Addis Ababa University

Center for Renewable Energy Technology

College Of Technology and Built Environment

Multidimensional Power Reliability Assessment of Adama Wind Farm

This thesis is submitted to the School of Graduate Studies at the Institute of Technology, Addis Ababa University, in partial fulfilment of the requirements for the degree of Master of Science in Renewable Energy Technology.

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Addis Ababa, Ethiopia

Certification

I, the undersigned, hereby certify that I have reviewed the thesis entitled "Multidimensional Power Reliability Assessment of Adama Wind Farm" and recommend its acceptance by Addis Ababa University, Addis Ababa Institute of Technology, Energy Center. This certification is submitted in partial fulfilment of the requirements for the degree of Master of Science in Renewable Energy Technology.

Name and Signature of Advisor: ___________________________

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Declaration

I hereby declare that this thesis represents my original research work and has not been previously submitted for any degree at this or any other university. All sources of information and materials utilized in the preparation of this thesis have been duly acknowledged. This thesis is submitted in partial fulfilment of the requirements for Master's Degree in Renewable Energy Technology at Addis Ababa University and is intended to be accessible in the university's library in accordance with its regulations.

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Acknowledgment

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Abstract

This research aims to evaluate the multidimensional power reliability of wind farms equipped with both geared and gearless wind turbines, considering their impact on overall efficiency and profitability. Through a comparative analysis, real-time data from operational wind farms is collected to assess power reliability metrics, employing qualitative and quantitative approaches. Statistical models such as fault tree analysis and reliability engineering techniques are utilized to calculate failure rates and downtime, determining the reliability indices of geared and gearless wind turbines. Factors such as wind availability, levelized cost of energy (LCOE), and identification of common failure modes and weakest components are considered. The results reveal that the gearless wind farm experienced a 12,700-hour shutdown due to a pitch fault, with sensors having a high failure rate of 8,950 occurrences. Common failure modes were over temperature and pitch angle, leading to estimated costs of 6.93 ETB, an LCOE of 78%, and availability. In the geared farm, the longest shutdown recorded was 3,700 hours caused by a yaw system fault, with the yaw system component having a high failure rate of 60,000 occurrences. Common failure modes were yaw motor failure and yaw twisting, resulting in estimated costs of 5.94 ETB, an LCOE of 83%, and availability. These findings provide valuable insights for optimizing wind farm operations and conducting comprehensive power reliability assessments.

Keywords: Gearless Wind Turbine, Geared Wind Turbine, Wind farm, LCOE, Power reliability, Failure modes, Downtime, Failure tree analysis, Failure rate, Shutdown duration, Efficiency, Reliability indices, Comparative analysis

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Nomenclatures

^{0}	Degree
^{0}C	Degree Celsius
'	Minutes of plane angle
"	Seconds of plain angle
m	Meter
km	Kilometer
m^2	Meter square
m/s	Meter per second
h	Hour
min	Minute
V	Volt
kv	Kilo volt
rpm	revolution per minute
w	Watt
p	Power
kw	Kilowatt
MW	Megawatt
kwh	Kilowatt hour
kwh/m^2	Kilowatt hour per meter square
mwh	Megawatt hour
Gw	Gegawatt
Gwh	Gegawatt hour
Gwm/s	Gegawatt meter per second
GWh/m^2	Gegawatt hour per meter square
Milli	Million ton

Acronyms

N	North
E	East
WppI	Wind power plant one
WppII	Wind power plant two
PM	Permanent magnet
PMDD	Permanent magnet direct drive
WTG	Wind turbine generator
O&M	Operation and maintenance
LCD	Load dispatched center
DFIG	Double-fed induction generator
LCOE	Levelized cost of energy/levelized cost of electricity
SCADA	Supervisory control and data acquisition
FMECA	Failure mode effect criticality analysis
KPA	Key performance indicator
CCN	Cost criticality number
DCN	Downtime criticality number
AFR	Annual failure rate
OGF	Observable and gradual failure
OFF	Observable fast failure
AUT	Aging undefined point of time
RF	Random failure
MTBF	Mean time between failures
FTA	Fault tree analysis
RBD	Reliability block diagram
HPP	Homogeneous Poisson process
PLP	Power law process
LED	Light emitting diode
NHPP	Non-homogeneous Poisson process
LWK	Lastkraftwagen
CAPEX	Capital expenditures
DECEX	Decommissioning expenditure
OPEX	Operating expert

CRF	Capital recovery factor
NPV	Net present value
TPI	Actual plant investment
AEP	Annual energy production
IGBT	Insulated-gate bipolar transistor
XML	Extensible markup language
WT	Wind turbine
WTG	Wind turbine generator
ETB	Ethiopian birr

Greek letters

λ	Lambda
μ	Micro sigh
η	Eta
Θ	Theta

Chapter One

1. Introduction

Concerns regarding the greenhouse effects of fossil fuel combustion and fuel consumption have escalated alongside the global rise in energy demand. This has led to global warming and the melting of ice caps, thereby necessitating the increased utilization of sustainable energy sources such as biomass, solar power, wave energy, and wind power[1]. Over the past 35 years, wind energy has become the prominent solution to these issues. The development, manufacturing, and operation of wind turbines are no longer limited to small-scale experimental projects but have transformed into a fully modern and established industrial sector. The growth trajectory of wind energy generation is expected to continue rapidly in the coming decades [2].

Ethiopia possesses a diverse array of renewable energy resources, including hydroelectric power, wind energy, solar energy, geothermal energy, and biomass. Although biomass remains the primary source of energy, hydropower represents the most significant renewable energy source in the country.

Table 1: Potential and Exploitation of energy in Ethiopia[3]

No	**Source**	**Unit**	**Exploitable**	**Exploited amount**	**Percentage amount**
1	Hydropower	GW	4.5	3.18	<17
2	Solar	KWh/m^2	5.2		<1
3	Wind	GWh/m^2	1350	O.324	<1
4	Geothermal	Gwm/s	7	0.0073	<1
5	Wood and Agriculture	GW	1140	566	80
6	Biogas	Million ton	1-3milli	17869	<1

1.1. Background

Ethiopia possesses substantial wind energy resources, notably concentrated around the principal East African Rift Valley, as well as in the northern and eastern regions of the country. Despite the considerable potential of wind energy, the development of wind farms in Ethiopia remains at a nascent stage. The estimated wind power potential exceeds 10,000 MW, with wind speeds ranging between 7 and 9 meters per second. However, the current installed capacity is limited to 324 MW, representing less than 5% of the estimated potential[3]. Adama Wind farm is one of the earliest installed wind farms in Ethiopia.

Table 2: Existing and upcoming wind plants (WPP) with their capacity[4]

No	Project	Generating capacity (MW)	Annual energy production (GWh)
	Connected to grid		
1	Adama I WPP	51	157
2	Adama II WPP	153	479
3	Ashegoda WPP	120	450
4	Ayisha WPP	300	592
	Total	424	1678
	Upcoming		
5	Messobo WPP	42	104
6	Assela WPP	100	197
7	Debre Birhan WPP	100	197
	Total	766	1584

Adama City is home to two wind farms, Adama One and Adama Two. The Adama One wind farm is located at 39° 13' 48" E latitude, 8° 32' 41" N longitude, and is 400–600 m wide and 5 km long, 95 kilometres from, Ethiopia's capital city, Addis Ababa. The total installed capacity is 51 MW, with 34 units each rated at 1.5 MW. The Gold Wind 1.5 MW wind turbine is powered by a permanent magnet (PM) generator which is without gearbox and is directly controlled by a three-blade rotor. The combination of a converter system and a synchronous PMDD (Permanent Magnet Direct Drive) generator provides a higher capacity for connecting to the grid. The power plant is connected to the grid by a power substation. The 132 kV transmission line is connected to the old Adama old grid and the rest to the LDC (Load and Dispatch Centre) [5].

