and creativity are important elements in explorative studies because these often aim at attaining knowledge that can lay the foundation for further studies.

b) **Descriptive approach**: the descriptive approach is best suited to investigations where there already is knowledge. In a descriptive study, only the essential aspects of the phenomenon are looked upon.

The wind turbine failure and downtime data which is useful for this thesis for reliability assessment has been collected as much data as possible using various sources of information, a number of journals, article and papers and other related works have been reviewed and assessment of existing wind turbine system in the case study site, understanding and adopting the system as a whole has been done. Secondary data has been collected with general background on a variety of views on the subject of the thesis. This study has used to see how reliability could be improved in wind turbine system by incorporating components reliability analysis through identifying the outstanding failures causes in the wind farm using appropriate engineering software tools (Matlab) and recommend best solution for mitigating the wind turbine component failure problems of the Adama 1 wind farm turbine systems on outstanding causes.

This thesis uses a quantitative approach as well as a qualitative approach. The main findings about the downtime and failures of the components are based upon statistical data which is analyzed with measurements used in reliability theory. The findings are then supported by information found in articles, books and interviews related to the area of failures within wind power systems.

• Quantitative analysis - based on statistical data from Adama 1 wind power plant SCADA.

• Qualitative analysis - based on articles, internet resources, site trips.

The general methodologies used in this thesis are shown figure below.

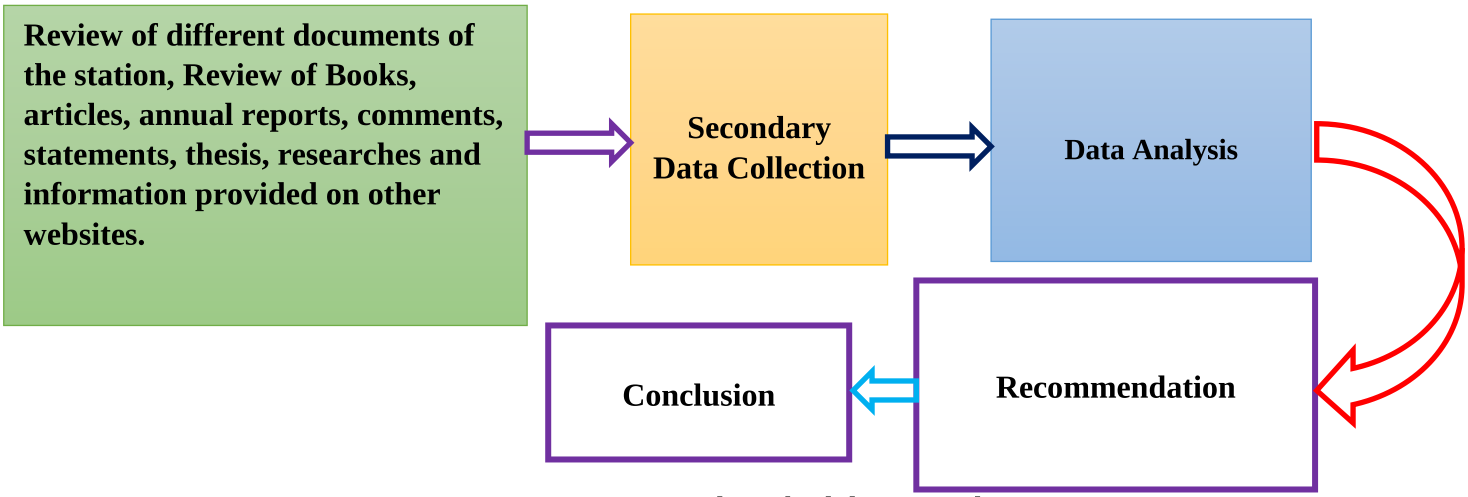


Figure 3.1: General Methodologies outline

3.2 Data Sources and Collection Methods

This part deals with the methodologies of data collection procedure that has been used for this thesis from the existing wind power plant. The study has been based on secondary data. The secondary data which was very necessary for this study was manually recorded from daily, monthly and yearly production and interruption report. Usually the interruption and production data are reported to the belonging head office (generation operation executives). Many of the interruption problems are temporary and mainly caused by component failure of each turbine, and due to external voltage block from Adama substation, and others causes and can easily be solved with little or no intervention from the system by simply resetting the system remotely from the SCADA.

In Adama 1WPP step up substation each interruption duration and frequency (number of interruption) of each turbine per hour is recorded but the causes of interruptions are not described and identified well. But to put an appropriate mitigation technique for the turbine failure problem in the case study area; it is critical to know the most outstanding reasons of turbine failure. After years of having inadequate records under existing systems the implementation of recording this power interruption source of causes was difficult but not an impossible task with technology and methodologies of documentation being of a significant benefit in this process which will benefit both internal and external users of this information.

This thesis data is mostly based on secondary data as the data gathered from the documents of Adama 1 WPP control room.

- **Data collection:**
    - Eight years (2012-2019 G.C) production data has been collected from Adama 1 WPP step up substation documents. All years stated in this thesis are in Gregorian calander.
    - Each turbine information, type of faults, number of failures and duration of outages information has been collected from the existing SCADA system.
    - The collected data has been used to clearly analyze the current status of the power plant.

3.3. Data Analysis Method

The information gathered from the secondary data are used for the analysis technique and the results will be completed using Matlab and Excel software, which incorporates appropriate detailed statistical functions. Conclusions on the consequences of current practices and recommendations for change will be developed to assist local authorities (EEP), consultants, engineers, public and private stakeholders for taking immediate action.

Therefor properly collected and organized data for effective output will be analyzed through the following methods:

- Identifying and determine the essential parameters required for the study.
- Developing the analysis with MATLAB R2019a and Excel software tools.

Based on the result of this analysis and assessment, recommend a solution that have been evaluated for potential reliability improvement on turbine failures.

In the data analysis, Excel data is loaded to mat lab software and mat lab excel analysis tool is used. The raw data obtained from Adama 1 wind power plant record is used as an input to the Mat lab. The purpose of this tool is to analyze wind data to prove a wind exists at a specific time and analyze the output energy based on that time. The power curves for total power plant, individual wind turbine and grouped wind turbines is shown by graph. Depending on the component failure frequency the annual plant working and shutdown is shown by graph. Some important items also included in the analysis are the average wind speed, capacity factor, and estimated annual energy production.

3.3.1. Wind speed model for selected geographic location

This is the estimation of wind speed model for the specific geographic location. In this work Adama 1 wind farm site is considered. In this step the wind speed model is developed by calculating the average and standard deviation of the discrete wind speeds. With this model frequency of occurrence and probability of the wind speed in that specific site can be obtained. This model also gives the probability distribution of the discrete wind speeds.

i. Wind speed statistics

The speed of the wind is continuously changing, making it desirable to describe the wind by statistical methods. One statistical quantity which is the average is calculated by a set of measured wind speeds ui. Standard deviation is calculated by the variance [12].

ii. Average wind speed

The measured wind speeds are in integer values, so that each integer value is observed many times during a year of observations. The numbers of observations of a specific wind speed u_i will be defined as mi.

The mean is then given by the following relation.

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{w} m_i \, u_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where, w is the number of different values of wind speed observed, n is the total number of observations.

Standard deviation:

To find the deviation of each number from the mean and then find some sort of average of these deviations. The mean of the deviations (ui – u) is zero, which does not indicate much. Therefore, square each deviation to get all positive quantities. The variance of the data is then given by the next equation.

$$\sigma^2 = \frac{1}{n-1}\left[\sum_{i=1}^{w} m_i \, u_i^2 \; - \frac{1}{n}\left(\sum_{i=1}^{w} m_i u_i\right)^2\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where, w is the number of different values of wind speed observed n is the total number of observations. Standard deviation is given by the following equation.

$$standard\ deviation\ = \sqrt{variance} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Frequency of occurrence:

This is the determination of the number of times in which the recorded wind speed occurred through the measured time. The percent value is given by:

$$f(ui) = \frac{number\ of\ hour\ in\ which\ ui\ is\ occered}{total\ number\ of\ hour\ in\ data} x100 \text{..........................} \quad (3.4)$$

3.3.2. WTG power curve

This is the data obtained from the turbine manufacturers installed at the wind site. This data contains the power output of the wind turbine generator at different wind speed and the rated wind speed for the rated power output, cut-in wind speed, cut-out wind speed of the wind turbine. This can be represented in the graphical form by plotting wind speed on x-axis and power output on y-axis. These power curve data are combined with the wind speed model obtained for Adama 1 wind site to obtain power generated at different wind speeds distributed through the year.

3.3.3. WTG power generation model

Wind turbine power generation model is obtained by combining the wind speed distribution and wind turbine generator power curve data. This model includes the total annual power generated; power generated at different wind speeds through the year. This is calculated by combination of subsection 3.3 and 3.4.

The probability P of the discrete wind speed ui being observed as,

$$P(u_i) = \frac{m_i}{n} \quad \text{...} \quad (3.5)$$

Where, P is probability, ui is measured wind speed at the interval I, mi is the hours in which ui is observed, n is the total number of hours.

The cumulative distribution function F (ui) as the probability that a measured wind speed will be less than or equal to ui is given in this equation.

$$F(u_i) = \sum_{j=1}^{i} P(u_j) \quad \text{...} \quad (3.6)$$

3.3.4. Probabilistic evaluation of power generated

This includes the probabilistic evaluation of the generated power at different wind speeds through the year. This is calculated by combining distribution of discrete wind speeds. This can be calculated by estimated energy output by the discrete wind speed and total energy estimated through the year. This is described in the equation 3.7 below.

$$P_g = \frac{power\ output\ from\ descrete\ wind\ speed}{total\ estimated\ energy\ output\ through\ year} \quad \text{……………….……..………. (3.7)}$$

The power generated can be calculated using the power formula given in the next equation.

$$P_m = C_p \left(\frac{1}{2}\rho A u^3\right) \quad \text{………………………………………..……………….. (3.8)}$$

Where, Cp is the capacity factor given by the turbine manufacturer

ρ is air density at the wind site kg/m^3

A is area swept by the turbine in m^2

u is the wind speed in m/sec

3.3.5. Calculation of Plant factor and Plant availability

Since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the Plant factor. Typical Plant factors [12] are 15–50%; values at the upper end of the range are achieved in favorable sites and are due to wind turbine design improvements. The plant factor is calculated by the following relation.

$$Plant\ factor = \frac{Actual\ Power\ \ generated\ in\ a\ time}{Rated\ power\ generated\ in\ a\ time} \quad \text{…………………………………………… (3.9)}$$

The value of Plant factor between 15 to 50% is good for wind power generation. And if the wind is continuous the Plant factor will be more except for planned and forced outage. Plant availability is the wind turbine generator which is available to generate power. This is obtained from the relation that is given in the next equation.

$$Plant\ Availability = \frac{Plant\ available\ for\ generation\ in\ hours}{Total\ hours\ in\ the\ analyzed\ data} x100 \quad \text{................................ (3.10)}$$

$$Plant\ unavailability = 1 - plant\ availability \quad \text{... (3.11)}$$

CHAPTER FOUR

DESCRIPTION OF THE STUDY AREA

4.1. Site Description

Adama one wind farm is located in the middle of Ethiopia, about 98Km from Addis Ababa and 3Km from Adama, with altitude elevation of 1824m which is approximate to 1976m. Adama/Nazret Wind Park is located in a strip of land, stretching from north east to southwest. Air density at the wind site is 1.004 kg/m^3. The geographical location of wind farm is shown in figure 4.1 below. The installed capacity of Adama one wind farm is 51MW with 34units of 1500kw wind turbines. The data considered for this thesis is Eight-year data which covers daily, monthly and yearly data from April, 2012 to December, 2019.

The project was officially commenced on June 14, 2011 with contract construction period of 12 months. The total investment is USD117 million, of which 85% from the preferential buyer credit of the Export-Import Bank of China and 15% by local currency. The installed capacity of the project is 51MW with 34 GW77/1.5MW units and the project will produce 157.4GWh of power annually to the grid through a 132kv step-up substation and an extension bay of Adama substation connected with 4.7km 132kv transmission line and 20km 33kv collecting line. The project has attached great attention of both Ethiopia and Chinese Governments, as it is the first state-of-art wind power project in Ethiopia supported by preferential buyer credit of Chinese government. The project is progressed smoothly with the effort of all related parties. On March 31, 2012. The first wind turbine generator generated power and connected with the national grid. On April 22, 2012, the last wind turbine generator was erected successfully and the fist wind turbine generator were put into commissioning and commercial operation on April 6, 2012.

Accordingly, HYDROCHINA Corporation with the support EEP’s wind study center, made the feasibility study incorporating the environmental Impact assessment for Adama/Nazareth wind farm. According to wind energy resources evaluation and calculation of power generation amount of wind farm and in consideration of various losses and auxiliary power, Adama I wind has an average annual energy output of 162.7 GWh.

Figure 4.1 Geographical Position of Adama/Nazret wind park

4.2 Selection of Wind Turbine

Considering maximal wind speed, average wind speed and turbulence intensity, the Project site was determined to be suitable for the IEC-II wind turbines. Seven kinds of wind turbines with capacity of 1500kW were compared with each other in the feasibility study to select from, which are Sinovel SL1500/82, Goldwind GW77/1500, Sany Electric SE8215 and SE7715. MY1.5se/1500, GE1.5 sle/1500, Nordex S77/1500. Through comparison and contrast of their technical and economic indexes, the feasibility study determined the Goldwind GW77/1500kW as the proposed turbine. The Goldwind GW77/1500kW wind turbine adopted a design of horizontal shaft, tri-blade, upwind, adjustment to the pitch of blade and Permanent Magnet Synchronous Generator. The range of survival temperature is -40°C~+50°C, the range of operation temperature is -30°C~+40°C, the design standard for the extreme wind speed is 59.5m/s (IEC IIA standard).

Table 4.1: Technical Parameters of WTGS

WTGS model	GW66/1500kW	GW70/1500kW	GW77/1500kW	GW82/1500kW	GW87/1500kW
Security level	IEC I A	IEC I A /IEC II A	IEC II A/ IEC III A	IEC III A	IEC III B
Rated power	1500kW	1500kW	1500kW	1500kW	1500kW
Inverter output voltage	620V	620V	620V	620V	620V
Diameter of rotor	66 m	70.34 m	76.84m	82.34m	86.6-88.3m
Swept area	3421 m^2	3885.9 m^2	4637.3m^2	5324.9 m^2	5874 ~ 6112 m^2
Hub height	65 m	65/85 m	65/85m	70m	70/75/85 m
Scope of rotation speed of rotor	10.6-20.5 rpm	8.8-19 rpm	8.8-17.3 rpm	8.8-17.3 rpm	8.8-17.3 rpm
Rated speed	20.5 rpm	19 rpm	17.3 rpm	17.3 rpm	17.3 rpm
Rated wind speed	13.1 m/s	12 m/s	11 m/s	10.3 m/s	9.9 m/s
Cut-in wind speed	3 m/s	3 m/s	3 m/s	3 m/s	3 m/s
Cut-out wind speed	27 m/s	25 m/s	22 m/s	22 m/s	22 m/s
Maximum survival wind speed (3 seconds)	78m/s	70m/s	59.5 m/s	52.5 m/s	52.5 m/s
Maximum allowable maintenance wind speed	11m/s	11m/s	11m/s	11m/s	11m/s
Scope of operating temperature	-30 ℃ – 40 ℃	-30 ℃ – 40 ℃	-30 ℃ – 40 ℃	-30 ℃ – 40 ℃	-30 ℃ – 40 ℃
Survival temperature of WTGS	-40 ℃ – 50 ℃	-40 ℃ – 50 ℃	-40 ℃ – 50 ℃	-40 ℃ – 50 ℃	-40 ℃ – 50 ℃
Design service life	≥20 years	≥20 years	≥20 years	≥20 years	≥20 years
Lightning protection design standard	IEC61400-24; IEC62305	IEC61400-24; IEC62305	IEC61400-24; IEC62305	IEC61400-24; IEC62305	IEC61400-24; IEC62305

4.3 Layout of Project Site

Adama 1 Wind farm is mountainous hilly terrain and the area is small, and the layout area is only one mountain ridge. At meanwhile, the factors of communication iron tower of ETV located in the middle of the sector and the church and residents in the north of the sector also have been considered in the arrangement scheme of Wind farm.

The installed capacity of the sector is 51MW, with 34 sets of wind turbines of 1500KW. Based on the limiting conditions of sector and in order to place the turbines along the mountain ridge in lines as many as possible, the distance between the two turbines at vertical prevailing wind direction shall be controlled as 3 times as the rotor diameter and five times at prevailing wind direction.