Table 3: Adama 1 wind farm-specific information [6]

Lightning Pro. sta.	Design life time	Ser. Tem.	Scope of opr. Temp	Max allo. mws.	Max ser. Ws. 3sec	Cut out wind speed	Cut in wind speed	Rated wind speed	Rated speed	Scope of rpm	Hub height	Swept area	Dia. Of rotor	Inverter Output voltage	Rated power	WTGs model
IEC61400-24:62305	≥20 years	-40^0C-50^0C	-30^0C-40^0C	11m/s	78 m/s	27m/s	3m/s	13.1 m/s	20.5 rpm	10.6-20.5 rpm	65m	$3421m^2$	66m	620V	1.5 MW	GW66/1.5MW

Adama II wind farm is in Adama, east of Addis Ababa, and 3 kilometres northwest of Adama city, at an elevation of 17412173m. The feasibility study states that the average wind speed in the area is 8–9 m/s, and the wind farm's central geographical location is 39° 12' 10" E, 8°34' 18" N. It is the second-largest wind farm in Ethiopia with 102 turbines and can generate 153 MW of electricity runs through doubly-fed induction generator (DFIG). As a result, it plays a significant role in diversifying electricity generation, which would otherwise depend exclusively on hydropower and thereby be susceptible to extreme weather conditions.

Nonetheless, the issue of dependability has always been a concern. The reliability of wind turbine systems is crucial for the success of wind energy projects. Poor reliability directly affects the project's revenue stream by increasing operation and maintenance (O&M) expenses and reducing power generation availability due to turbine downtime. Therefore, the focus of any system, whether it involves subsystems or component failures, is to discuss the factors that contribute to the uncertainty in estimating wind turbine component reliability.

A wind turbine's machine model, design, and construction quality are the main factors that affect its reliability. The machine's response to the wind environment determines the loading applied to the components, and the turbine's dependability varies depending on the operating conditions. The wide range of possible component failures, such as yaw systems, pitch drive electronics, power electronics, gearbox torque arms, generator bearings and windings, and gearbox bearings, emphasizes how little is known about the load and operating conditions of large wind turbines [7].

Fault tree analysis, binary decision diagrams, power law processes, the Markovian method, the Weibull distribution, and exponential laws are some of the reliability studies, modelling tools, and techniques available. Each technique has its specialties and setup. Reliability can be studied based on failures, operating time, and cost-related issues.

With a particular focus on the Adama wind farm as the research object, this study addresses the issues pertinent to wind turbine reliability in wind turbine power generation projects. The farm's current state is discussed in the first section, which also presents the main faults, parts, and sub-assemblies that are most prone to deformation and their causes. The final section evaluates the levelized cost of energy and discusses about power reliability and reliability modelling tools.

1.2. Problem statement

Power-generating companies must have a dependable power production system. However, this is not always the case, necessitating the assessment of power reliability in wind farms. The Adama wind farm, with a turbine rating of 1.5 MW, experiences frequent failures during operation, compromising power reliability even with corrective measures in place. Wind farms often face high failure rates and downtime, making power reliability a pressing concern. It is crucial to understand the failure rate, downtime, failure modes, severity of failures, logical relationships between failures, availability, and the cost of lost energy. SCADA data was utilized to measure the severity, power reliability, and availability of the Adama wind farm. By assessing the power reliability of the system, it becomes possible to identify the weakest components and subsystems of the farm and implement corrective measures. Additionally, this report serves as a valuable resource for other wind farms, as the Adama wind farm is the oldest. It discusses areas for improvement, and failure modes, and provides a comparison between geared and gearless wind turbines. This study main goal is to determine and evaluate the impact of common failure modes, characteristics, and turbine technologies on the entire farm in terms of cost, energy quality, failure rate, and downtime.

1.3. Objective

1.3.1. General Objective

The general objective of this research is to assess the power reliability of the Adama wind farm from multiple dimensions.

1.3.2. Specific Objective

- Study Fault characteristics of the farm
- Assessing the availability of the turbines, and
- Estimate the economic performance of the wind farm
- Compare the gearless and geared wind farms

1.4. The significance of the study

The common failure modes, the failure rate, downtime, and their effects on expected power and levelized cost of energy will be discovered as a result of this research.

- It will be the basis for future research.
- Knowing the status of Adam Wind Farm will be helpful.
- A similar study can be conducted on all wind farms in Ethiopia.
- This will help to determine the profitability of future farms.

1.5. Research questions

The following research questions were examined in this study:

- What are the main failure characteristics of wind farms?
- What was the previous economic performance of wind farms?
- How do technologies affect the performance in the same climate zone?

1.6. Thesis outline

This research is composed of five chapters. The introduction, study background, problem statement, study objectives, study significance, etc. are all included in the first chapter. The second chapter reviews the literature, highlighting the key findings and research conducted in that specific field thus far. Data sources, data collection strategies, suitable data analysis approaches, software tools, and methodology and methods are all covered in the third chapter. All analysis methods, from identifying general failure modes to training mathematical models, are also covered in this section. The results and conclusions of the study are examined in the fourth chapter. Lastly, recommendations and conclusions are included in the fifth chapter.

Chapter Two

2. Literature review

2.1. Wind Energy

The source of the renewable energy contained in the earth's wind resource is the sun [8]. However, the process of extracting energy from wind isn't an easy task, and as a result, the middle tool of the wind strength system, the wind turbine, undertakes the critical venture of changing wind into electricity [9].

2.1.1. Types of wind turbine

The complex machine that is behind converting wind energy into electricity is known as wind turbine. The actual conversion process in modern wind turbines uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting first in mechanical power production and then in its transformation to electricity in a generator [8].

There are various criteria for classifying wind turbines: Based on the axis around which they rotate, turbines rotate around a horizontal axis, and Vertical axis turbines. Based on the place they will be used onshore and offshore [10]. It is not a single working machine instead it is an assembly of different components.

The rotor, which is composed of the blades and the supporting hub, is one of the primary subsystems of a typical (land-based) horizontal axis wind turbine. The wind turbine's rotating components, aside from the rotor, includes the drive train, which normally consists of shafts, a gearbox, a coupling, a mechanical brake, and a generator. The yaw system, bedplate, and housing are all part of the main frame and nacelle subsystem. The foundation and tower serve as the primary structural. The primary components of the electrical system are the machine controls and its balance, which includes cables, switchgear, transformers, and potentially electronic power converters[8].

In addition, wind turbines are not differentiated by the above criteria, but technological progress also plays a fundamental role, depending on the drive system, direct transmission, and gearbox. Types of generators are classified as permanent magnet and dual-feed induction generators. The following images illustrate their differences.

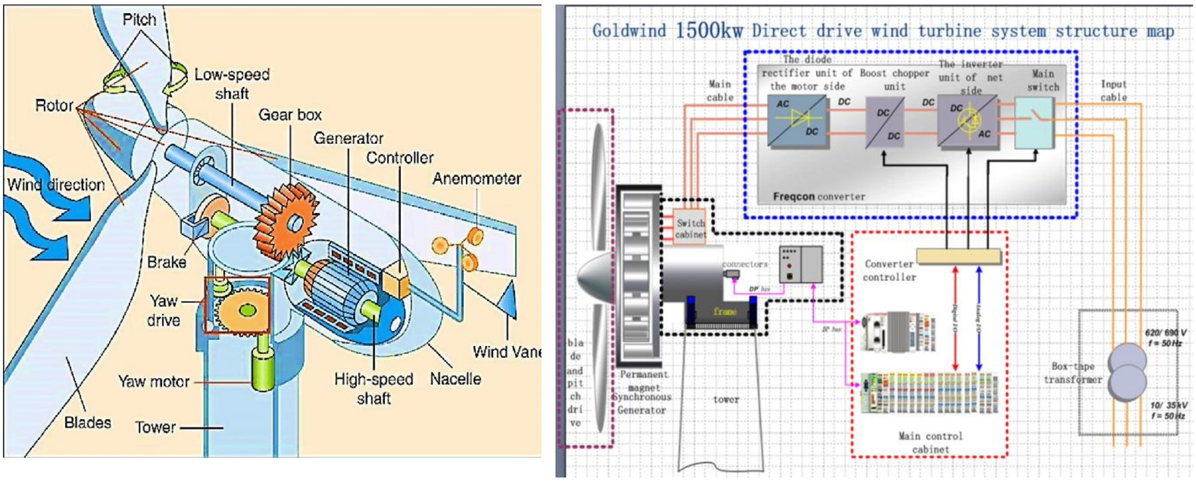


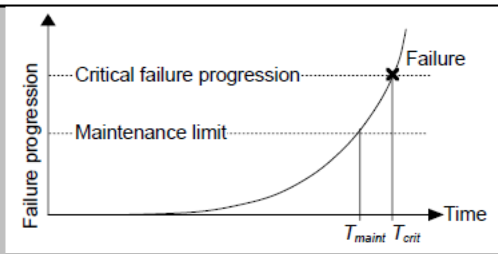
Figure 1: Horizontal axis wind turbine [11]

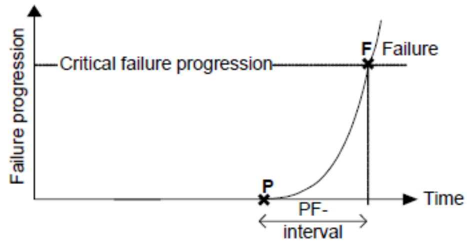
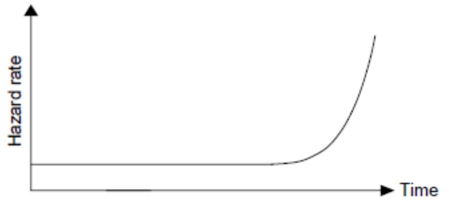
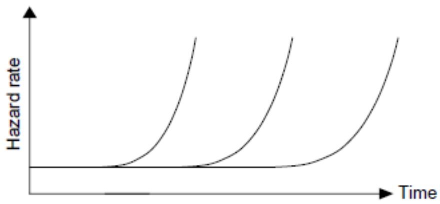
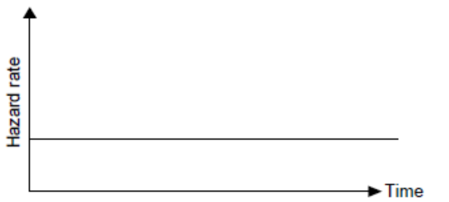
Because of the enormous complexity of wind turbine power production systems, disintegration, and faults in the working subsystems such as electrical, mechanical, control, and structural systems occur regularly.

2.2. Fault characteristics of wind turbine

Fault characterization on wind turbines refers to the identification and analysis of faults or abnormalities in the operation of wind turbines. This is accomplished through a variety of monitoring and analysis techniques, including vibration analysis, current and voltage monitoring, temperature sensing, and blade pitch monitoring[12]. By analysing this data, it is possible to detect and diagnose faults in the turbine's components, such as the gearbox, generator, or rotor blades, before they lead to a catastrophic failure[13][14]. Fault characterization can help improve the reliability and efficiency of wind turbines, and can help reduce maintenance costs by enabling proactive maintenance and repair.

Table 4: Failure characteristics[15]

Code	Description	Fault characteristics
OGF	Observable and gradual failure progression. The error can be identified prior to the occurrence. ..	

OFF	Observable fast failure progression. point P represents the initial moment at which an emerging payment default becomes identifiable. When the deviation surpasses a predefined threshold, an error (F) is triggered, also called PF model.	
ADT	Aging is characterized as a specific point in time at which the hazard rate, denoted as z(t), increases. Within the Weibull model framework, the aging process is typically represented by an aging parameter (α) with values generally ranging between 3 and 4	
AUT	Aging is characterized by a continuous increase in hazard rates over time, rather than occurring at a specific, well-defined moment. Within the context of the Weibull model, it is assumed that the aging parameter (α) takes a value approximately equal to 2.	
RF	The hazard rate of random failures is independent of time. This is typical for parts that fail because of external shocks, such as some electrical parts.	

The inability of a subassembly to fulfil its designated function under specified conditions results in the item being classified as in a failed state, as opposed to an operational or functional state. [16]. A failure occurs when a wind turbine ceases to generate power due to one or more components failing. These failures can be structural such as tower crake, mechanical failure like gearbox failure, and electrical failures such as control and sensor failures. And failure creates a huge loss.

The operational and maintenance expenses of wind turbines (WTs) should be taken into account, typically constituting between 65% and 95% of the initial investment cost of the installation [17]. Unplanned maintenance is a primary cause of malfunctions in various system components, including the yaw system, rotor blades, rotor hub, gearbox, hydraulic system, control, and power electronic systems, as well as the generator and rotor speed/pitch sensors.

Such unscheduled maintenance activities represent approximately 30% to 60% of the total operational and maintenance costs of WTs, leading to prolonged downtimes and consequent reductions in electricity generation. [17].

Although operation and maintenance are costly, replacement and energy loss costs have undeniable effect. Depending on the component and working environment, wind turbines have different failure modes and characterizations. Each component has a unique failure rate, cause, and severity. The most common failure rates are discussed further below.

Table 5: List of typical faults, their occurrence, and severity[18]

Fault	Failure rate [19]	Potential cause	Severity [17]
Generator	4%	Wind loading, intense weather conditions, immoderate vibration, voltage instabilities, mechanical and electrical failure of the bearings	Most sever
Gear box	4%	Axial cracking in bearing, lubricant contamination, gears, filtration machine troubles	Most sever
Mechanical break system	6%	Manufacturing defects, damage to brake callipers, brake discs, and brake pad	Most sever
Yaw system	8%	Twist, wear out, yaw bearing friction and failure	Sever
Rotor blade	7%	Fatigue, corrosion, surface deterioration, exfoliate, rupture, blade misalignment, lightning strikes	Sever
Rotor	5%	Wind loading, weather extremes,	Sever
Drive trine	2%	Failures of the bearing, gear, axial bearing cracking, lubricant contamination, and overloading	Sever

Electrical components	23%	Overloading of the electric system, insulation failure, connection issues, calibration issues, and software issues	Less severe
Control system	18%	Voltage anomalies, electronic malfunction, and software failure	Less severe
Sensors	10%	Fixed, arbitrary, biased, or no Measurements	Less severe
Hydraulic system	9%	Malfunctions, contaminated lubricant, and leakage	Less severe

2.2.1. Failure modes of wind turbine components

A final valuable assessment of the FMEA outcomes involves analysing the occurrence frequency of specific failure modes and their underlying root causes. As illustrated in Figure 2, material failure emerges as the most prominent failure mode, indicating that enhancing material quality in wind turbines (WTs) should be a primary focus for improving reliability [20]. As equivalent to failure modes studying failure root causes is a relevant task. Research indicates that factors such as corrosion, mechanical overload, vibration fatigue, the presence of debris, overheating, maintenance errors, installation defects, connection failures, design flaws, and pipe punctures serve as fundamental root causes of wind turbine failures [21].