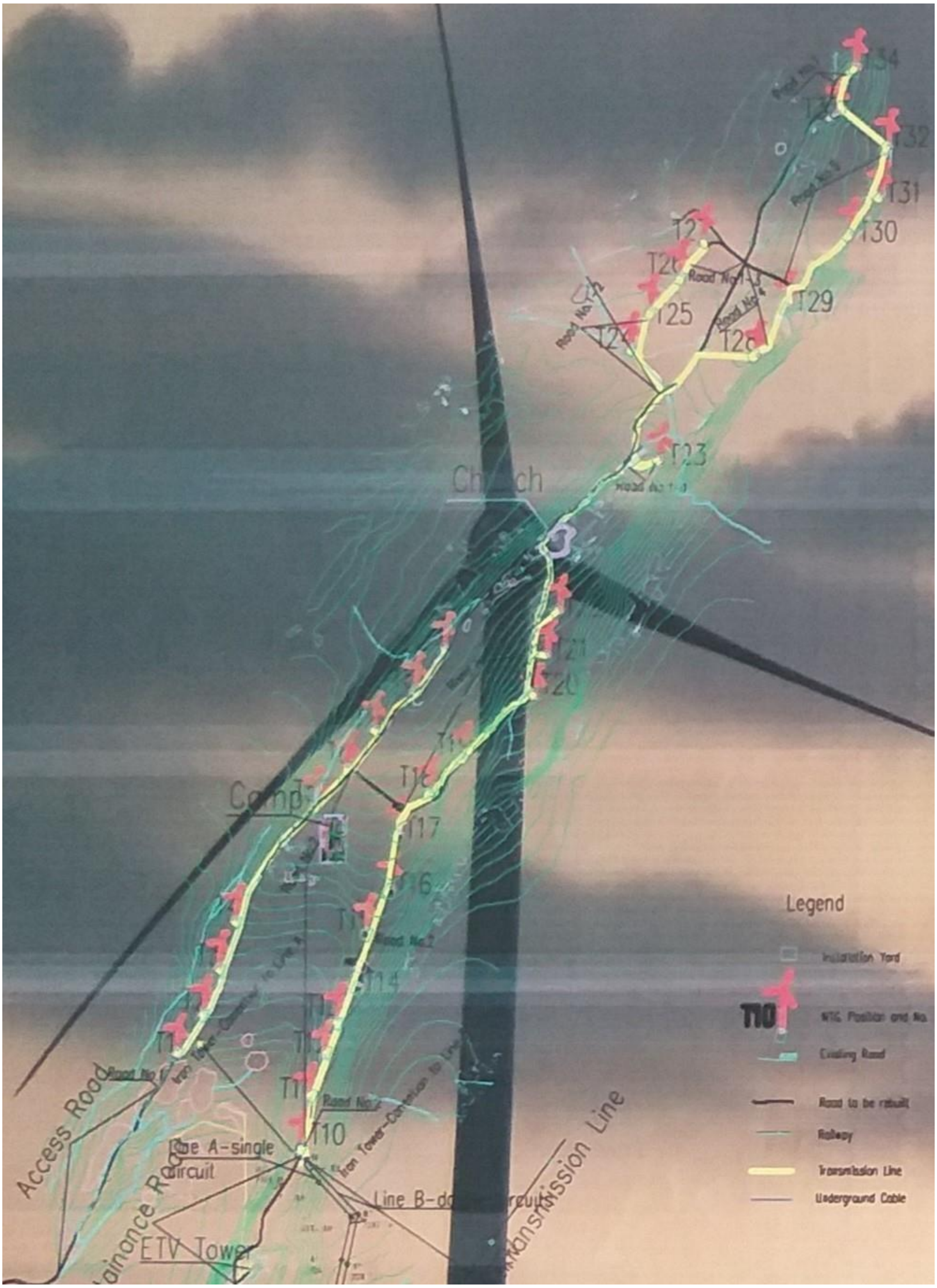


Figure 4.2: Adama 1 wind farm layout

4.4 Electricity Production Estimation

The 34 sets of Goldwind GW77/1500kW wind power units were installed in the selected site and the total installed capacity is 51MW. According to the feasibility study report, the wind resource map of Adama 1 wind power plant calculated through Meteodyn-WT software with the effect of air density, wake flow, control, turbulence reduction, and rotor surface pollution etc., the annual electricity volume of the wind farm, the full load hours per year and the capacity factor were calculated, and is 162.7 GWh, 3189 and 0.36 respectively. However, later with the Micro-siting optimization, the annual average electricity generation of Adama 1 wind farm was calculated to be 157.4GWh, and the full load hour is 3087h, and the capacity factor is 0.35. The full load hours in feasibility study is 3189h, compared with the feasibility study, current full load hours decreased about 102h [21].

Adama /Adama city is located at a few kilometers away from Adama Wind Farm. Referring to the current grid system around Adama Wind farm, Nazret city became the target territory of electric power produced by the proposed wind farm, while the extra electric power to be transmitted to Addis Ababa through Koka 132kV substation. Referring to the grid system around the territory of Adama1WPP, there are three options for the voltage grade at 230kV, 132kV and 45kV respectively. Two stages of step-up were applied for the wind farm. The electric power from wind power turbines will be step-up to 33kV by Unit substation and conveyed to the national grid after integrated together. The total installed capacity will be 51 MW with annual power production for 3189 hours. It was recommended that a single circuit of 132kV transmission line to be applied considering the economic cost with capacity and length of distance. According to the voltage level and number of outgoing lines, analysis made on two alternatives or types for conductor selections and it was recommended that LGJ-240 conductor type shall be applied preliminarily with reasonable margin which is economical capable for power transmission up-to 64MW at annul production hours of less than 5000.

The main territory of electric power consumption will be Nazret city, as previous analysis. Nazret existing 132/15kV substation is located at 7.5km away from the south of the wind power. Two alternatives were considered for grid interconnection and possible analysis was made.

Making a comprehensive technical and economic evaluation and comparison on the two alternatives, it was recommended and determined to apply for Adama 1 WPP for inter connected system by: building a new 33kV/132kV substation within the territory of wind farm which is to be connected to Nazret 132/15 KV substation by a single circuit 132kV overhead line with LGJ-240 conductor for about 7.5km [21].

4.5 Terms and Definition

- Standard IEC: -Standard IEC-61400-1 wind turbine classification.
- Wind shear: -wind speed variation with height above ground
- Weibull distribution: -Probability function used to describe the wind speed distribution within a specified time period (normally one year).
- Turbulence Intensity: -Rate of the wind speed standard deviation to the mean wind speed over a specified period of time.
- V_{ave} (m/s): -Average wind speed
- V_{ref} (m/s): -Extreme wind speed; the extreme 10-minute average wind speed with a recurrence period of 50 years.
- Inflow angle: -It gives vertical inclination of the flow at the result point location (in degree).
- Shadow flicker: -Occurrence of periodic changes in light intensity due to the shadow of a wind turbine blade passing over a point of interest.

4.6 Features of WTG

- Rating: - 1.5MW each
- Blades: - 3Numbers
- Hub Height: - 65 meter (made up of steel tubular tower)
- Cut in wind speed: - 3 m/sec, Cutout wind speed: - 22 m/sec Rated wind speed- 11 m/sec

CHAPTER FIVE

DATA ANALYSIS, RESULT AND DISCUSSION

5.1. Production Data Analysis

Electrical power generation from wind is established in Ethiopia in 2012, and has significantly increased in the last few years. Currently Ethiopia generate power from wind and feed to the national grid. The total installed wind power in Ethiopia today is 324MW which is generated from wind power plants and there are additional upcoming wind power stations in the near future. The following table shows the annual total power production of the case study site since its initial generation, which was April 2012.

Table 5.1: Production detail of each year in KWh

Months	2012	2013	2014	2015	2016	2017	2018	2019
January	0.00	19,372,221.00	19,376,386.00	19,299,930.00	17,576,308.00	12,585,505.00	13,615,002.00	14,830,581.00
February	0.00	17,935,990.00	14,102,233.00	18,238,443.00	21,611,042.00	10,871,508.00	9,540,733.00	12,211,067.94
March	0.00	10,225,716.00	14,634,748.00	19,267,780.00	14,411,020.00	13,205,966.00	13,075,770.00	9,500,580.00
April	1,635,467.00	8,455,579.00	14,605,190.00	20,913,330.00	7,066,994.00	14,211,111.00	5,831,947.00	7,973,090.00
May	2,798,562.00	8,543,030.00	9,903,395.00	8,396,040.00	8,113,183.00	7,463,550.00	9,291,102.00	10,602,627.00
June	7,246,057.00	14,212,119.00	11,935,421.00	10,797,541.00	12,734,720.00	10,774,842.00	10,344,683.00	10,816,066.00
July	4,296,915.90	18,768,146.00	19,818,247.00	11,781,585.00	7,671,648.00	14,917,420.00	12,769,398.00	12,461,998.00
August	8,005,359.54	13,011,131.00	12,608,346.00	10,193,130.00	7,499,001.00	12,137,030.00	8,275,835.00	11,320,689.00
September	6,775,344.50	5,465,401.00	6,538,236.00	5,614,965.00	3,283,420.00	4,667,907.00	4,735,148.00	6,452,341.00
October	11,839,218.60	11,550,741.00	14,055,987.00	18,890,030.00	8,297,160.00	9,941,629.00	10,751,390.00	11,320,689.00
November	11,915,470.80	16,926,880.00	18,345,132.00	20,038,000.00	15,950,152.00	13,128,207.00	12,914,614.00	6,452,341.00
December	20,631,540.00	21,390,759.00	21,627,646.00	23,198,990.00	18,940,582.00	14,821,022.00	15,362,708.00	12,465,866.00
Total	**75,143,935.34**	**165,857,713.00**	**177,550,967.00**	**186,629,764.00**	**143,155,230.00**	**138,725,697.00**	**126,508,330.00**	**126,407,935.94**

Figure 5.1 shows the total yearly production of the case study site since its first operation. As we can see from table 5.1 the first generation was started in April 2012. The annual production exceed the plant capacity in 2013, 2014 and 2015. As it has been stated in chapter four, the annual energy production capacity of the case study site is 162.7GWh.

In this Thesis, the annual expected energy yield (energy production) of a WT is also estimated using the reliability data. Given the general performance of the WT, the annual energy production can be analyzed.

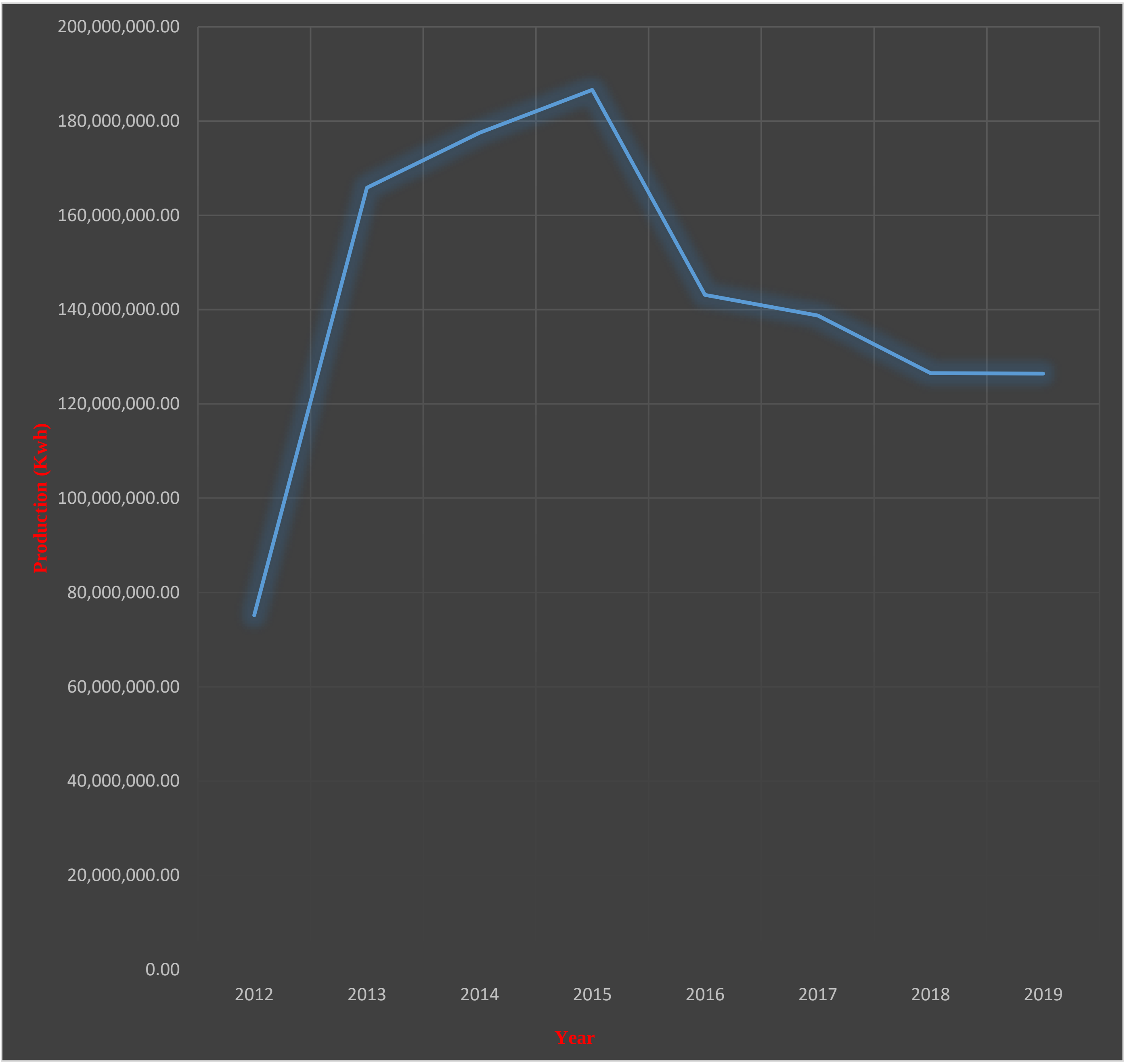


Figure 5.1: Yearly Production

Based on the data we get from the above table we can see that the output power or energy produced from the station touches the maximum point in the years2013, 2014 and 2015. But after months goes down up to current time.

Table: 5.2: Daily production of selected month in MW

Days	Daily Load of January in MW						
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
1	31	27	25	21	30	13	31
2	33	33	20	39	20	18	20
3	42	28	26	47	28	23	18
4	27	21	16	45	21	17	19
5	16	15	22	31	22	23	18
6	14	14	20	27	16	23	20
7	19	26	33	24	11	16	16
8	29	23	39	19	9	17	13
9	11	25	26	15	18	13	20
10	20	19	15	25	23	20	24
11	34	29	31	19	20	24	26
12	38	35	35	15	12	26	22
13	30	32	34	9	14	22	15
14	39	37	31	8	8	15	21
15	24	29	35	9	17	21	19
16	30	26	38	8	11	19	27
17	26	21	33	21	17	15	23
18	21	13	23	16	19	12	17
19	23	30	17	25	19	16	22
20	28	36	25	42	15	23	12
21	34	29	31	36	18	27	14
22	38	30	32	27	18	23	21
23	40	28	27	22	14	17	18
24	38	29	29	16	17	22	15
25	23	19	27	25	18	12	13
26	21	11	22	32	19	14	18
27	22	14	19	18	7	21	14
28	7	14	21	23	10	18	17
29	11	29	17	20	17	15	18
30	22	36	6	37	18	13	19
31	16	41	28	23	20	8	7

The following figure (Figure 5.2) shows the daily load of selected month (January) in each eight years. As we can understand from this figure the generated load of every month goes up and down base on wind variability and component failures as well as some external voltage block causes.

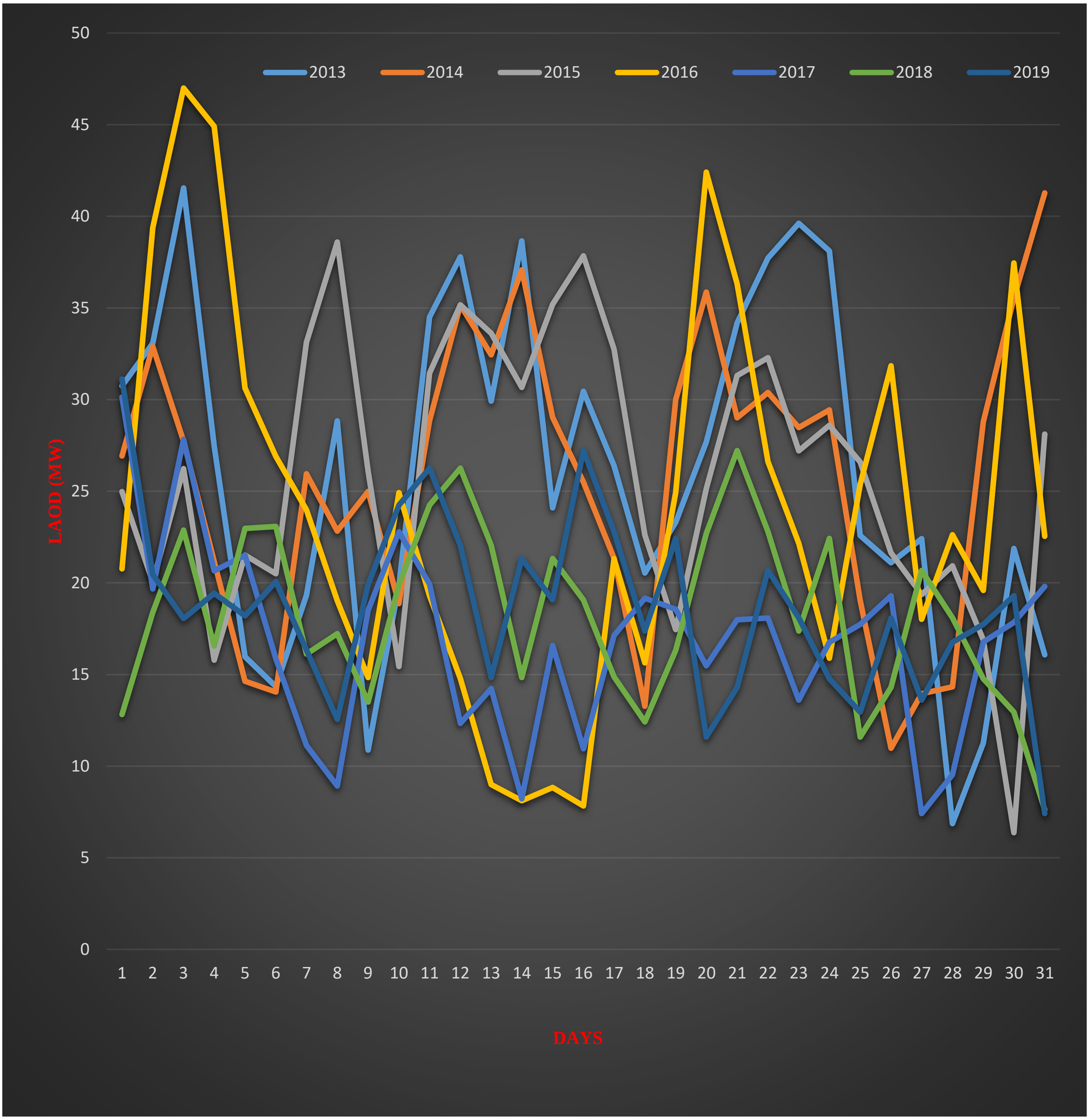


Figure 5.2: Curve of daily production

The finding shows that the reason is the continuous shut down of the power plant due to failure of components in the turbine. Components of wind turbine which are very prone to failure affects the plant output. Electrical system which are very sensitive for failure includes all the controlling, measurement and protection devices.

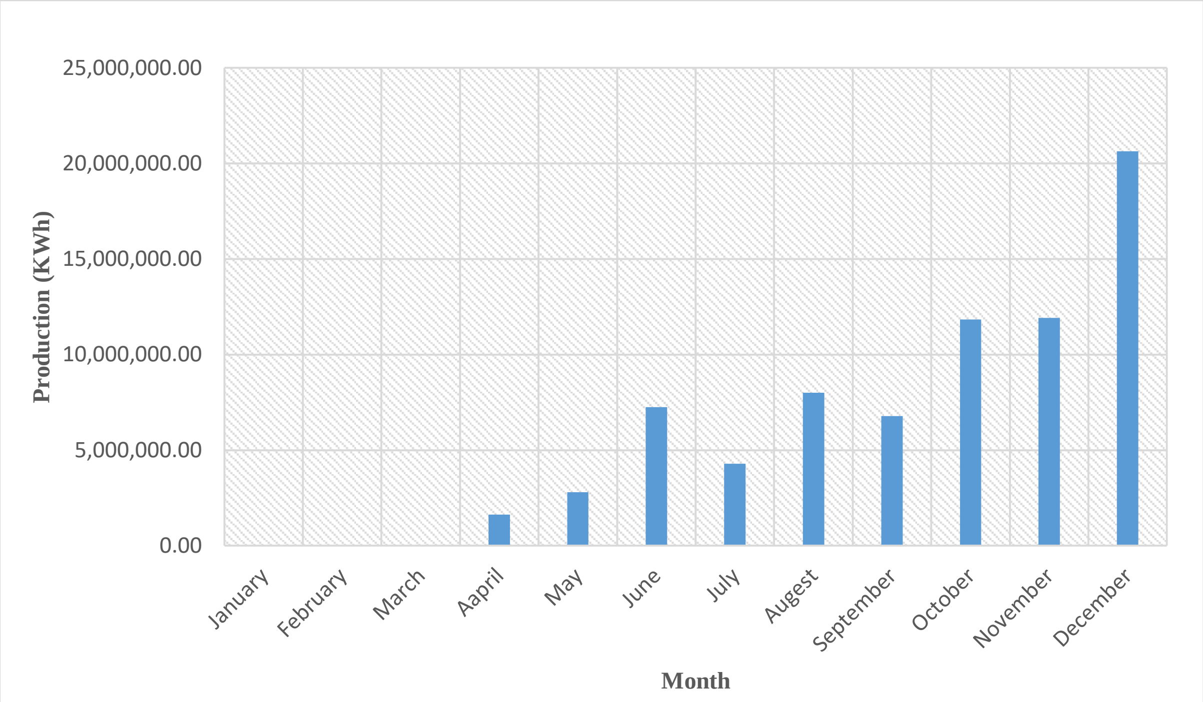


Figure 5.3: Monthly Production of 2012

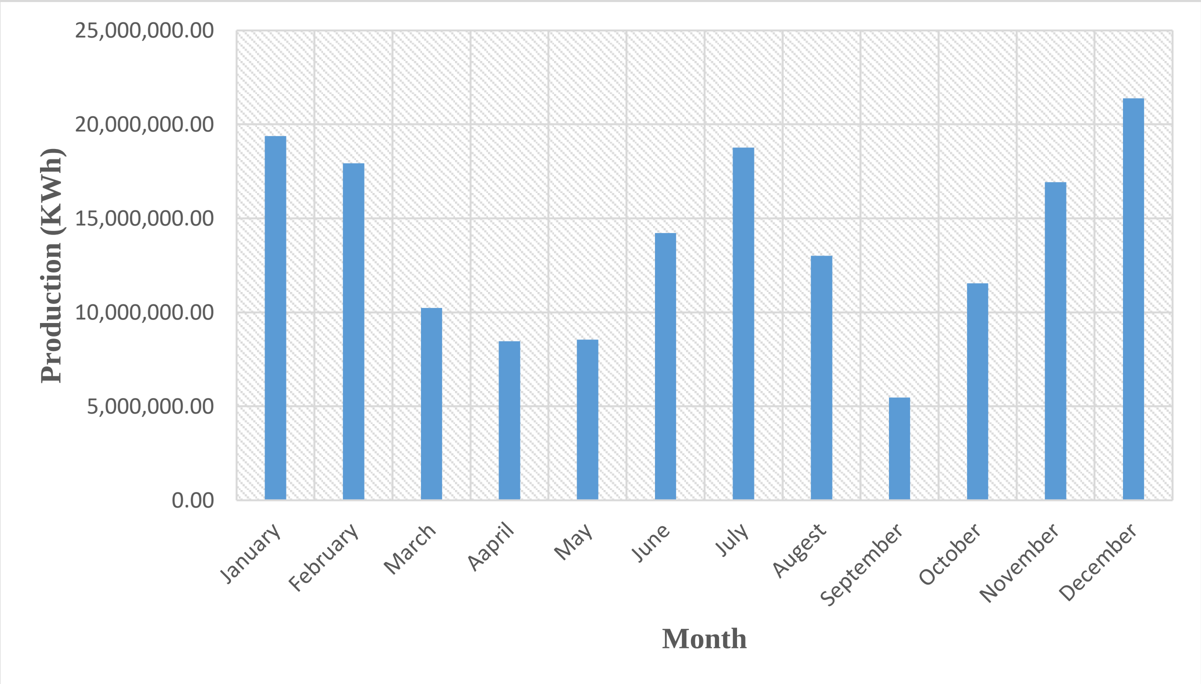


Figure 5.4: Monthly production of 2013

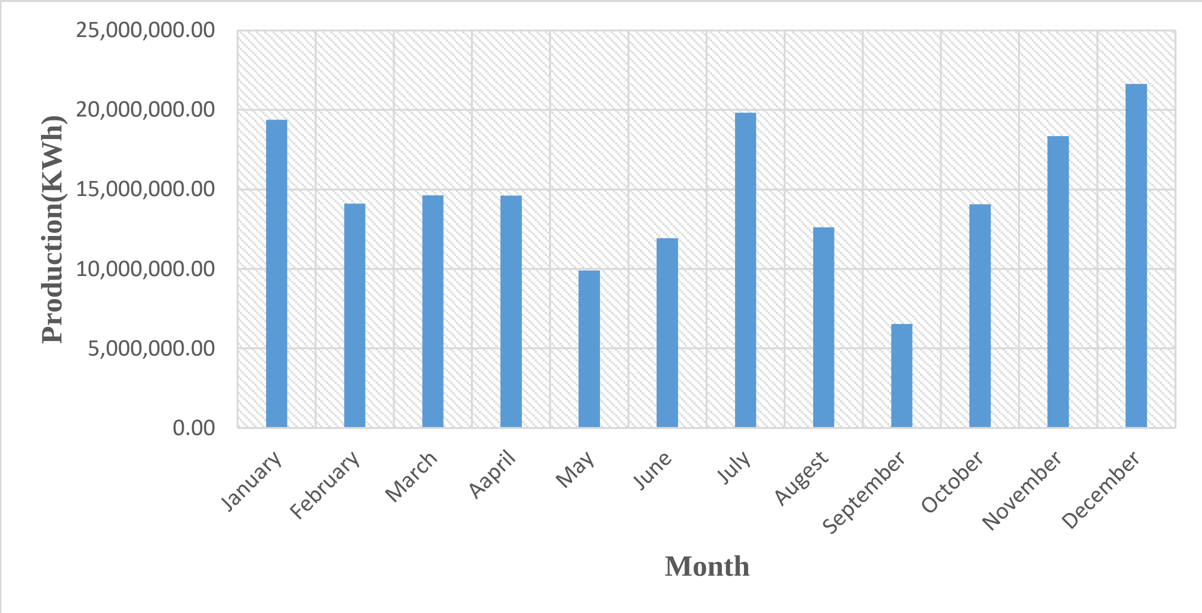


Figure 5.5: Monthly production of 2014

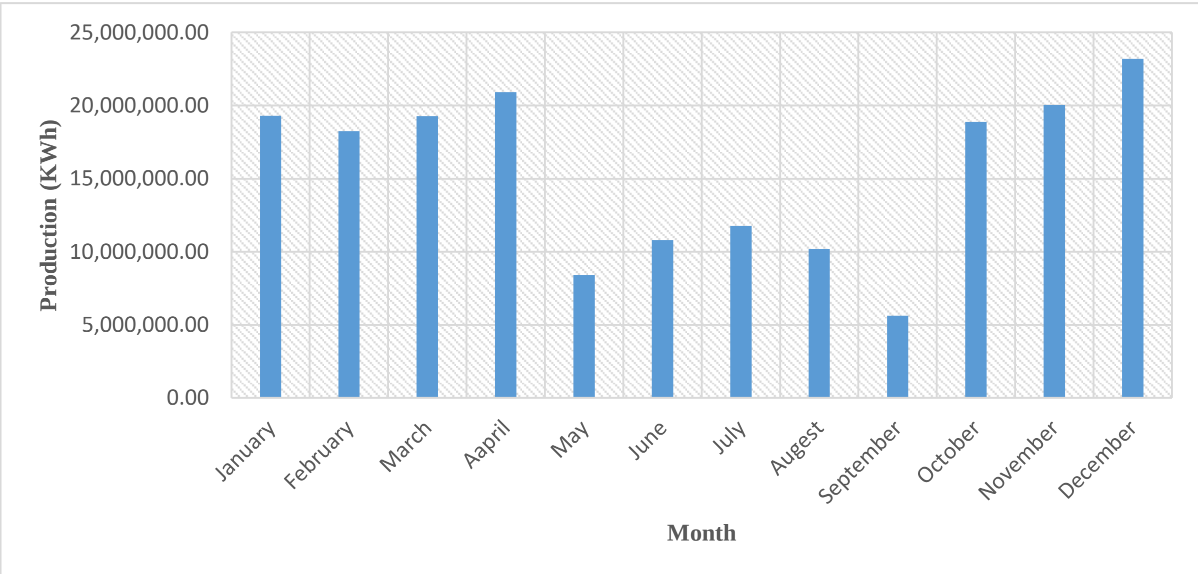


Figure 5.6: Monthly production of 2015

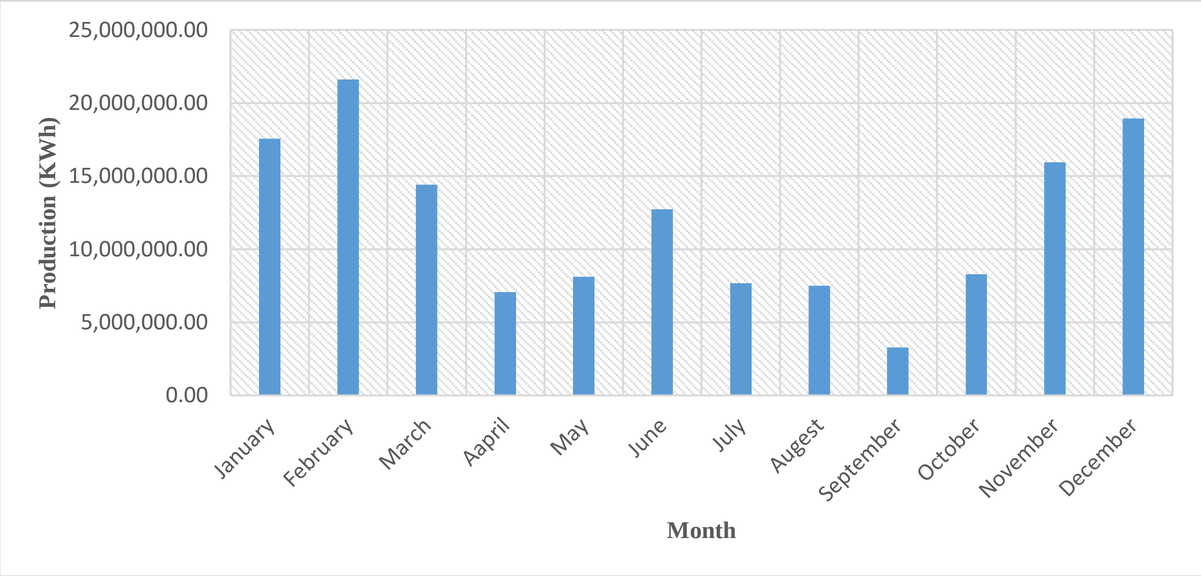


Figure 5.7: Monthly production of 2016

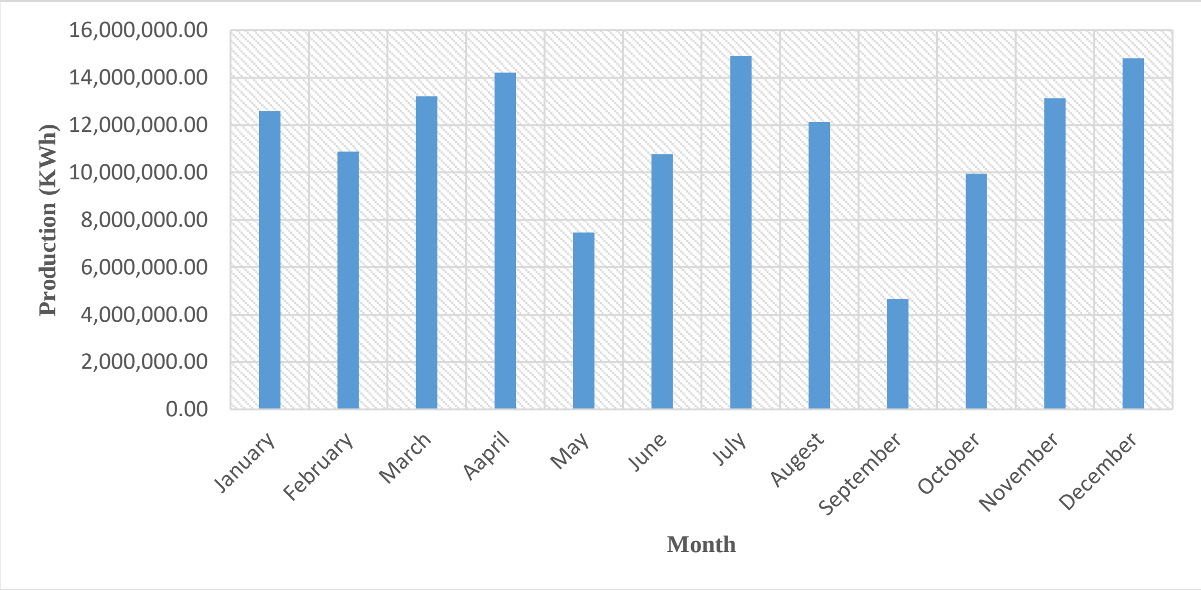


Figure 5.8: Monthly production of 2017

From figure 5.3 up to 5.10 we can understand that the monthly production varies from month to month because of different shutdown or wind speed behaviors occurred at site. The characteristics of the produced power made the grid very difficult to manage the power. By relying on this wind farm output forecasting the power demand is very difficult.