2.2.1.1. Blade

The primary purpose of wind turbine blades, which are the wings of the turbine, is to capture wind. They frequently experience alternating stress and complex environments, and they have a high failure rate. Fracture, edge crack, stuck, motor failure, pitch, and bearing failure are the primary failure modes.

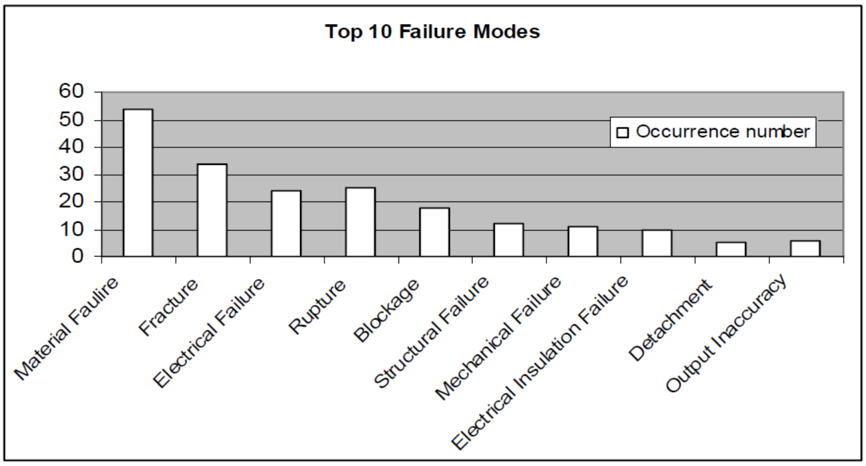


Figure 2: Top 10 failure modes in FMEA[20]

The rotor bearing accelerometer in the hub detects excessive vibration; high stresses are recorded by the wind turbine blade vibration sensor, and operating instrumentation is used to detect it [22]. In the following section, the primary failure modes are covered.

a. Leading Edge Erosion

The main cause of the leading-edge erosion (shown in A

B

Figure 3: A) The leading edge corrosion [18] **and B) Micro cracking** [25]

) of wind turbine blades is the impact of airborne particles like dust, rain, hail, etc. Most of the leading-edge erosion takes place at the blade's tip, but it can also happen inside the blade structure over time [23]. The leading-edge erosion will cause the blade to become rougher, which will increase the resistance to rotation. It will therefore have an impact on economic benefits and lower wind turbine power generation efficiency.

b. Micro-Cracking

Under standard operational conditions, cyclic loading induces fatigue degradation in wind turbine blades, manifesting as micro-cracks within the blade material, as depicted in **Error! Reference source not found.**. The gradual accumulation of these micro-cracks can precipitate blade fracture, potentially impact adjacent wind turbines and result in severe accidents. Furthermore, wind turbine blades functioning in extremely cold environments are susceptible to brittle fractures within the material, as well as icing on the blades and sensors. Under more adverse conditions, the progression of micro-cracking may accelerate significantly, culminating in blade failure and potentially causing the collapse of the entire wind turbine structure[24].

A **B**

Figure 3: A) The leading edge corrosion [18] **and B) Micro cracking** [25]

2.1.1.1.Converter and controller system

The controller deactivates the turbine at elevated wind speeds to prevent damage to various turbine components. The primary causes of controller system failures include voltage fluctuations, electronic malfunctions, and software errors [19]. There are two types of controllers in the wind turbine system, pitch, and torque.

To discuss the first one, the frequency of faults occurring within the electrical system of a pitch-controlled wind turbine is notably significant. These faults contribute substantially to the longest machine downtime observed in both component-specific and single-failure scenarios. Furthermore, the inherent complexity and ambiguity of the pitch-controlled system pose considerable challenges to accurately modelling the relationships between underlying mechanisms and resultant faults using mathematical approaches[11]. A torque controller is designed to follow a trajectory that permits the wind turbine to run at maximum power extraction in the below-rated regime. This controller is based on the achievement of zero speed-tracking error. The controller does not know the turbine torque, so estimation is used to account for its impact[26].

2.1.1.2. Generator

The generator constitutes a critical component responsible for converting mechanical energy into electrical energy. It exhibits a relatively high failure rate due to its connection to the high-speed shaft of the wind turbine gearbox, which is subjected to time-varying mechanical torques. In direct-drive wind turbines, the generator is directly coupled to the rotor, further influencing its operational reliability[4].

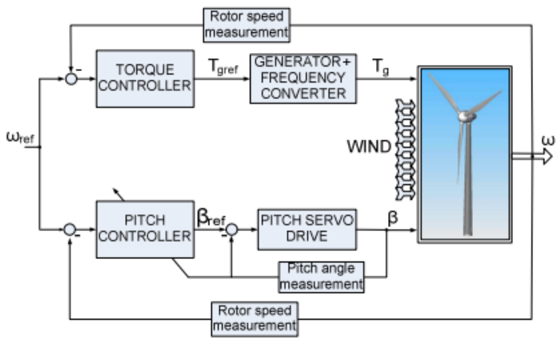


Figure 4: Classical wind turbine control system[27]

Zhange et al. [28]diagnosed wind turbine generators and motors using the Gaussian process Metamodel and the researcher concluded motors and generators failed because of windings, and overheating.

2.1.1.3. Gearbox

The wind turbine gearbox transmits torque with speed increase which is a bridge between the rotor and generator. The failure modes of the gearbox are internal gear tooth failure and detected by the vibration sensor. Early detection of developing gearbox damage can be achieved by comparing the energy produced with vibration and oil debris particle count[29]. Gearboxes represent one of the most costly components within wind turbine systems; consequently, failure rates exceeding initial projections have contributed to increased costs associated with wind energy [30]. Furthermore, the uncertainty surrounding the future lifespan of gearboxes is a significant factor driving the escalation of wind turbine prices.

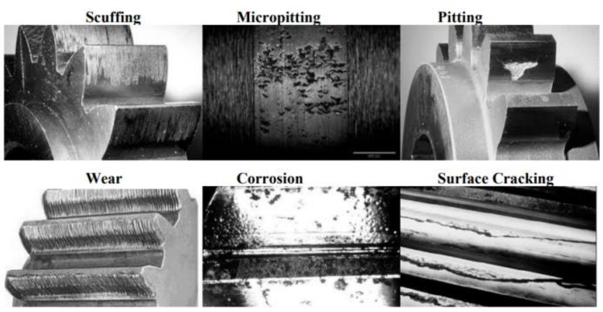


Figure 5: Modes of gear failures[31]

According to the reliability study reported by Rohrig et al. [19], electrical components and control system malfunctions accounted for approximately fifty percent of wind turbine (WT) failures. In contrast, failures related to generators and gearboxes occurred less frequently but were associated with extended periods of downtime. Mechanical brake systems play a vital role in ensuring the structural integrity and operational safety of WTs, as they fulfil two essential functions: stabilizing the nacelle during rotation and securing its orientation relative to the wind. Damage to mechanical brake systems poses significant challenges, as the subsequent repair and replacement of components are both complex and costly.