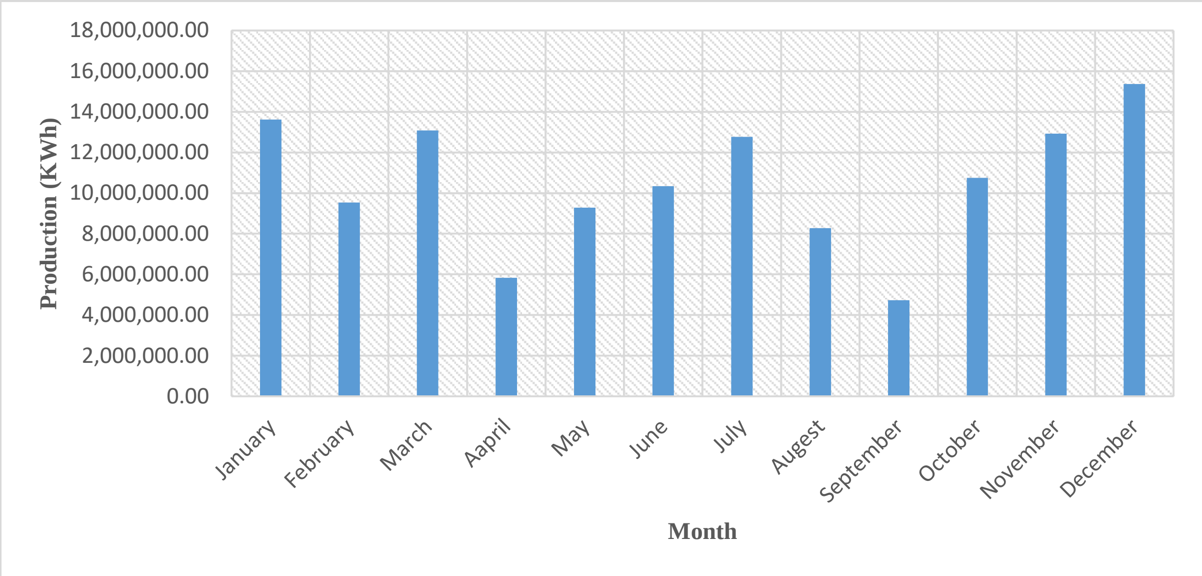


Figure 5.9: Monthly production of 2018

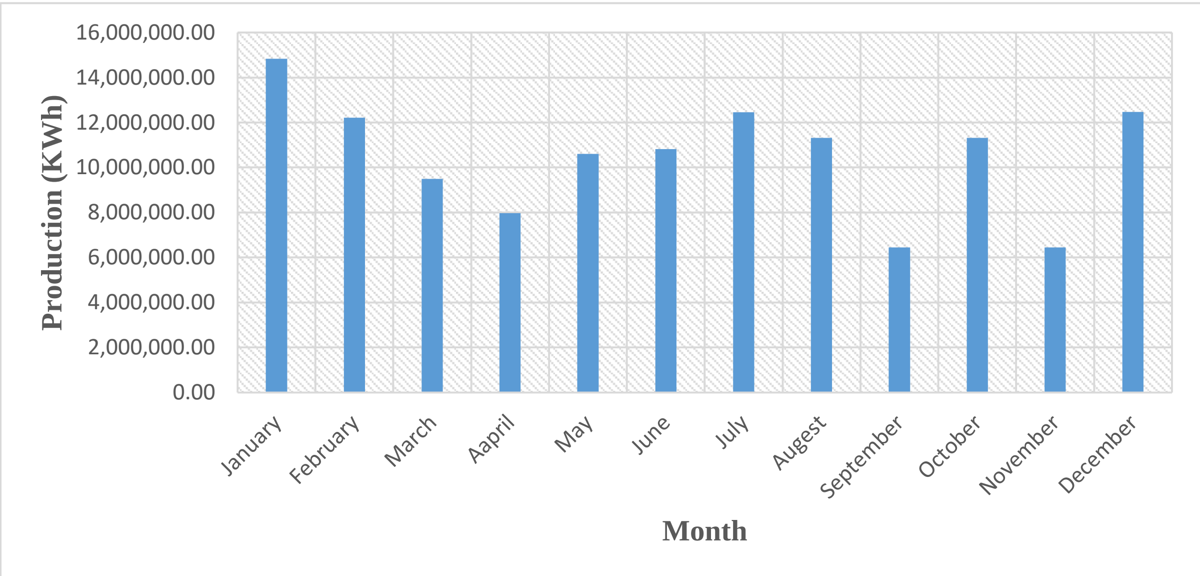


Figure 5.10: Monthly production of 2019

Table 5.3: Average daily wind speed and average daily load of September, 2019

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Av.Wind(m/s)	5	6	6	6	6	5	6	8	9	8	7	7	6	10	11	12
Av.Load(MW)	9	11	12	12	10	10	9	12	16	20	16	12	11	20	26	25
Days	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
Av.Wind(m/s)	8	8		8	8	8	11	7	7	9	9	8	9	9	7	
Av.Load(MW)	28	16	14	16	22	24	27	18	18	20	20	17	20	19	13	

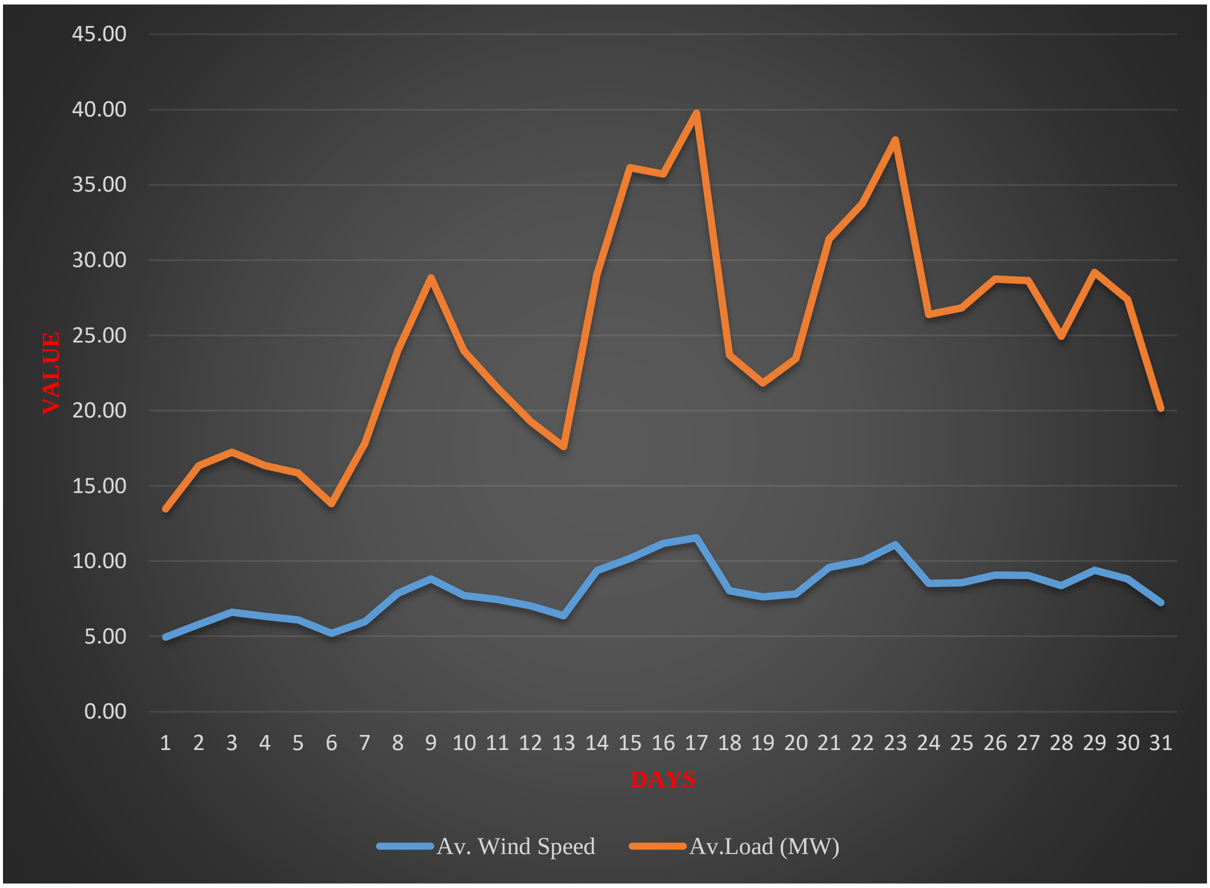


Figure 5.11: Daily Station Load vs wind speed

Table 5.4: Average wind speed of 2016

Averege wind speed of , 2016												
Days	Januar y	Febru ary	March	April	May	June	July	Auges t	Septe mber	Octobe r	Novem ber	Decemb er
1	8	11	7	5	4	7	9	6	5	5	11	10
2	8	8	8	4	6	7	8	10	5	6	9	10
3	7	12	8	6	7	7	7	11	5	8	10	11
4	5	11	6	3	5	6	7	10	5	6	10	12
5	5	11	7	6	4	7	5	8	6	8	12	9
6	5	10	8	6	6	8	7	5	5	11	11	8
7	5	11	10	5	7	8	8	3	7	11	10	10
8	9	9	10	7	5	7	4	4	4	8	9	12
9	7	9	10	6	5	8	0	5	5	8	9	11
10	9	9	11	6	6	9	0	7	5	6	10	11
11	10	12	10	5	7	7	7	9	5	4	10	12
12	11	13	8	4	8	9	9	5	5	4	10	10
13	9	9	8	5	6	8	7	8	4	8	11	9
14	8	5	5	6	7	8	5	8	7	10	8	10
15	7	7	9	7	6	10	4	6	4	9	3	10
16	9	11	10	4	5	10	8	4	3	10	4	8
17	10	7	8	5	6	9	11	5	4	11	3	8
18	7	7	6	8	7	9	9	7	4	10	8	7
19	8	8	6	7	6	9	8	7	3	8	8	9
20	8	8	7	5	6	10	8	6	4	9	10	10
21	11	8	10	4	6	9	5	5	5	8	9	12
22	8	8	7	5	6	5	8	6	8	8	9	13
23	11	6	7	4	6	7	8	8	8	9	9	12
24	11	7	5	2	6	8	8	8	6	9	11	10
25	10	6	4	7	6	9	9	6	7	9	10	12
26	12	6	5	7	6	8	9	8	8	9	9	10
27	12	5	4	6	8	8	8	7	9	9	8	12
28	8	4	3	5	5	8	7	6	9	10	8	9
29	7	5	5	4	6	9	9	5	8	12	9	8
30	10	5	5	5	6	7	7	4	7	10	9	7

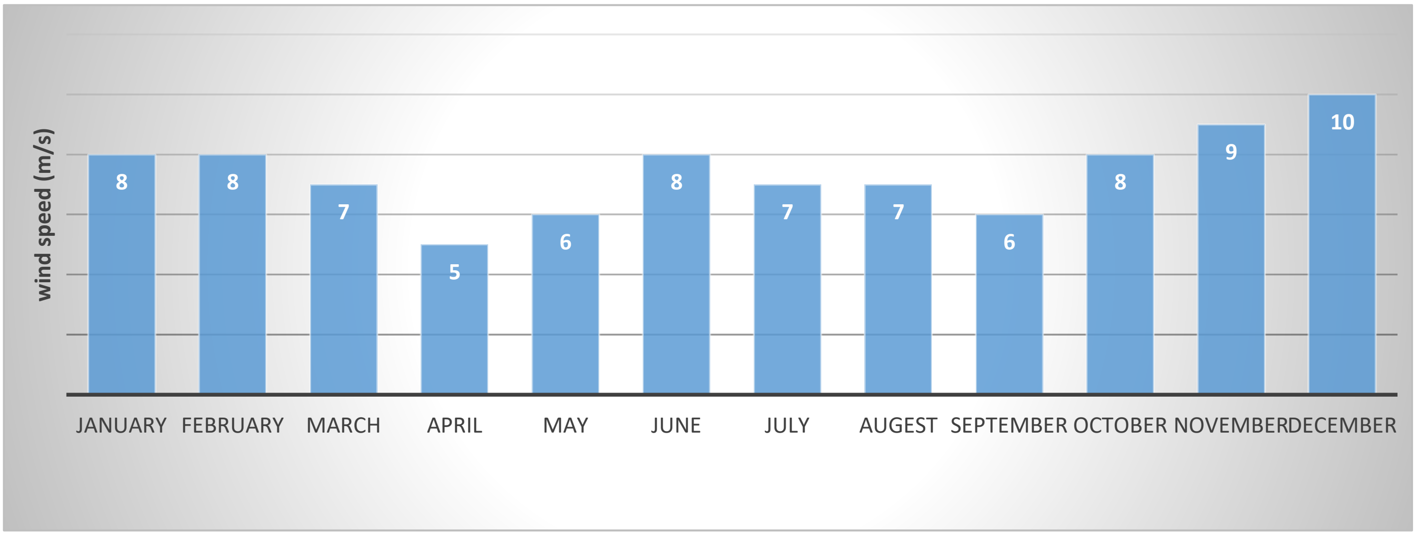


Figure 5.12: Average wind speed in each month of 2016

Table 5.5: Average wind speed of 2017

Averege wind speed of , 2017												
Days	Januar y	Febru ary	March	April	May	June	July	Auges t	Septe mber	Octobe r	Novem ber	Decemb er
1	9	7	11	9	4	6	7	6	4	8	10	8
2	10	6	9	8	5	6	7	6	4	8	10	8
3	10	8	8	7	5	6	7	7	4	10	7	9
4	11	6	9	10	5	8	8	7	4	9	9	10
5	11	9	9	10	3	7	8	4	4	11	8	12
6	10	11	8	5	3	7	10	4	3	11	8	12
7	11	10	10	8	6	7	7	9	5	9	7	11
8	11	8	8	12	6	7	8	6	4	8	8	11
9	10	5	8	11	7	6	8	7	4	9	12	11
10	8	10	7	8	7	6	6	6	6	12	12	13
11	7	10	8	6	6	7	8	8	7	10	11	11
12	9	8	6	10	5	7	9	9	5	11	12	11
13	10	8	7	11	6	7	9	5	5	9	11	11
14	10	11	9	9	7	8	8	4	4	10	8	8
15	9	11	4	8	6	11	8	7	4	9	5	9
16	10	10	7	8	7	9	7	7	4	9	9	10
17	10	7	8	9	5	6	8	7	5	8	12	11
18	8	7	7	10	4	8	5	6	7	9	11	11
19	8	11	7	11	5	8	7	6	8	8	11	10
20	8	11	8	10	4	9	9	7	10	10	10	6
21	7	11	9	11	4	5	8	4	9	11	9	7
22	7	10	10	12	4	3	8	3	12	9	9	8
23	11	21	11	11	5	6	8	5	7	6	10	11
24	12	10	7	10	5	5	9	6	5	8	10	13
25	10	10	11	7	5	5	6	4	5	7	9	13
26	9	9	11	4	5	5	7	5	5	9	10	10
27	9	9	9	3	6	5	7	6	5	10	12	9
28	10	12	9	6	5	7	8	4	9	10	11	9
29	10	13	10	3	5	7	8	6	10	9	10	6
30	10	12	10	4	5	7	8	4	8	5	10	7

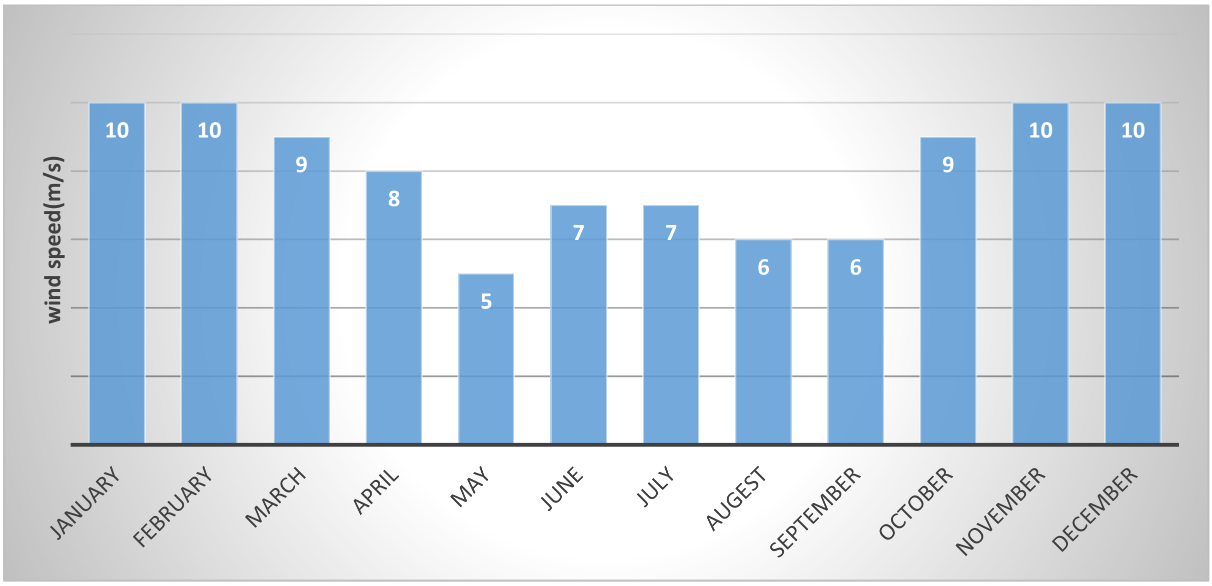


Figure 5.13: Average wind speed 2017

5.2 Calculation of Plant factor and Plant availability

- **Plant factor:** The plant factor is calculated by the equation 3.10 and is calculated as follows:

$$Plant\ factor = \frac{Actual\ Power\ \ generated}{Rated\ power}$$

The value of Plant factor, between 15 to 50% is good for wind power generation. And if the wind is continuous the Plant factor will be more except for planned and forced outage.