Table 6: Summary of modes of failure of wind turbine[32]

Objects	Function	Failure mode	Detection method
Blade	Capture wind	Fracture, edge crack, stuck, motor failure, pitch bearing failure	Excessive vibration sensed by the rotor bearing accelerometer in the hub; high stresses recorded by operating instrumentation
Main shaft	Transmit large torque	Fracture	Low-speed sensor; bearing vibration sensor
Yaw system	Enable the nacelle to rotate on the tower	Increased bearing Friction	Yaw error signal sensor
High-speed shaft	Stop and hold the shaft during shutdown and Operation	Low or higher brake torque	Tachometer
Gear box	Transmit torque with speed increase	Internal gear tooth Failure	Vibration sensor
Hub assembly	Transmit torque from blades	Structure failure; bolt failure	Rotor bearing accelerometer; periodic inspection for loose or missing bolts
Oil seals	Retain oil in main bearing housing; exclude foreign Matter	Cut or wear in lip	Low oil switch

Filters	To extract and hold all particulate contaminants from hydraulic fluid	Case leakage	Low oil; level switch
Generators	Generate electric power	Overheat; fault; jammed bearing; bearing seizure; over speed;	Protective relays; Overspeed detection; testing
lubrication	Lubricate gearbox and rotor bearing	Loss of oil; overheating; oil under temperature	Oil flow switch; oil temperature sensor; air temperature

2.2. Reliability of wind farm

Reliability is the likelihood that a product or system will perform its intended functions satisfactorily (i.e., without failure and within specified performance limits) for a specified period under specified environmental and usage conditions [33]. In addition, the reliability of a complex machine, such as a wind turbine, is affected by the reliability of its subsystems, which include both hardware and software and the connection of these components [34].

The reliability of wind turbines presents a multifaceted challenge due to the potential failure of numerous components under diverse operational conditions, extended service life requirements, and narrow economic margins. Nevertheless, enhancing the reliability of both individual turbines and entire wind power plants characterized by sustained performance over time is essential for advancing the competitiveness and success of the wind energy sector.

2.2.1. Reliability measures and indices

These metrics can be used to evaluate various designs or innovations of components and to identify the most suitable option [35].

In evaluating the reliability of a wind turbine, its primary components are conventionally classified into three categories: structural, electrical, and mechanical. This classification is justified by the distinct reliability assessment characteristics, methodologies, and models applicable to each category. For structural components, including blades, towers, and foundations, the probability of failure serves as a key metric and is typically analysed using structural reliability theory. In contrast, the lifespan of electrical and mechanical components is generally modelled according to the classical bathtub curve. [9].

1. Failure rate λ,

The Failure rate λ is a reliability index that represents the rate at which the product fails; this is the ratio of number of failures to operating time.

$$\lambda = \frac{n_f}{t} \quad \text{Eq. 1}$$

Where, $\lambda = Failure\ rate,$ $n_f = Number\ of\ failure$ $t = Oprating\ time(cycles)\ in\ hour$

2. Repair rate μ,

The repair rate μ is a reliability index that represents the rate at which the product is repaired; this is the ratio of the number of repairs to operating time.

$$\mu = \frac{n_r}{t} \quad \text{Eq. 2}$$

Where, $\mu = Repair\ rate, n_r = Number\ of\ repair, t = Oprating\ time(cycles)\ in\ hour$

3. Mean Time Between Failure (MTBF), Ɵ

The MTBF is a reliability index for repairable units, and the inverse of the failure rate λ, which is only implemented if the intensity of the failure remains constant over time. This is the ratio of operating time to number of failures.

$$\Theta = \frac{t}{n_f} = {}^{1}/_{\lambda} \quad \text{Eq. 3}$$

Where, Ɵ =MTBF, $t = Operaing\ time$ $n_f = Number\ of\ failures$

4. Mean Time To Failure (MTTF), Ɵ

The MTTF is a reliability index for non-repairable a unit; which is the ratio of operating time to the number of failures.

$$\Theta = \frac{t}{n_f} = {}^{1}/_{\lambda} \quad \text{Eq. 4}$$

Where, Ɵ =MTTF, $t = Operaing\ time$ $n_f = Number\ of\ failures$

5. Mean time to repair, or downtime (MTTR)

The average time it will take for a subassembly to recover from any failure (MTTR).

$$MTTR(\Theta) = \frac{Operating\ time\ (cycle)}{Number\ of\ repair} = {}^{1}/_{\mu} \quad \text{Eq. 5}$$

Where, Ɵ =MTTR, $t = Operaing\ time$ $n_r = Number\ of\ repair$

6. Availability p

Availability is the probability of finding a system in an operational state in the future [36].

$$p = \frac{T_m - T_n}{T_m} = 1 - (\lambda/\mu) \qquad \text{Eq. 6}$$

p The average annual availability of wind turbines in a wind farm, T_m = the number of hours at a given time, T_n the number of shutdown hours due to failure or maintenance[9]

Ramu et al. [5] investigated the performance analysis of wind farm power quality based on the evaluation of power and energy production performance indices from the production analysis aspect and harmonic emission analysis; it is within the allowable limit set by international standards and the farm is in a good state.

2.2.2. Reliability Models

Reliability models are time-dependent functions that depict the evolution of the equipment failure risk. Thus, reliability models are lifetime distributions expressed in various ways, all of which define the distribution of a continuous random variable lifetime t [33].

As a working principle, to predict system performance, the modeling process divides the system into discrete components and organizes them in a way that simulates their physical functions. It then uses empirical data to derive statistical distributions for estimating failure rates [7]. Researchers have used different reliability models.

Hence, reliability models can be classified as qualitative and quantitative models. Qualitative methods include Pareto, fault tree analysis (FTA), and reliability block diagram (RBD). Quantitative reliability includes Markova analysis, power law processes, and binary body diagrams [37].

2.2.2.1.Reliability block diagram (RBD)

The configuration of a reliability block diagram delineates the logical relationships among failures within a system, as opposed to illustrating their logical or physical interconnections. Such a diagram may depict the entire system or any subset or combination thereof that necessitates analysis concerning failure, reliability, or availability. It also serves as an analysis tool, demonstrating how each component of a system works, and how each component can affect the overall operation of the system [35].

The modeling technique is intended to be applied primarily to systems without repair, and where the order in which failures occur does not matter. The software used for RBD is a commercially available package called Raptor, and other software is available[7].