Table 5.6: Calculated yearly plant factor

Year	Plant factor
2012	17.05%
2013	37.64%
2014	39.74%
2015	41.77%
2016	37.12%
2017	31.05%
2018	28.31%
2019	28.29%

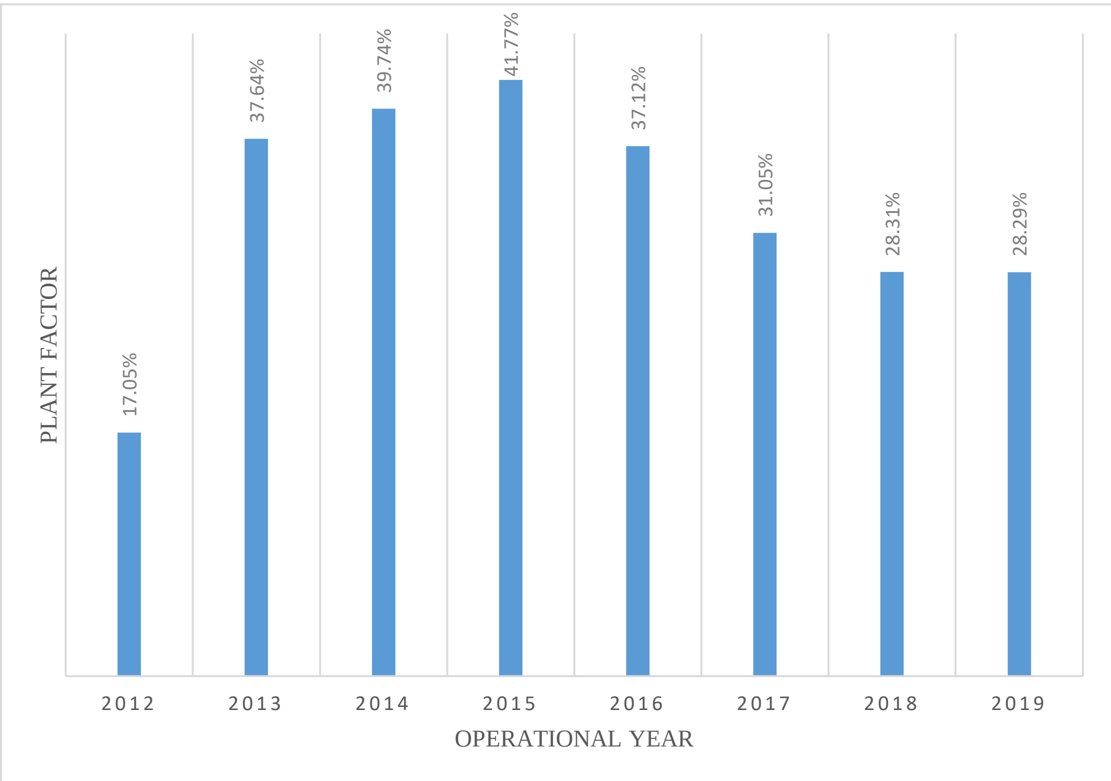


Figure 5.14: Plant Factor of each year

- **Plant availability:** Plant availability is the wind turbine generator which is available to generate power. This is obtained by mathematical relation which is given in equation 3.11.table 5.7 shows the total down time of case study plant in each year,

Table 5.7: Total wind turbines outage hours

Year	2015	2016	2017	2018	2019
Total outage hour	1079hr	755hr	1190hr	1615hr	1531hr

Table 5.8: Total wind turbines annual Availability

Year	2015	2016	2017	2018	2019
Availability	86%	90%	85%	80%	81%

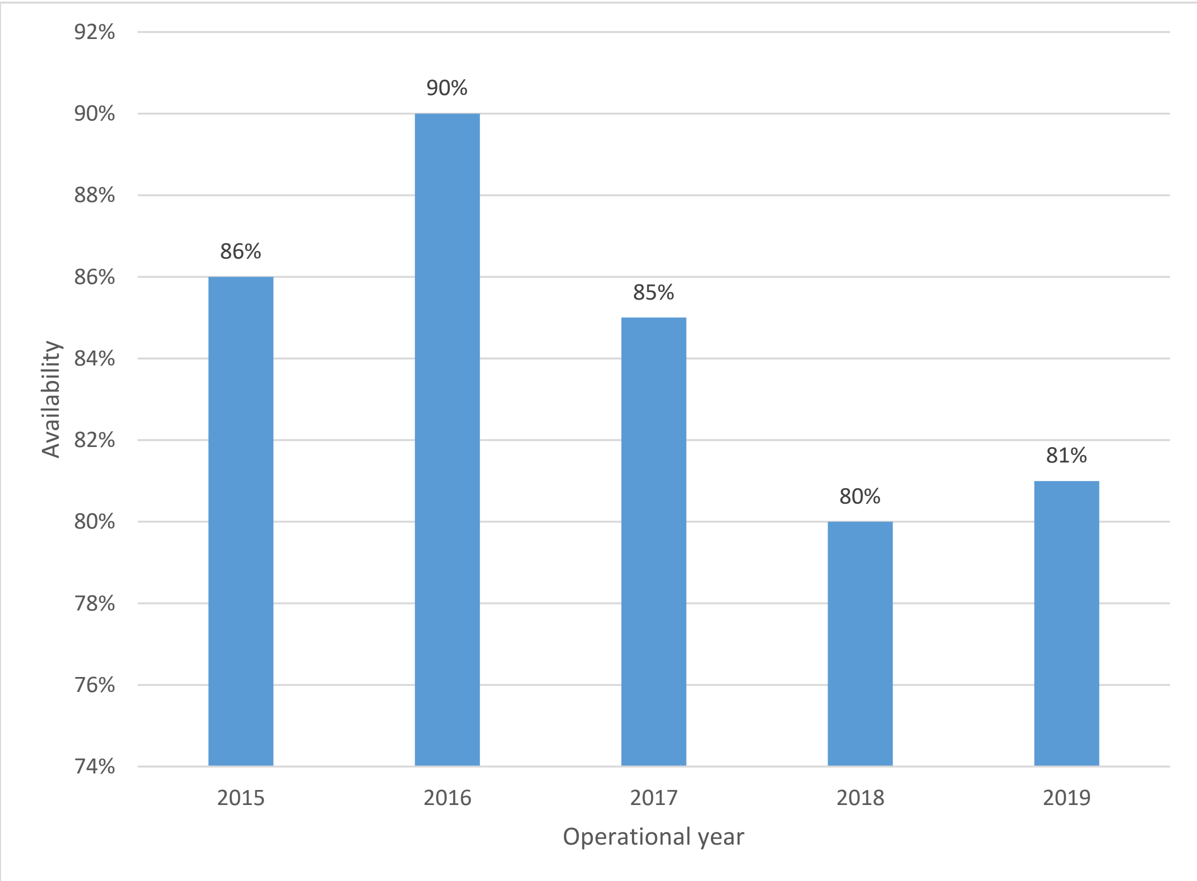


Figure 5.15: Availability of the plant

In figure 5.15 above the turbines availability for five years are shown. The availability of three years before 2015(2012, 2013, and 2014) are not shown here. Because the data used to measure availability for those years is not found in at the station, because of SCADA error.

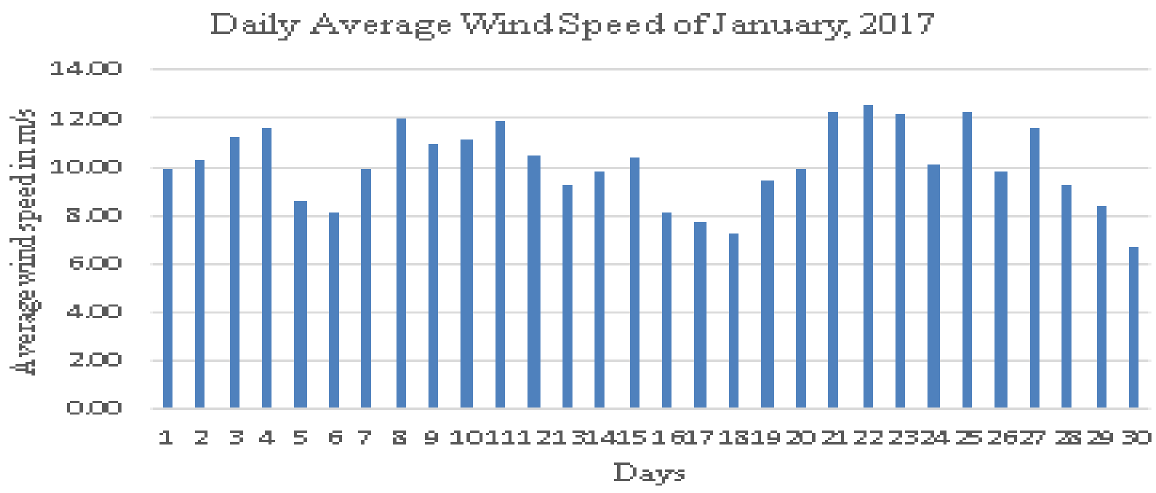


Figure 5.16: Daily Average wind speed of January, 2017

Figure 5.16 shows the daily average wind speed in selected month. It has been stated in the introductory part that the average wind speed of the plant is 11m/s. We can see here from figure 5.16 that it is almost near to the average wind needed for the production.

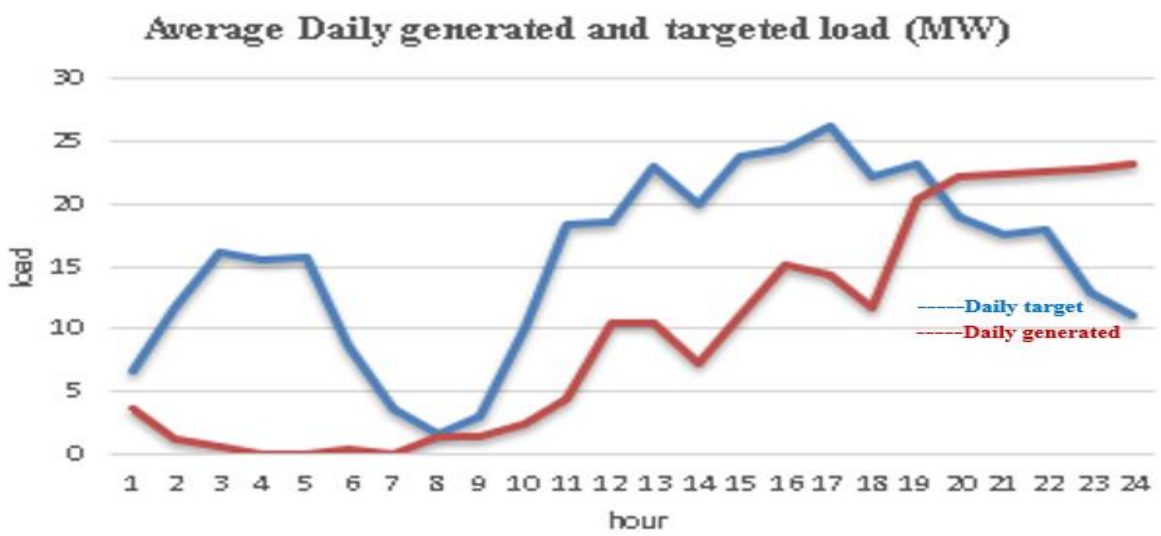


Figure 5.17: Average daily generated vs targeted power

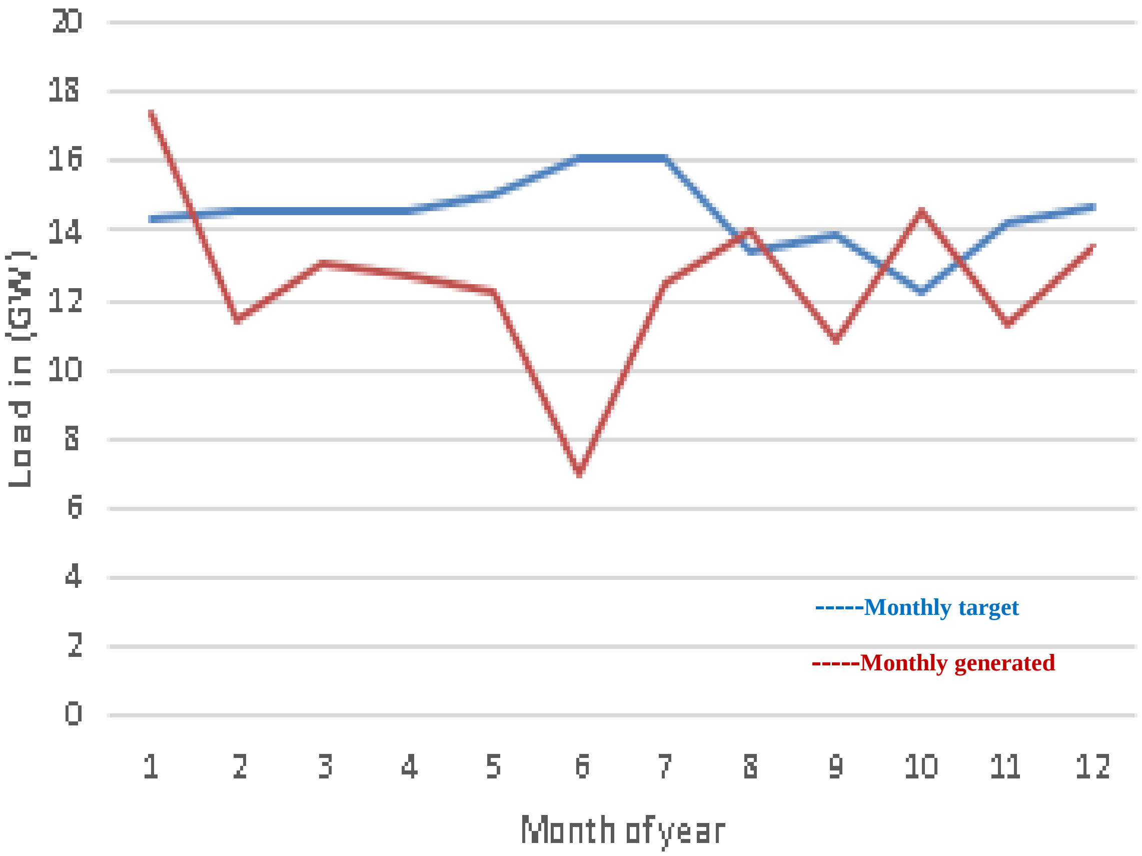


Figure 5.18 Monthly Target and generated load in 2017

Figures 5.17 and 5.18 shows that the daily and monthly targeted and generated load in MW respectively. Both figures shows the megawatt generated doesn't meet the target.

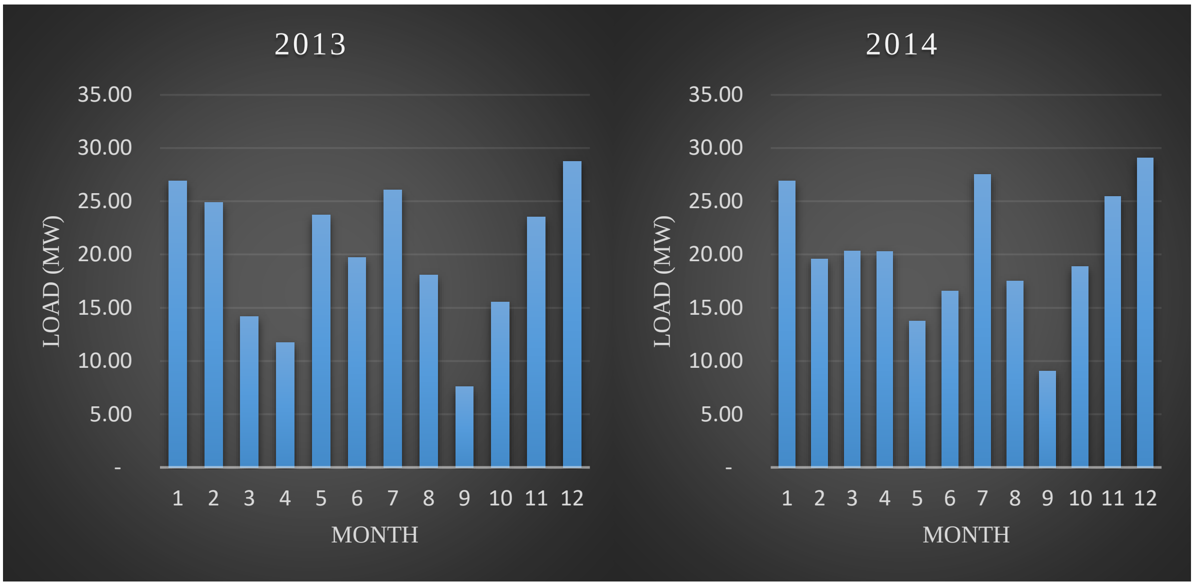


Figure 5.19 Daily Load of first six month

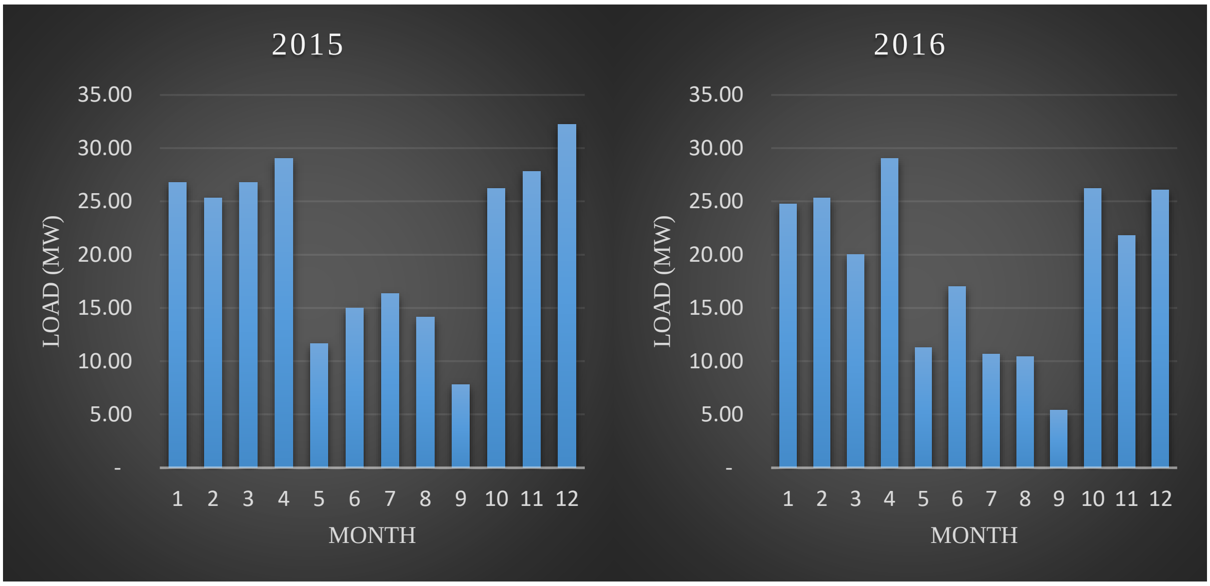


Figure 5.20: Daily Load of first six month

The average monthly load of each year is shown in Figure 5.19 and 5.20 below for year from 2013 up to 2016. And figures 5.21 and 5.22 show the monthly load of years 2017 up to 2019 respectively.

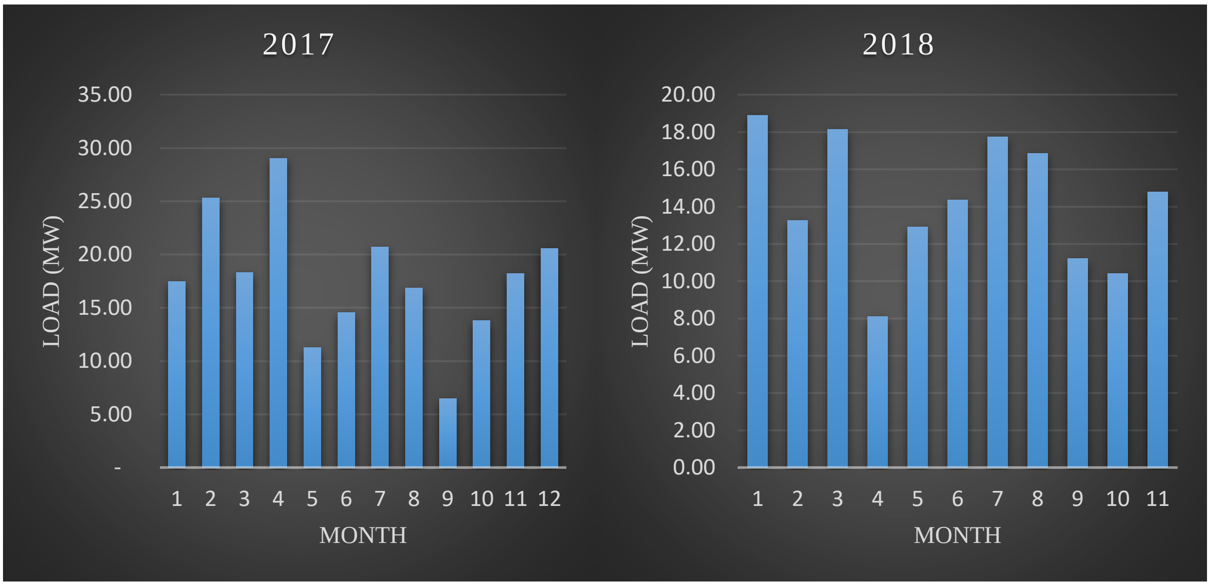


Figure 5.21: Daily Load of each second six month

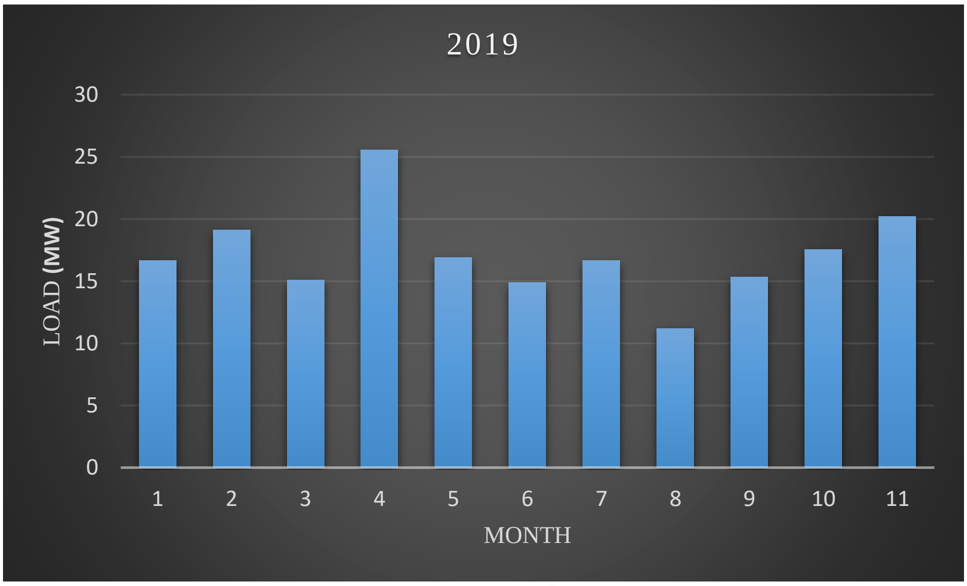


Figure 5.22: Daily Load of each second six month

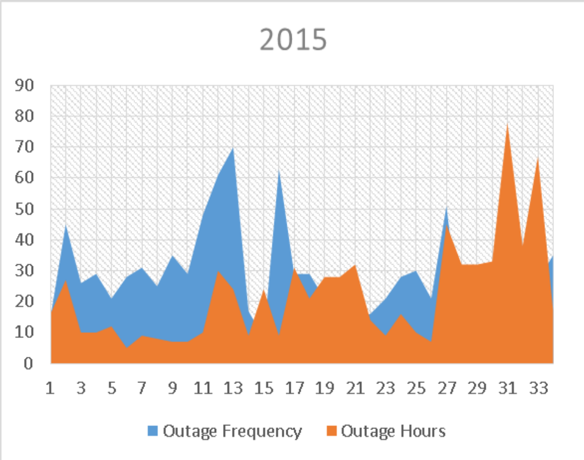
5.3 Failure Data Analysis

In this section, WT subassembly reliability data are presented and analysed in terms of failure rates and downtimes in order to determine the critical subassemblies and to compare the reliability statistics for WTs. All 34 wind turbines are analysed. Since there are discrepancies in the manner of data reporting, failure and downtime per failure statistics and stop event and downtime per stop statistics are treated separately. It should be noted that in the subsequent analysis, the common taxonomy introduced has been used to group the data.

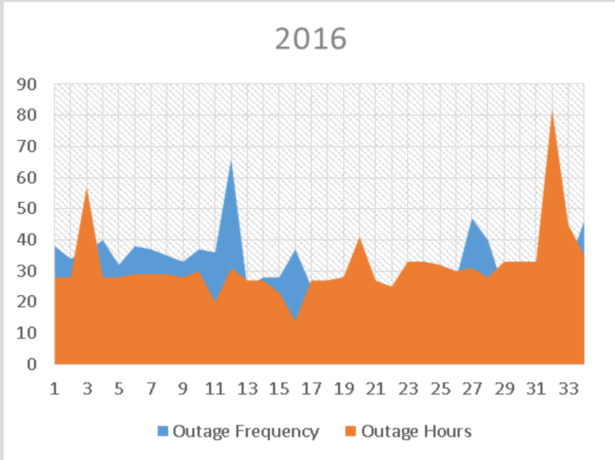
Table 5.9: Turbine failure frequency and outage hour from 2015 -2019

Turbine Number	2015 Outage Frequency	2015 Outage Hours	2016 Outage Frequency	2016 Outage Hours	2017 Outage Frequency	2017 Outage Hours	2018 Outage Frequency	2018 Outage Hours	2019 Outage Frequenc	2019 Outage Hours
1	38	28	15	16	22	28	31	50	45	32
2	34	28	45	27	78	46	262	98	856	85
3	36	57	26	10	66	41	154	127	219	5
4	40	28	29	10	27	36	53	50	128	128
5	32	28	21	12	20	17	26	43	42	21
6	38	29	28	5	23	16	51	92	32	21
7	37	29	31	9	16	30	0	0	0	0
8	35	29	25	8	18	15	42	57	49	22
9	33	28	35	7	7	1	50	81	128	29
10	37	30	29	7	27	11	63	22	577	143
11	36	20	48	10	47	92	56	82	82	122
12	66	31	61	30	29	48	7	1	264	82
13	25	27	70	24	49	91	3	22	51	30
14	28	27	17	9	21	22	39	50	58	84
15	28	23	8	24	57	53	16	27	8	7
16	37	14	63	9	3	1	37	16	0	16
17	25	27	29	31	22	88	21	96	36	53
18	27	27	29	21	28	34	40	22	52	68
19	28	28	21	28	13	83	103	35	257	29
20	26	41	20	28	33	39	26	51	38	55
21	26	27	15	32	18	79	310	93	445	76
22	22	25	16	14	13	9	15	45	67	43
23	27	33	21	9	21	42	15	49	22	9
24	33	33	28	16	17	25	63	48	11	35
25	32	32	30	10	37	27	11	28	104	25
26	27	30	21	7	20	9	47	34	206	20
27	47	31	51	45	13	12	64	71	71	32
28	40	28	10	32	25	9	19	30	214	52
29	24	33	14	32	18	9	68	32	50	21
30	28	33	15	33	34	45	34	29	50	42
31	32	33	21	78	20	17	26	29	34	33
32	44	82	24	38	26	26	37	60	107	39
33	32	45	27	67	28	17	30	28	83	33
34	46	35	35	17	40	72	30	17	40	39

In this section, five years data sources with failure rate and downtime per failure statistics are analysed to the subassemblies reliability and its variations among these data sources. As it has shown in figure 5.23 the number of failure per turbine per year for all considered years is not constant. It varies from turbine to turbine and year to year. Mostly failed turbine produces less energy if and only if its outage time is as much as long. That means many times failure doesn't indicate less production. Failure of turbine affects the production if it stays out of service for long period of time. We can see the failure frequency per turbine for each year and we can understand from figure below (a, b, c, d, e) how long the turbines were out of service in 2015, 2016, 2017, 2018 and 2019 respectively.

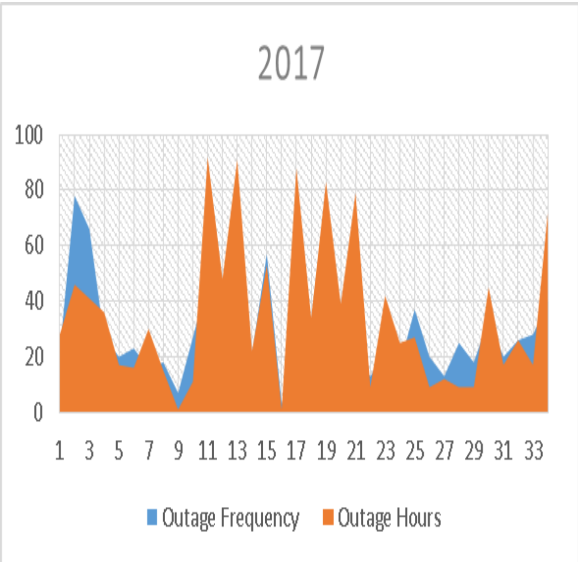

2015
90
80
70
60
50
40
30
20
10
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33
Outage Frequency
Outage Hours

(a)

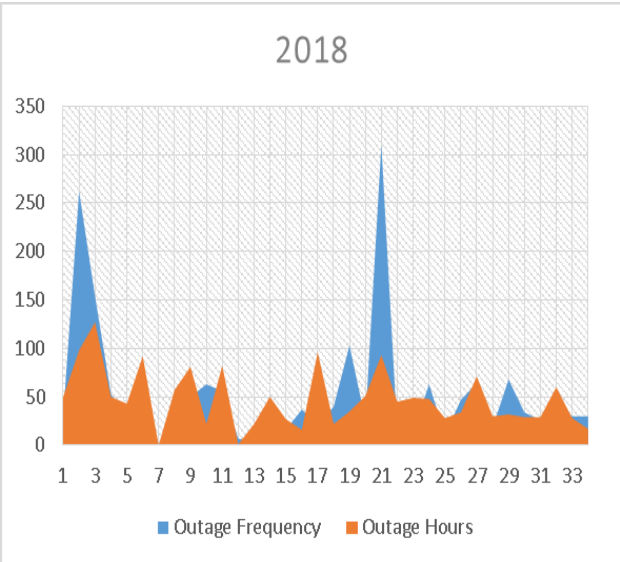

2016
90
80
70
60
50
40
30
20
10
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33
Outage Frequency
Outage Hours

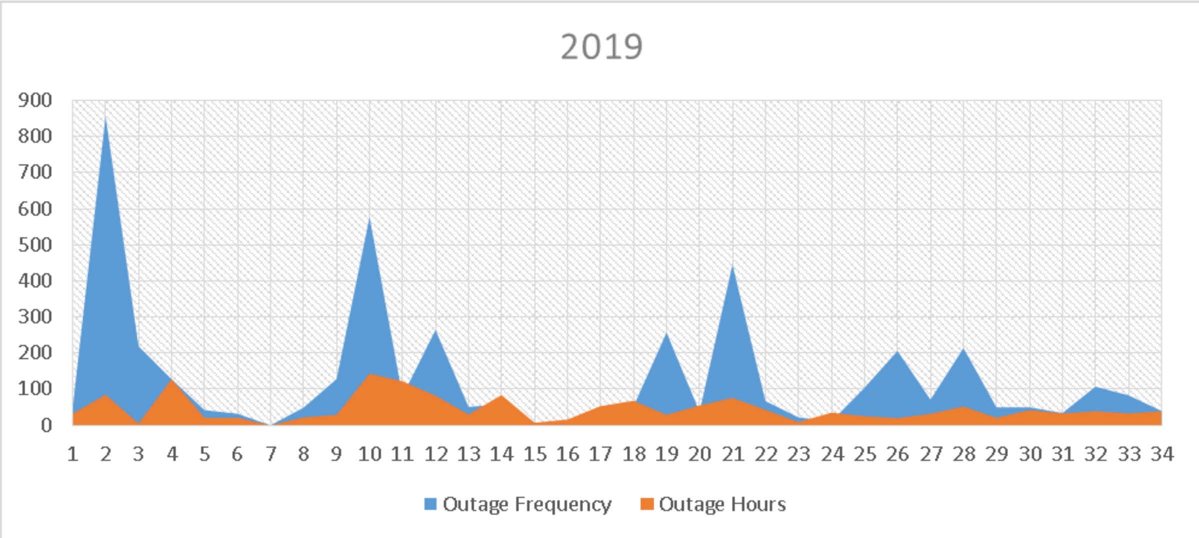
(b)

(c)


2017
100
80
60
40
20
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33
Outage Frequency
Outage Hours

(d)


2018
350
300
250
200
150
100
50
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33
Outage Frequency
Outage Hours



(e)

Figure: 5.23 Failure outage and frequency

The failures data used for this thesis covers failures of turbines for the selected eight-year period. The sample failure data is attached in appendix A. But the secondary data obtained from SCADA sometimes doesn't include all real information. This is because of the problem that, if the turbine is out of grid or if it doesn't have electric supply it do not send real-time signal to the server. So in this thesis, all the grid disconnected turbines doesn't considered.

Figure5.23 shows the total number of failures per turbines in the operational year. The question how many times a single turbine fail in a year is answered in this figure. But it does not mean that most failure have long downtime or stay long time out of service.

The annual failure rate per turbine in each operational year is plotted. Those figures gives a better view of the failures since it takes into account the frequency of component failure in each turbine, i.e. the number of failures within a single turbine in that operational year. We can understand from the graph that failures are not the some in each turbine.

Some turbines (Like turbine number 2, 3, 10, 21, 22, 33, and 31 failed many time in each year, when compared to others. But the problem is how long they stayed out of service. Does it mean a turbine which have a lot of failure produces low production? This question will get the answer in the following the following discussion. Here from the figure the most remarkable finding is that the outage of turbines rated higher yaw system.

Most of outages occurred because of yaw system are affected by wind system characteristics. The second important finding is that the trend of decreasing production is not found only because of number of failures. Instead it appears as the failure duration is increasing.

The total failure of individual wind turbine system components in all eight year is very huge data. So for this thesis work only sample data are selected for analysis purpose. But anybody can get further information from the attached Appendix A
Based on the collected values from table 5.10, subassemblies exhibiting higher average failure rates include:

- Electrical
- Control system
- Pitch system
- Blades and hub

Subassemblies exhibiting lower average failure rates include:

- Brakes
- Shafts and bearings
- Nacelle
- fan

Table 5.10 shows that there are large variations in failure rates and downtimes between different subassemblies. In terms of failure rate, pitch system, electrical, and yaw are the three subassemblies with the largest variations, while air brake, nacelle, and shafts and bearings are the three subassemblies with the smallest variations. The design flexibility is a reason for these statistics since subassemblies with more design options (pitch, electrical, and yaw) often result in disparities in failures experienced. In terms of downtimes, the three highest variability assemblies are structural, yaw, and mechanical brake; the lowest downtime variability assemblies are shafts and bearings, hydraulic, and electrical.

Table 5.10: Sample of duration and failure frequencies of turbine components.