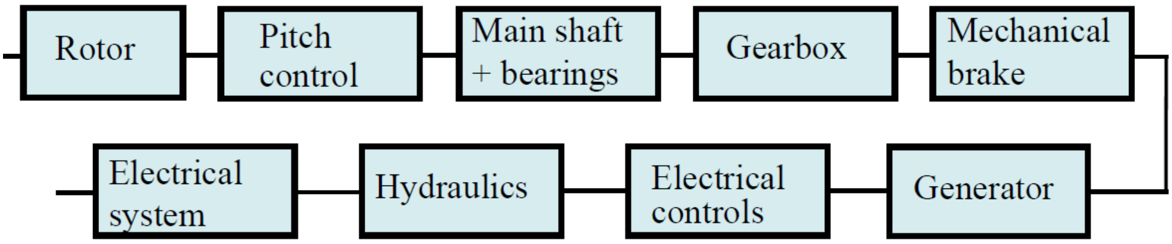


Figure 6: Specified reliability diagram of wind turbine[35]

- Reliability

$$R = e^{-\lambda t} \quad \text{Eq. 7}$$

$$R_{series} = R_1 \times R_2 \times \dots \dots R_N \quad \text{Eq. 8}$$

$$R_{Parallel} = 1 - (1 - R_1)(1 - R_2) \quad \text{Eq. 9}$$

Hill et al.[7] Conducted research on wind turbine reliability using the raptor model, raptor is intended for scenario modeling, allowing the user to simulate various operating scenarios and determine their impact on the overall performance of the individual turbine and the wind farm as a whole. Based on the baseline data, "weak link" analyses for the system can be performed to determine the components that contribute the most to cost, downtime, and availability. The generator and gearbox are the turbine's unacceptable or weak links.

2.2.2.2.Fault Tree Analysis

Fault trees (FTs) represent graphical techniques utilized to model the propagation of failures within a system, specifically illustrating the manner in which component-level failures culminate in system-level failures [38]. Furthermore, this approach constitutes a top-down, deductive analytical method employed to assess the impact of initiating faults and events on complex systems. Additionally, fault tree analysis (FTA) is highly effective in evaluating a system's resilience to single or multiple initiating faults[39].

Digitalis et al. [40] established a fault tree model to study the reliability analysis of crucial subsystems of wind turbines and found that the electrical and control systems, as well as the hydraulic system, need to be redesigned with improved performance and reliability because they are critical for the operation of each WT individually as well as the entire wind farm. Kang et al. [41] developed a fault tree model for wind turbines to discuss the order dependencies and redundancy of fault events leakage and overpressure are the most common causes of pitch and hydraulic systems failure. Marquez et al. [42] used fault tree analysis (FTA) to identify and monitor the wind turbine's key components and completed the qualitative evaluation of the wind turbine's state, but the authors ultimately chose Binary Decision Diagram (BDD) for quantitative analysis due to its low computational cost.

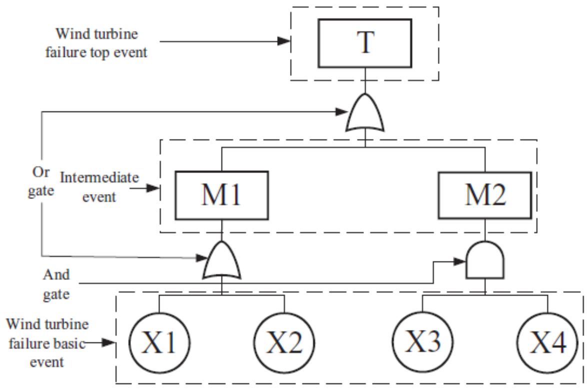


Figure 7: Fault tree model [9]

2.2.2.3.Bathtub Curve

The bathtub curve is a reliability tool used to model the reliability of a machine or unit system throughout the machine's lifetime.

Homogeneous Poisson Process (HPP). An HPP is a Poisson process in which the rate of event occurrence is the same concerning time t [43].

Non-Homogeneous Poisson Process (NHPP) or Power Law Process (PLP). A NHPP/PLP is a Poisson process, with a non-constant recurrence rate concerning time t [44].

Kaidis et al. [45] validated the applicability of the bathtub curve by analysing comprehensive operational data spanning the entire life cycle of wind turbines. Their failure data analysis identified the pitch subsystems, frequency converters, and control communication systems as the components exhibiting the highest failure rates within wind turbine faults. In a study aimed at enhancing wind turbine reliability Fekih et al. [46] employed a model-based fault monitoring and fault-tolerant control framework, highlighting its advantages, capabilities, and inherent limitations. These model-based approaches utilize mathematical representations alongside input/output data derived from wind turbine operations. Furthermore, Kang et al.[41], investigated the performance of three groups of wind turbines in Germany, all of identical turbine types but situated in distinct climatic wind fields. Their findings demonstrated that variations in geographical location and climatic conditions significantly influence wind turbine failure rates.

Faulstich et al. [36] developed a Homogeneous Poisson Process (HPP) model based on failure statistics collected from wind turbines between 1994 and 2004. Their analysis focused on failure data from Germany and Denmark, countries with substantial wind energy capacities. The authors assumed that failures occur randomly over time, leading to an HPP model characterized by parameters $\beta = 1$ and $\lambda = 1/\eta$ (i.e., a constant failure rate $\lambda = t$). This assumption was justified by the relatively young age of the turbines studied, indicating that the deterioration phase had not yet commenced.

Another study by Taver et al.[47]quantify how wind speeds affect turbine reliability and which components are most affected, again using Wind stats data. Byon et al. [37] investigated the grouped failure statistics data for turbines in Germany, published in LWK. Unlike Wind stats data, Geiss et al. [48] provided wind turbine models along with their data.

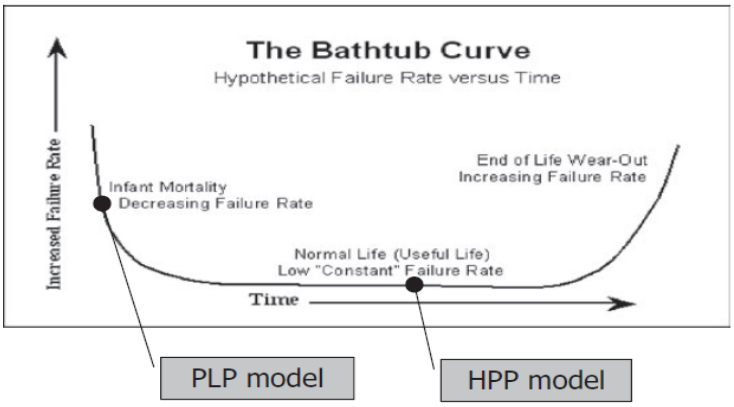


Figure 8: Bathtub curve: The intensity function [36]

Byon et al. [37] try to construct an NHPP version of a wind turbine Model V39/500. Unfortunately, the chi-squared test rejects the speculation that the NHPP version suits the statistics for the complete wind turbine gadget and gearbox. Byon et al. [37] declare that the rejection is because of a loss of real turbine operation time, which causes the possibility calculation to be inconsistent with the data.

2.2.2.4.Markovian analysis

A Markov chain is a universal model for stochastic process description, assuming that the future is independent of the past given the present. There are discrete and continuous time Markov chains. The major drawback is the state space explosion.

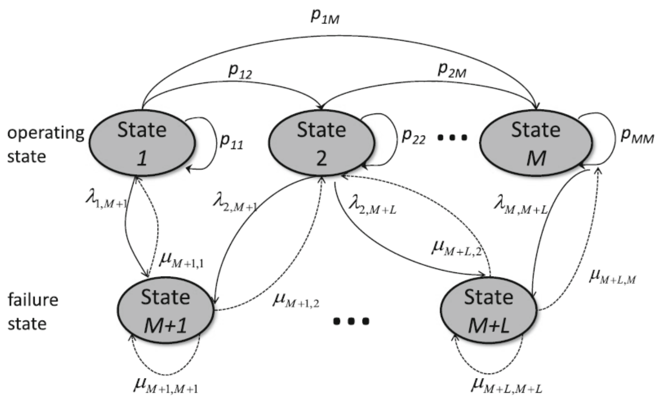


Figure 9: State transition diagram for Markovian deterioration system[49]

1; . . .; M deterioration levels, there are L different types of failures, μ repair rate, and λ failure rate. M is the new state at M+L the system we worn out. The sum of the outgoing state must be 1 because it is probability.