Wind turbine Id	Triggered Time	End Time	Failure Description	Failure Duration
1	1/4/2019 11:01	1/4/2019 11:08	Error_converter step up DC link voltage high	00:07:20
1	1/4/2019 12:41	1/4/2019 12:43	Error_Gen speed over speed 1#	00:02:29
1	1/4/2019 12:50	1/4/2019 12:52	Error_Gen speed over speed 1#	00:02:29
1	1/4/2019 13:29	1/4/2019 14:40	Error_converter grid side voltage high	01:11:35
1	1/4/2019 15:37	1/4/2019 15:40	Error_converter step up DC link voltage high	00:03:30
1	1/26/2019 08:42	1/26/2019 12:38	Error_grid_voltage low	03:55:14
1	1/31/2019 20:22	1/31/2019 21:16	Error_converter grid side voltage high	00:53:53
1	2/12/2019 16:16	2/12/2019 17:06	Error_grid_LVRT over time	00:49:58
1	3/3/2019 21:23	3/3/2019 21:25	Error_Gen speed over speed 1#	00:02:28
1	3/24/2019 08:06	3/24/2019 10:55	Error_grid_voltage low	02:49:03
1	3/26/2019 20:10	3/26/2019 20:12	Error_converter IGBT ok signal loss	00:02:05
1	3/27/2019 19:24	3/27/2019 19:33	Error_converter IGBT ok signal loss	00:08:52
1	3/27/2019 19:54	3/27/2019 19:57	Error_converter step up DC link voltage high	00:03:15
1	3/30/2019 12:06	3/30/2019 12:33	Error_converter grid side voltage high	00:27:38
1	4/1/2019 10:26	4/1/2019 10:29	Error_yaw moving right feedback signal loss	00:02:07
1	4/3/2019 17:55	4/3/2019 18:23	Error_grid_voltage_super high	00:27:49
1	4/4/2019 20:57	4/4/2019 21:53	Error_grid_voltage_super high	00:56:19
1	4/13/2019 10:46	4/13/2019 11:17	Error_grid_LVRT over time	00:30:43
1	4/14/2019 23:32	4/15/2019 02:38	Error_grid_frequency low	03:05:49
1	4/17/2019 04:26	4/17/2019 09:01	Error_grid_frequency low	04:34:49
1	4/19/2019 20:48	4/22/2019 09:36	Error_converter grid side voltage high	2.12:47:55
1	5/1/2019 17:57	5/1/2019 18:35	Error_grid_LVRT over time	00:38:24
1	5/6/2019 10:35	5/6/2019 10:57	Error_converter grid side voltage high	00:21:38
1	5/6/2019 16:58	5/6/2019 17:00	Error_Gen speed over speed 1#	00:02:29
1	5/28/2019 16:49	5/28/2019 16:54	Error_converter IGBT ok signal loss	00:05:13
1	6/14/2019 00:44	6/14/2019 00:47	Error_converter IGBT ok signal loss	00:03:23
1	6/15/2019 11:36	6/15/2019 11:58	Error_converter grid side voltage high	00:21:44
1	6/22/2019 05:54	6/22/2019 06:20	Error_converter grid side voltage high	00:26:36
1	7/12/2019 19:50	7/12/2019 19:59	Error_converter step up DC link voltage high	00:09:04
1	7/29/2019 03:32	7/29/2019 03:50	Error_grid_voltage low	00:17:34
1	8/9/2019 09:49	8/9/2019 10:07	Error_grid_LVRT over time	00:18:04
1	8/16/2019 02:31	8/16/2019 03:01	Error_converter grid side voltage high	00:29:31
1	8/16/2019 03:03	8/16/2019 03:15	Error_1# pitch code error	00:12:05
1	8/16/2019 03:18	8/16/2019 08:47	Error_1# pitch code error	05:29:35
1	8/29/2019 15:40	8/29/2019 15:43	error_yaw_acceleration_nacelle_limit	00:02:25
1	9/6/2019 10:16	9/6/2019 10:44	Error_grid_LVRT over time	00:28:38
1	9/29/2019 15:36	9/29/2019 16:02	Error_converter grid side voltage high	00:25:59
1	10/13/2019 10:21	10/13/2019 10:39	Error_converter step up DC link voltage high	00:18:30
1	10/19/2019 13:42	10/19/2019 13:47	Error_converter IGBT ok signal loss	00:05:28
1	11/8/2019 19:02	11/8/2019 19:10	Error_converter capacitor cooling fan feedback loss	00:08:12
1	11/23/2019 01:54	11/23/2019 02:49	Error_converter grid side voltage high	00:55:28
1	12/3/2019 14:59	12/3/2019 15:15	Error_Gen speed over speed 2#	00:15:45
1	12/10/2019 12:45	12/10/2019 12:48	Error_grid_current unsymmetric	00:02:54
1	12/14/2019 19:27	12/14/2019 19:37	Error_converter IGBT ok signal loss	00:09:05
1	12/21/2019 17:11	12/21/2019 17:46	Error_converter grid side voltage high	00:35:12

Table 5.11: Failure description of WTG 1in 2015 G.C

Wind turbine Id	Failure Description	Failure Duration	Count
1	Error_grid_voltage low	12.11:19:40	7
1	Error converter step up DC link voltage high	00:03:08	1
1	Error converter grid side voltage high	35.16:12:41	4
1	Error_Gen low temperature	00:02:25	1
1	Error_grid_LVRT over time	2.07:42:45	5
1	Error converter grid side IGBT over current	2.13:47:34	1
1	Error_Gen speed over speed 1#	00:02:28	1
1	Error_grid_frequency low	00:02:14	1
1	Error converter IGBT ok signal loss	00:02:31	1
	Total	52:01:46	22

Table 5.12: Failure description of WTG 7 in 2015

Wind turbine Id	Failure Description	Failure Duration	Count
7	Error_grid_voltage low	02:13:52	3
7	Error converter step up DC link voltage high	00:17:51	1
7	Error converter grid side IGBT over current	00:32:20	1
7	Error converter DC link voltage high	00:07:39	2
7	Error converter grid side voltage high	55.10:46:56	3
7	Error_grid_LVRT over time	7.07:54:36	2
7	Error_profibus_10# station power supply	00:00:52	1
7	Error converter IGBT ok signal loss	00:02:29	1
7	Error_profibus_42# station diagnostic	22:57:06	1
7	Error nacelle fuse	00:01:33	1
	Total	108:32:21	16

The contribution of failure of a single turbine and the downtime totally results the reduction of production of the power plant. But number of outages is not similar with outage hours seen on each turbine. This means that, a turbine may have a lot of temporary outages or self-removed faults. Downtime is the main issue which concerns the maintenance strategy, because it directly affects the

5.4 Other Factors Affecting the Production

The external voltage blocks sometimes matter the total production of the power plant. Due to external phenomena shutdown required on WTG. These external phenomena include planned outage, forced and miscellaneous outage. Forced outage is common for all case study year. The details of external outage are listed in Appendix C.

5.4 Result and Discussion

The thesis provides a comprehensive review of present and past initiatives gathering holistic information on O&M of WT. Future research can be based on the information collected and prepared for this thesis. It can be of particular interest to prioritize or motivate future research work.

Results on the performance of WT can be considered to be reliable. There is no reason to doubt the comparison of capacity factors which shows a high shutdown dependency. Publications lack detailed definitions of the availability calculation which weakens the significance of the assessment of wind power.

It is clear that weather affects turbines' reliability and operators and researchers are in harmony when it comes to the need for improvements in the field of reliability and O&M of the turbines. Maintainability plays big role in the operation of the turbine.

The maintenance strategy and the correct inventory of spare parts are both aspects of high maintainability. It is therefore important to apply right amount of maintenance to prevent the risk of expensive failures and to keep the plant healthy. During the examination of failures of WTGs in Adama1 wind farm, questions about how the data collected was raised. In communications with the people daily working in these areas they agreed that there are some issues when it comes to reporting the failures correctly and also in the willingness to report failures. When failure statistics are being analyzed several important issues must be considered are:

1. When a major incident happens, for example when a cooling fan at the bottom of tower, the consequence is severe and the repair and downtime will be significant. Therefore, one cannot just look into failure incident for that time only, but one has to examine the trends within the failures for several years, because it affects the total plant output.
2. Secondly, there is a rapid development of new techniques and different designs within the wind power industry, thus when looking at statistics one has to know if it is relevant for the new designs. Some of the infant problems may have been eliminated or improved. So, when examining the statistics, one has to know that some of the data are old and that one has to evaluate the data concerning to the type of design.
3. Most people /the power plant worker/ collect the data from the wind power production in different way. Primarily it is the production and generated power that is measured on SCADA and in second measurements of failures and maintenance history of the wind

turbine. These ways of collecting the data are somewhat similar in theory but vary in practice. Different parts of the system are put in the statistical database and when later on compiled into statistics tables one usually groups up problems concerning different components. The way of grouping data differs between people to people working in this station. A comparison of the thirty-four wind turbine generators has done. We can see trends and similarities between these turbines.

CHAPTER SIX

CONCLUSSION AND RECOMMENDATION

6.1. Conclusions

This thesis presents an analysis of the RAM of various systems that widely used in wind power generation. These analyses include all subassemblies which represent three subsystems in the WTGs. These subsystems are electrical subsystem, mechanical subsystem, and other subsystem. This analysis gives more knowledge about what priority of these components from manufacturing, operation, and maintenance prospective. An extensive review of the most up-to-date publicly available WT subassembly reliability data also presented. Eight year data sources for case study area WTs are investigated, and the failure and downtime statistics are analysed. In addition, plant factor and plant availability evaluation using reliability data are calculated and found that, the plant factor for years 2012 to 2019 are summarized in tables 5.6 and 5.8. From the analysis, it can be observed that; there are significant variations in both the failure rates and downtimes of turbine subassemblies from different analysed data of eight years.

The volume of data, collection duration, location, and WT power rating are all possible contributing factors to the WT reliability uncertainty. In addition, the WT failure rate distribution is highly skewed to the right, which infers that the large data sources with low failure rates are dominant and the small to medium data sources with high failure rates are the sources of uncertainty in the data range.

The criticality of subassemblies is quite consistent for different data sources. In terms of failure rates and downtimes, the electrical, control, generator, drivetrain, blades, hub and pitch systems are the four most critical subassemblies for Adama 1 wind turbines are the most critical subassemblies for both onshore and offshore WTs.

It is very important to develop probabilistic reliability evaluation technique useful for electric power industries which are expected to power from wind. It is therefore very important to obtain suitable wind speed characteristics data and appropriate techniques to develop power.

The analyses concerning wind turbine reliability show in general that:

- There is already substantial operational experience to find general trends of wind turbine reliability.
- While efficiency is developing quite promising, reliability decreases with turbine complexity as we understand from assessed power plant.
- The absolute number of failures increases results that the reduction of output power which finally affects the national grid

The high and increasing number of damages and shutdowns lead to a high effort for operation and maintenance as well as to a comparably low availability. Thus, there is an urgent necessity to improve the reliability of electrical subassemblies in wind turbine system and to improve the detection of upcoming faults. Additionally, from the analyses of operational experience with total turbine systems (especially electrical and mechanical systems), the following can be derived.

- Especially the share of failure rates of the electrical subassemblies increases
- The faults of electrical subassemblies are wide-spread over their components
- Failures of the converter are most due to failures in semiconductor parts

Obviously, faults of electrical subassemblies in wind turbine may occur at a variety of different parts, are located in different components and they may suffer from different root causes, making a prediction of these faults difficult or impossible. The developments of faults and the most affected components in the wind system are not yet sufficiently known. The share of failure rates of the electrical subassemblies increases, but does not have a major effect of the availability due to high maintenance efforts. By statistical means, weak points could be identified and typical cases could get distinguished. All these results would help to diagnose faults more accurate.

Operational experience, documented in a way it can be evaluated by statistical and scientific means, can give valuable findings about weaknesses of the technology in use at the power plant. However, a clear and unambiguous database is needed. Currently, the common way documenting faults and maintenance activities is not suitable for standardized and automated evaluations. Thus, operational experience is often not used to improve the design and therefore reliability.

6.2. Recommendation

Further studies need to be considered on the causes for the failures wind turbine components. In order to solve reliability problems in the future and for the current wind power plants, the reliability data helps to estimate which component will widely available for maintenance work.

The number and classification of alarms built into the whole system needs to be critically reviewed with the aim of reducing and rationalizing responses where possible.

This is critical for reducing the number of “false alarms” and overall interventions required. But these reliability analysis methods mainly focus on direct drive wind turbine technology. It will also helpful to apply for gear derived systems since most of failed components are common for both. The effects of the reliability analysis are limited if the system is simplified and seen as a series or parallel connection.

Based on the abovementioned analysis, some key recommendations are proposed. The fatigue failure is the common failure modes of wind turbines. It needs to study the whole wind turbine fatigue life, reliability and behaviours of each wind stations in Ethiopia, to reduce the wind power disturbance from national grid.

Combining loads and fault statistical data, the gradual change mechanism of health status needs to be studied with the function of key components and mechanism characteristics, and to seek the physical representation that is related to the component health status.

This is helpful to develop the trend model and thresholds of the physical representation of fault status. Ethiopian Electric Power could develop pre fault estimation technique for all wind power plants to reduce the downtime of any failure of wind turbine components. Considering the influences of the random wind speed and waves, the dynamic reliability of the wind turbine structure and drivetrain needs study by EEP to know the characteristics of turbine systems. Following this, it is possible to estimate the dynamic reliability of the whole wind turbine.

Therefore, it is essential and urgent to develop a set of the reliability engineering model and test method of wind turbines considering the influences of wind behaviours.

Different countries trend shows that most wind turbines have been installed both SCADA and CMS, but they are independent and cannot achieve the mutual support of test results. Therefore, it is meaningful to mix two sets of the test data based on SCADA and CMS. Following this, the feature data can be extracted and transferred to the data center by the Internet. When the feature data reach the data center, they can be used to calculate and assess the dynamic reliability of wind turbines through engineering models and hardware and software equipment immediately, which will cut the operation and maintenance cost and improve the operating efficiency of wind turbines sharply which is good to apply in our country.

REFERENCES

[1] The Wind Energy Operations & Maintenance Report. Wind Energy update. [Online]. Available: http://www.windenergyupdate.com/, 2017.

[2] M. EL-Shimy, “Wind Energy Conversion Systems: Reliability Perspective,” in Encyclopedia of Energy Engineering and Technology, 2nd ed., vol. 4, pp.2184–2206, Taylor & Francis, New York, 2015.

[3] M. EL-Shimy, “Wind Energy Conversion Systems: Reliability Perspective,” in Encyclopedia of Energy Engineering and Technology, 2nd ed., vol. 4, pp.2184–2206, Taylor & Francis, New York, 2015.

[4] B. Kekezoglu, et al, ‘Reliability assessment of wind energy system considering turbine dimensions’ Yildiz Technical University, Electrical & Electronic Faculty, İstanbul, 2017

[5] Dao C, et al. Wind turbine reliability data review and impacts on levelised cost of energy. Wind Energy. 2019

[6] Yan-Fu Li, S. Valla, Enrico Zio. Reliability assessment of generic geared wind turbines by GTSTMLD, model and Monte Carlo simulation. Renewable Energy, Elsevier, 2015

[4] Mone C, Hand M, Bolinger M, Rand J, Heimiller D, Ho J. Cost of Wind Energy Review. USA: National Renewable Energy Laboratory; 2017

[5] Gonzalez E, Reder M, Melero JJ. SCADA alarms processing for wind turbine component failure detection. J Phys Conf Ser. 2016; 753(7):072019.

[6] Faulstich Stefan, Pfaffel Sebastian, Hahn Berthold, Hirsch Johanna. Performance and reliability benchmarking using the cross-company initiative WInD- Pool. 2015

[7] Sheng S. Wind Turbine Gearbox Reliability Database, Condition Monitoring, and Operation and Maintenance Research Update. 2016

[8] Carter C., Karlson B., Martin S., and Westergaard C. Continuous Reliability Enhancement for Wind (CREW) Program Update. 2016

[9] Ma Z, An G, Sun X, Chai J. A study of fault statistical analysis and maintenance policy of wind turbine system. In: International Conference on Renewable Power Generation (RPG 2015). 2015

[10] EWEA, FinancingandInvestmentTrends2016, Vol.9, EWEA, Brussels, Belgium, May 2017.

[11] H. Badihi and Y. Zhang, "Passive fault-tolerant cooperative control in an offshore wind farm," Energy Procedia, vol.105, pp. 2959–2964, 2017.

[12] Caichao Zhu and Yao Li, November 10th 2017Reviewed: February 5th 2018Published: March 21st 2018.

[13] Su C, Yang Y, Wang X, Hu Z. Failure analysis of wind turbines: case study of a Chinese wind farm. In: 2016 Prognostics and System Health Management Conference. 2016

[14]. SPARTA. System performance, availability and reliability trend analysis: portfolio review. March 2017.

[15] Sinha Y, Steel JA. A progressive study into offshore wind farm maintenance optimisation using risk based failure analysis. Renew Sustain Energy Rev. 2015.

[16] Leite G de NP, Araújo AM, Rosas PAC. Prognostic techniques applied to maintenance of wind turbines: a concise and specific review. Renew Sustain Energy Rev. 2018.

[17] Portfolio Review 2016; System Performance, Availability and Reliability Trend Analysis (SPARTA): Northumberland, UK, 2016.

[18] Carroll, J.; McDonald, A.; McMillan, D. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy 2015.

[19] Jung, H.; Pfaffel, S.; Faulstich, S.; Bübl, F.; Jensen, J.; Jugelt, R. Abschlussbericht: Erhöhung der Verfügbarkeit von Windenergieanlagen EVW-Phase 2; FGW eV Wind Energy and Other Decentralized Energy Organizations: Berlin, Germany, 2015.