Database-based statistical methods and load-based stress-strength interference theory are the two types of reliability analysis methods that were the main focus of the researcher [7], In general, industry estimates show that failure rates of wind turbines decrease with time. Kahrobaee and Asgarpoor [50] conducted research on the time-based reliability of wind farms using a Markovian method, Which can be used to optimize the number of repair crews and maintenance strategy by incorporating the maintenance model. Wiley et al. [51] studied power reliability using the Markovian method; the data used was not failure but instead the fluctuating wind speed. The Markovian method does not use past data; only the current and nearly past data are used.

2.2.2.5. Power law process

The Power Law Process (PLP) version has acquired a whole lot of interest within the repairable structure's literature because of the simplicity of its mathematical computations and the appealing physical explanation of its parameters. It belongs to the class of non-homogeneous Poisson process (NHPP) models [52].

Boaler et al. [52] investigated the performance of the PLP model and assessed various repairable data sets utilizing the maximum likelihood estimation (MLE) method, which can be derived from the application of the probability characteristic. Additionally, they employed a regression estimation approach primarily based on the mean time between failures (μTBF) characteristic of cumulative failure time data. Based on the selected error measurement criteria, the regression estimation method demonstrated significantly improved predictive accuracy and provided a reliable estimation of the μTBF. Baker et al. [53] used PLP for the analysis of failure data from one or more repairable systems.

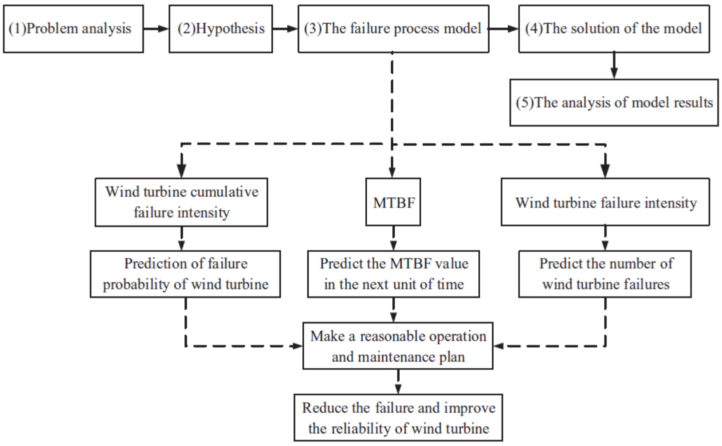


Figure 10: Power low process flow chart [9]

2.2.3. Power reliability

Power reliability refers to the extent to which the functioning of components within a bulk power system ensures the delivery of electricity to the substation in accordance with established standards and in the required quantity. [54]. However, in the generation operation concept, the reliability of the farm is evaluated by the availability of the systems.

Several factors can affect the reliability of the power supply. These include Electrical harmonics, design, temperature, load capacity, voltage fluctuations, environmental factors, and maintenance. To maintain high levels of power reliability, it is important to address these factors and maintain a robust and resilient power supply system.

T. Winter conducted an investigation into reliability assessments within power systems[55]. The foundational theory presented in the report offers a comprehensive understanding of the methodologies employed in performing reliability calculations during power system reliability studies. Additionally, the report utilizes the NEPLAN software as a computational tool to facilitate these calculations.

2.2.3.1. Power system reliability evaluation

The power system reliability typically involves assessing the ability of a wind turbine to generate power reliably and consistently over time. This can be done through a variety of methods, such as failure mode and effect analysis, fault tree analysis, Monte Carlo simulation, and different methods can evaluate the system in general.

2.2.4. Levelized cost of energy

The economic feasibility of wind energy projects is contingent upon their capacity to produce electricity at a minimal operating cost per unit of energy. Therefore, precise estimation of all costs associated with electricity generation throughout the system's lifespan is crucial. Various methodologies are employed to assess the operating cost per unit of energy generated by a wind energy conversion system, among which the Levelized Cost of Electricity (LCOE) is one of the most widely utilized. The LCOE for a wind energy conversion system is defined as the ratio of the total annualized cost of the wind power conversion apparatus to the annual energy output produced by the system [56].

[57] Studied the levelized cost of energy for both renewable and non-renewable energy. In addition, the proposed new optimization model includes the idea of generating and avoiding carbon taxes. On the other hand, the LCOE calculation tool developed in the [58] The study encompasses all capital, operational, and decommissioning expenditures (CAPEX, OPEX, and DECEX) incurred throughout the project's lifespan. Furthermore, these expenditures were utilized in conducting sensitivity analyses. The results of the sensitivity analyses across all substructure types demonstrate that even minor variations in parameters can be critical and substantially influence the overall levelized cost of energy (LCOE).

Steps to analyse LCOE (Re-Vision)

The subsequent procedures and corresponding formulations are used to determine the commercial LCOE.

Step 1: Determine Annual Revenue Requirements

Step 2: Levelizing Annual Revenue Requirements

Step 3: Calculating the Fixed Charge Rate

The Fixed Charge Rate (FCR) is the percentage of the total plant cost that is required over the project life per year to cover the minimal annual revenue requirements.

The FCR is calculated in three steps:

1. Calculate the Capital Recovery Factor (CRF) as follows:

$$CRF = \frac{Discount\ rate}{(1+Discount\ rate)^{Book\ life}-1} + Discount\ rate \quad \text{Eq.10}$$

This formula indicates that the CRF is a direct function of the Discount Rate (yearly cost of money) and the Book Life (project duration in several years).

2. Calculate the levelized annual charges by multiplying the CRF by the NPV.

3. Calculate the Levelized annual FCR by dividing the levelized annual charges by the Total Plant Investment (TPI) or Book Cost.

Step 4: Calculating the Cost of Electricity

LCOE is also investigated. The levelized cost of energy is generally evaluated as

$$LCOE = \frac{CAPEX \times FCR + OPEX}{AEP} \quad \text{Eq.11}$$

Where $CAPEX$ is the capital expenditure; FCR is the fixed charge rate; $OPEX$ is the operating expense and AEP is the annual energy production.

OPEX is evaluated using Equation (4) with the sum of the repair costC_{repair}, the labor cost C_{labor} and the other cost of repair C_{other} including land fees and insurance costs. AEP is evaluated as the product of power curve P (f), wind speed frequency distribution f (U), and availability as shown in Equation (5). The total downtime can be divided into downtime $T_{downtime}$ and the scheduled downtime $T_{scheduled}$ due to the scheduled maintenance as shown in Equation (6).

$$OPEX = C_{repair} + C_{labor} + C_{other} \quad \text{Eq.12}$$

$$AEP = \sum P(u) \times f(u) + Availability \quad \text{Eq.13}$$

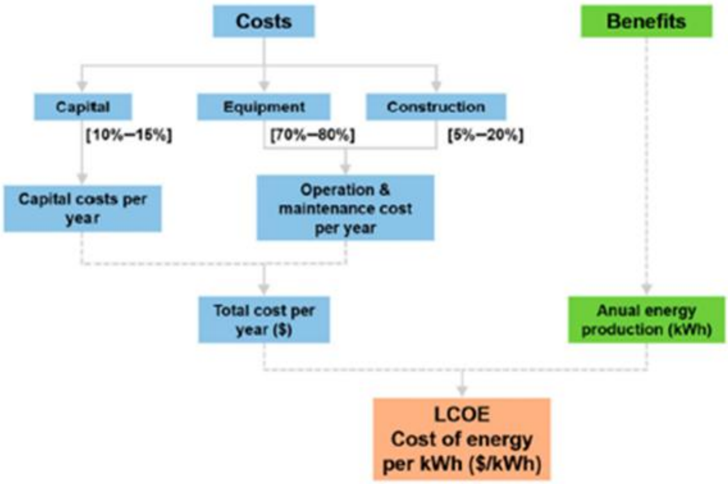


Figure 11: LCOE Cost of energy [59]

The research conducted by[57] indicates the levelized cost of energy (LCOE) is observed to decline substantially over time when optimal site selection and favourable market conditions are present. Findings from this study indicate that escalations in specific expenses, including those related to wind turbines, grid connection, and taxation, contribute to an increase in the average production costs represented by the LCOE. Furthermore, the results imply the existence of technology-specific factors that may impact advancements within the market.