[20] Símon Einarsson Wind Turbine Reliability Modeling pdf, 2016

[21] Caichao Zhu and Yao Li, Reliability Analysis of Wind Turbines, November 10th 2017

[22] A. Bechkaoui, A. Ameur, S. Bouras, and A. Hadjadj, "Opencircuit and inter-turn short-circuit detection in PMSG for wind turbine applications using fuzzy logic, "EnergyProcedia, vol. 74, pp. 1323–1336, 2015.

[23] WindEurope, Wind Energy Will Reduce Costs Sharply Over Next Five Years, IEA Report Finds, and Vol. 27, WindEurope, Brussels, Belgium, 2016.

[24] WindEurope, Costs Come down Again in 1 GW German Onshore Wind Auction, Vol. 23, WindEurope, Brussels, Belgium, 2017.

[25] WindEurope, AvoidingFossilFuelCostswithWindEnergy.A Report by the European Wind Energy Association, WindEurope, Brussels, Belgium, 2014.

[26] Fraunhofer IWES. The WInD-Pool: Complex Systems Require New Strategies and Methods; Fraunhofer IWES: Munich, Germany, 2017.

[27] Chai, J.; An, G.; Ma, Z.; Sun, X. A study of fault statistical analysis and maintenance policy of wind turbine system. In International Conference on Renewable Power Generation (RPG 2015); Institution of Engineering and Technology: Stevenage, UK, 2015.

[28] Carlsson,F.;Eriksson,E.;Dahlberg,M. DamagePreventingMeasuresforWindTurbines: Phase1—Reliability Data. Elforks Report 10:68. 2010. Available online: http://www.elforsk.se/Programomraden/El--Varme/ Rapporter/?download=report&rid=10_68_ (accessed on 8 February 2016).

[29] Carter, C.; Karlson, B.; Martin, S.; Westergaard, C. Continuous Reliability Enhancement for Wind (CREW): Program Update: SAND2016-3844; Sandia National Laboratories: Albuquerque, NM, USA, 2016.

[30] Reder, M.D.; Gonzalez, E.; Melero, J.J. Wind turbine failures—Tackling current problems in failure data analysis. J. Phys. Conf. Ser. 2016.

[31] Hahn, B. Wind Farm Data Collection and Reliability Assessment for O&M Optimization: Expert Group Report on Recommended Practices, 1st ed; Fraunhofer Institute for Wind Energy and Energy System Technology—IWES: Kassel, Germany, 2017.

[32] ISO 14224: Petroleum, petrochemical and natural gas industries --Collection and exchange of reliability andmaintenance data for equipment; 2016.

[33] Hahn B (Ed.), et al. Expert group report on recommended practices - 17. Wind farm data collection and reliability assessment for O&M optimization. IEA Wind, to be published;2017.

[34] Technical Guidelines for Power generating Units, Part 7: Maintenance of power plants for renewable energy, Category D2: State-Event-Cause Code for power generating units (ZEUS). FGW; 2016.

[35] IEC 61400-25:Communications formonitoring and control of wind power plants. Series of standards; 2006-2016.

[36] IEC 61400-26: Time-based (IEC 61400-26-1), production-based (IEC 61400-26-2) availability for wind turbine generating systems, (IEC TS 61400-26-3)Wind energy generation systems -Part 26-3: Availability for wind power stations;2011/2014/201

[37] ReliaSoft, "Reliability Importance Measures of Components in a Complex System." [Online].Available: http:// ww.weibull.com/hotwire/issue66/relbasics66.htm.[Accessed: 01-Jan-2018].

Appendix A: Sample average wind speed and average power

Wind Turbine	Average Wind Speed	Average Power	Wind Turbine	Average Wind Speed	Average Power	Wind Turbine	Average Wind Speed	Average Power
1	2.45	18.93	11	9.97	1,091.30	19	3.06	52.25
1	2.93	37.44	12	2.56	17.09	19	3.49	76.75
1	3.56	74.29	12	2.9	36.54	19	3.99	113.64
1	4.08	114.71	12	3.48	69.77	19	4.51	168.68
1	4.54	146.07	12	3.91	103.06	19	5.04	218.53
1	5.12	207.99	12	4.58	160.6	19	5.51	289.85
1	5.41	254.03	12	5	205.16	19	5.89	331.18
1	6	360.58	12	5.46	274.06	19	6.49	443.68
1	6.48	420.84	12	6.02	359.76	19	7.19	531.49
1	6.98	530.68	12	6.48	423.53	19	7.56	635.22
1	7.48	637.52	12	7.13	546.67	2	2.16	2.56
1	7.93	751.18	12	7.49	651.86	2	2.58	14.11
1	8.58	901.08	12	7.97	746.83	2	2.91	30.83
1	9.06	979.53	12	8.51	867.56	2	3.57	70.52
1	9.59	1,069.36	12	9.09	973.7	2	4.07	103.81
10	2.52	16.71	12	9.54	1,068.91	2	4.44	131.33
10	2.94	32.99	12	9.8	1,100.67	2	5	205.29
10	3.39	62.84	14	2.51	11.93	2	5.52	281.27
10	4.12	118.65	14	3.12	43.3	2	6.05	367.78
10	4.51	149.25	14	3.64	80.1	2	6.53	459.37
10	4.95	197.04	14	4.03	103.15	2	7.04	574.67
10	5.51	275.11	14	4.53	144.2	2	7.46	651.37
10	6.02	351.24	14	4.95	184.07	2	7.92	737.94
10	6.46	440.32	14	5.46	243.98	2	8.61	912.65
10	6.99	541.06	14	6.08	357.11	2	9.05	995.64
10	7.54	674.23	14	6.42	412.15	2	9.5	1,051.20
10	7.9	746.38	14	7.03	535.01	20	2.53	12.61
10	8.46	892.54	14	7.48	628.25	20	3.06	40.95
10	9.02	1,025.85	14	8.03	753.3	20	3.56	72.02
10	9.46	1,109.07	14	8.52	860.99	20	3.96	97.47
11	2.62	15.51	14	8.97	997.43	20	4.46	139.39
11	2.89	28.81	14	9.53	1,070.80	20	5	200.08
11	3.54	71.67	14	10.08	1,119.08	20	5.6	282.85
11	4.11	114.94	18	2.55	23.51	20	6.05	345.46
11	4.56	145.62	18	2.97	35.57	20	6.45	431.31
11	4.97	185.6	18	3.51	73.2	20	7.01	538.12
11	5.48	253.35	18	3.98	102.2	20	7.52	642.74
11	6.08	344.26	18	4.56	136.86	20	7.97	749.69
11	6.52	424.99	18	5.02	191.52	20	8.3	823.82
11	6.98	520.13	18	5.48	248.32	21	2.47	10.49
11	7.52	633.6	18	6.06	342.31	21	3.02	40.79
11	7.91	749	18	6.46	404.3	21	3.64	79.17

11	8.5	879.49	18	6.99	508.5	21	4	101.12
11	9.05	1,015.79	18	7.47	596.48	21	4.46	138.37
11	9.55	1,098.71	18	8.2	713.91	21	4.99	195.66
11	9.97	1,091.30	18	8.47	812.89	21	5.54	269.53
12	2.56	17.09	19	2.42	10.89	21	5.96	344.05
21	6.48	425.88	27	5	177.25	31	4.98	186.24
21	7.02	547.27	27	5.54	251.6	31	5.47	244.64
21	7.36	648.07	27	5.94	314.95	31	6.1	332.59
21	8.03	780.26	27	6.53	409.93	31	6.55	391.01
21	8.33	842.25	27	6.93	494.51	31	7	528.39
22	2.32	3.9	28	2.61	20.68	31	7.32	630.08
22	2.96	30.18	28	2.93	31.74	31	7.81	564.16
22	3.51	59.32	28	3.51	70.88	32	2.21	2.17
22	4.04	98.14	28	4	100.24	32	2.4	7.5
22	4.53	130.62	28	4.58	143.23	32	3.08	44.51
22	4.95	168.86	28	4.97	186.42	32	3.43	68.26
22	5.59	243.98	28	5.46	257.6	32	4.02	107.83
22	5.99	300.52	28	6.02	338.65	32	4.51	150.2
22	6.57	387.4	28	6.4	418.63	32	4.98	208.51
22	6.89	438.89	28	7.04	529.18	32	5.53	275.9
22	7.52	564.03	28	7.43	614.7	32	5.98	344.06
22	8.06	655.9	28	7.99	782.76	32	6.49	442.36
22	8.45	742.64	29	2.61	13.83	32	6.93	518.48
22	8.8	821.9	29	2.98	33.31	34	2.52	11.87
24	2.15	18.19	29	3.48	63.52	34	2.81	22.66
24	2.54	15.46	29	3.97	95.82	34	3.55	74.25
24	3.01	42.81	29	4.56	140.04	34	3.99	105.36
24	3.49	67.05	29	4.99	189.11	34	4.52	151.64
24	4.03	103.28	29	5.47	251.51	34	4.97	198.56
24	4.58	150.94	29	5.94	312.06	34	5.48	259.49
24	4.96	196.86	29	6.42	391.48	34	6.04	348.32
24	5.54	276.34	29	7	490.76	34	6.55	440.59
24	6.1	360.39	29	7.44	560.94	34	7.01	525.73
24	6.43	410.85	3	3	32.22	34	7.39	588.35
24	6.98	509.83	3	3.56	63.6	4	3.45	6.38
24	7.56	623.35	3	4.07	105.91	4	4.06	28.55
26	2.48	18.15	3	4.48	138.48	4	4.54	57.84
26	3	39.01	3	5.01	197.1	4	4.95	80.79
26	3.51	65.94	3	5.43	261.65	4	5.52	119.42
26	4	97.61	3	5.87	313.27	4	5.95	158.33
26	4.53	146.41	3	6.48	417.04	4	6.48	221.67
26	4.94	187.41	3	6.97	530.2	4	6.98	283.73
26	5.51	263.7	3	7.53	638.91	4	7.47	356.69
26	6.04	332.55	3	7.94	735.4	4	7.99	440.17
26	6.54	421.56	3	8.35	826.24	4	8.6	571.34

26	6.94	486.59	3	8.89	960.84	4	8.9	629.76
26	7.41	591.22	3	9.47	1,098.17	4	9.36	722.12
27	2.62	4.88	31	2.47	8.39	4	9.93	835.13
27	2.91	18.02	31	2.87	22	5	2.09	0.85
27	3.58	57.2	31	3.53	64.34	5	2.51	21.58
27	4.04	88.05	31	3.97	91.54	5	3	45.08
27	4.53	124.59	31	4.51	133.75	5	3.49	70.84
5	4.03	107.37	5	4.03	107.37	9	6	325.65
5	4.47	150.83	5	4.47	150.83	9	6.48	405.69
5	4.93	205.31	5	4.93	205.31	9	7.05	522.62
5	5.61	308.1	5	5.61	308.1	9	7.45	604.06
5	6.02	369.83	5	6.02	369.83	9	7.99	717.61
5	6.45	456.59	5	6.45	456.59	9	8.51	825.39
5	7	549.89	5	7	549.89	9	9	917.54
5	7.48	677.41	5	7.48	677.41	9	5.46	244.32
5	7.89	766.71	5	7.89	766.71	9	6	325.65
5	8.31	834.28	5	8.31	834.28	9	6.48	405.69
6	2.64	6.4	6	2.64	6.4	9	6	325.65
6	3	24.32	6	3	24.32	9	6.48	405.69
6	3.49	54.11	6	3.49	54.11	9	7.05	522.62
6	3.97	85.25	6	3.97	85.25	9	7.45	604.06
6	4.48	120.31	6	4.48	120.31	9	7.99	717.61
6	5	178.44	6	5	178.44	9	8.51	825.39
6	5.48	237.13	6	5.48	237.13	9	9	917.54
6	5.97	314.58	6	5.97	314.58	9	5.46	244.32
6	6.51	401.98	6	6.51	401.98	9	2.5	8
6	6.92	489.74	6	6.92	489.74	9	3.05	29.95
6	7.39	606.31	6	7.39	606.31	9	3.55	69.7
6	8.04	727.46	6	8.04	727.46	9	3.99	98.63
6	8.47	823.38	6	8.47	823.38	9	4.46	134.91
6	8.94	919.21	6	8.94	919.21	9	4.96	183.65
8	2.23	11.25	8	2.23	11.25	9	2.5	8
8	2.51	18.08	8	2.51	18.08	9	3.05	29.95
8	3.12	53.33	8	3.12	53.33	9	3.55	69.7
8	3.58	78.46	8	3.58	78.46	9	3.99	98.63
8	3.97	98.89	8	3.97	98.89	9	4.46	134.91
8	4.43	132.66	8	4.43	132.66	9	4.96	183.65
8	4.98	189.81	8	4.98	189.81			
8	5.44	256.64	8	5.44	256.64			
8	5.99	353.35	8	5.99	353.35			
8	6.48	434.6	8	6.48	434.6			
8	7.03	549	8	7.03	549			
8	7.49	662.57	8	7.49	662.57			
8	7.99	763.62	8	7.99	763.62			
8	8.52	865.52	8	8.52	865.52			

Appendix B:

Plant Factor and Availability

$$Plant\ factor = \frac{Actual\ Power\ \ generated}{Rated\ power}$$

- For 2012

$$Plant\ factor = \frac{75{,}143{,}935.34kw}{51000kwx8760}\text{x}100=17.05\%$$

- For 2013
- $Plant\ factor= \frac{165{,}857{,}713.00kw}{51000kwx8760}x100=$ 37.64%

- For 2014
- $Plant\ factor= \frac{177{,}550{,}967.00kw}{51000kwx8760}x100=$ 39.74%

- For 2015
- $Plant\ factor= \frac{186{,}629{,}764.00kw}{51000kwx8760}x100=$ 41.77%

- For 2016
- $Plant\ factor= \frac{165{,}857{,}713.00kw}{51000kwx8760}x100=$ 37.12%

- For 2017
- $Plant\ factor= \frac{138{,}725{,}697.00kw}{51000kwx8760}x100=$ 31.05%

- For 2018
- $Plant\ factor= \frac{126{,}508{,}330.00kw}{51000kwx8760}x100=$ 28.31%

- For 2019
- $Plant\ factor= \frac{126{,}407{,}935.94kw}{51000kwx8760}x100=$ 28.29%

Plant Availability

For 2015

- *Plant Availability*= $\frac{7562hr}{8760hr}x100$=86%

For 2016

- *Plant Availability*= $\frac{7885hr}{8760hr}x100$=90%

For 2017

- *Plant Availability*= $\frac{7450hr}{8760hr}x100$=85%

For 2018

- *Plant Availability*= $\frac{7025hr}{8760hr}x100$=80%

- For 2019

- *Plant Availability*= $\frac{7109hr}{8760hr}x100$=81%

Appendix C

ADAMA I WIND POWER PLANT
MONTHLY OUTAGE REPORT FOR (2017 G.C)

SR. NO.	Line / WTG NO.	FROM DATE	FROM TIME	TO DATE	TO TIME	TOTAL TIME HRS.	ENERGY LOSS MU	REASONS
PLANNED OUTAGES								
	Line							
	WTG							
FORCED OUTAGES								
	Line/Unit							
	WTG							
MISCELLANEOUS OUTAGES								
	Line	4/21/2009 12/30/2016	8:42	4/21/2009 12/30/2016	11:15	3:33		External Voltage block
	WTG		8:42		11:27,11:28, 12:30	3:45,3:46,3:47		
	Line	4/21/2009 12/30/2016		4/21/2009 12/30/2016				External Voltage block
	WTG							
MISCELLANEOUS OUTAGES								
	Line	4/21/2009 12/30/2016		4/21/2009 12/30/2016				External Voltage block
	WTG							
MISCELLANEOUS OUTAGES								
	Line	4/21/2009 12/30/2016		4/21/2009 12/30/2016				
MISCELLANEOUS OUTAGES								
	LINE	13/10/09	15:02	13/10/09	17:11	2:09		External Voltage block
	WTG	13/10/09	15:02	13/10/09	17:28,17:30, 17:32	2:26,02:28,2:30		
	LINE	29/10/09	14:11	29/10/09	14:59	0:48		External Voltage block
	WTG	29/10/09	14:11	29/10/09	15:16,15:18, 15:23	1:05,1:07 ,1:12		

ADAMA I WIND POWER PLANT

MONTHLY OUTAGE REPORT FOR (2017 G.C)

SR. NO.	Line / WTG NO.	FROM		TO		TOTAL TIME HRS.	ENERGY LOSS MU	REASONS
		DATE	TIME	DATE	TIME			
PLANNED OUTAGES								
	Line	1/11/2009	23:55	2/11/2009	5:28	5:33		External Voltage block
	WTG	1/11/2009	23:55	2/11/2009	6:02,6:03, 6:05	6:07,6:08, 6:11		
MISCELLANEOUS OUTAGES								
	Line/Unit	11/7/2009	3:43	11/7/2009	4:20	0:37		External Voltage block
	WTG	11/7/2009	3:43	11/7/2009	4:20	0:37		
	Line/Unit	13/7/2009	16:22	13/7/2009	16:52	0:30		External Voltage block
	WTG	13/7/2009	16:22	13/7/2009	17:49,17:46, 17:43	0:27,0:24, 0:21		
MISCELLANEOUS OUTAGES								
	Line	23/12/2009	16:43	23/12/2009	18:30	1:47		External voltage block
	WTG	23/12/2009	16:13	23/12/2009	18:35,18:34, 18:33	1:52, 1:52, 1:50		
MISCELLANEOUS OUTAGES								
	Line	4/11/2017	6:20	4/11/2017	9:36	3:16		External Voltage Block
	WTG	4/11/2017	6:20	4/11/2017	9:52, 9:54, 9:56	3:32, 3:34, 3:36		