[60]The sensitivity of LCOE to the Hassle variable modifications whilst exclusive variability of stochastic parameters are considered; for instance, while wider ranges (better scatter dataset) in turbine cost, O&M, and assist shape fees are considered, they seem to have a better effect on LCOE than within the case of the bottom scatter dataset; additionally, some parameters consisting of installation, contingency, and challenge consenting and improvement charges, which might be discovered to have a considerable effect within the maximum scatter dataset case, they are no longer impactful at the LCOE for the bottom scatter dataset. The cumulative probability function of downtime and repair cost for each mode of failure was analyzed, showing that the uncertainty of LCOE could be reduced by about 30% [59].

Chapter Three

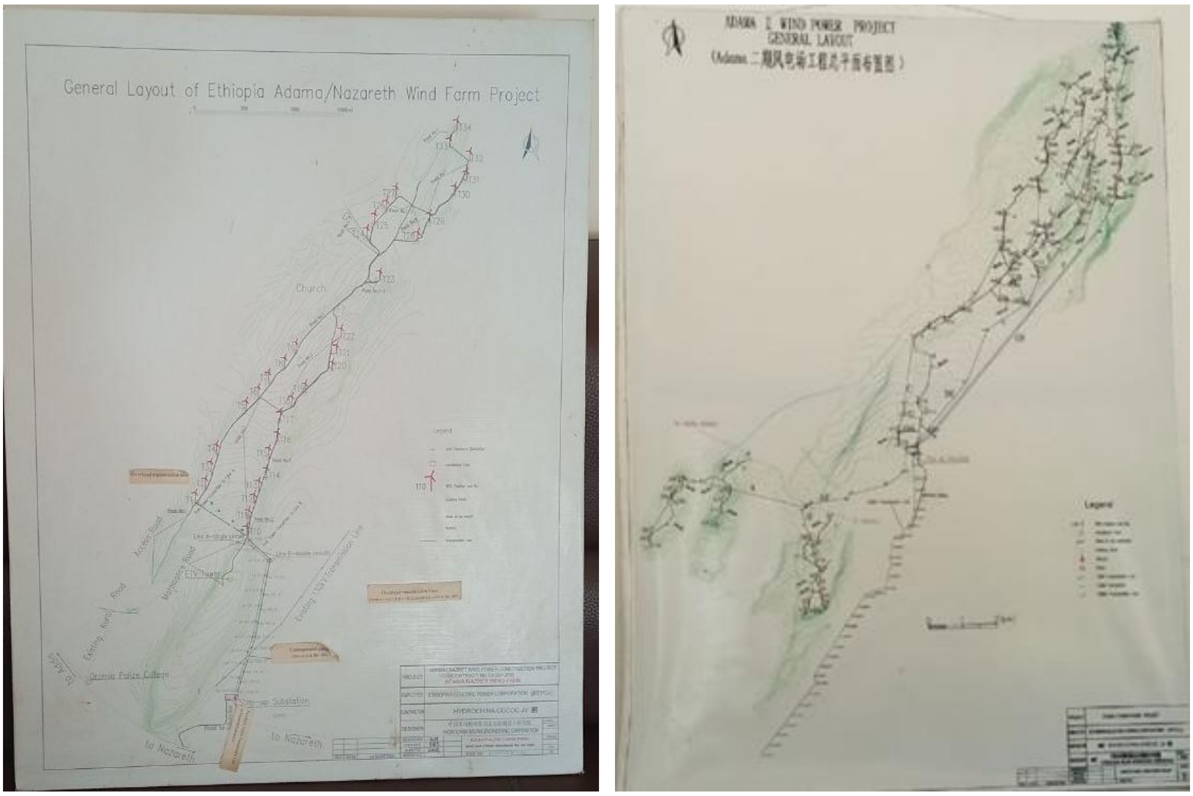
3. Methodology

This section describes the methodology applied to the multidimensional power reliability assessment of the Adama Wind Farm. Both Adama I and II wind farms are located in Adama, thus their only difference is technology, and this research addresses the downtime and failure rate from the history of the farm. The technology variable is tested; in addition, the study assumes a Nonhomogeneous Poisson distribution. Achieving an accurate and comprehensive analysis of power reliability requires a robust research methodology that combines both quantitative and qualitative approaches as therefore both approaches are applied in this research.

3.1. Study area description

The Adama Wind Farm is situated centrally in Ethiopia, approximately 95 kilometers from Addis Ababa and 3 kilometers from Nazareth. The facility has an installed capacity of 51 MW, comprising 34 units of GW77/1.5 MW turbines. It generates an annual electricity output of 157.4 GWh, which is supplied to the national grid via a 132 kV step-up substation and an extension bay at the Nazret II substation. The connection is facilitated by a 4.7-kilometer 132 kV transmission line and a 20-kilometer 33 kV distribution line.

Adama II Wind Farm is an onshore wind power project with a capacity of 153 MW, located in the Oromia region of Ethiopia. This project produces approximately 479 GWh of electrical energy annually.



A B

Figure 12 Adama I wind farm (a) and Adama II wind farm (b) layout

3.2. Data source and Mode of collection

Wind turbine equipment records and failure reports can differ widely in terms of detail, format, and data integrity. Fortunately, for wind turbine reliability engineers, there are frequently multiple data sources available to investigate and characterize equipment records for life data analysis, such as supervisory control and data acquisition (SCADA), inspection reports, maintenance work orders, and wind stats newsletters. One difficulty with life data analysis is that collecting and validating data may require more than 80% effort. Another issue is the inconsistent definition of failure events, which can vary throughout a wind turbine's life cycle or for different purposes, even within an organization [61][62].

3.2.1. Data collection and processing

The failure data, which is both qualitative and quantitative data, from 2015 to 2021 is collected from the SCADA system of the Adama I wind farm and from 2014 to 2022 from the SCADA system of the Adama II wind farm via direct connection. From Adama I Wind Farm, all 34 turbines' data were gathered, but from Adama II Wind Farm, by using the random data sampling method because all data had the same number of selection chances, only 16 wind turbines were included from 102 wind turbines. The collected data include the turbine number, trigger time, end time, and failure description. Furthermore, only primary source data were used. The data were cleaned of duplicate and irrelevant information through simple observation. However, the Adama II data are gathered in XML format, therefor in the process of converting it to an Excel worksheet, many cells are filled with 0 values. Nevertheless, the missing data were filled in using the glossary provided by the manufacturer. In addition, From the Adama I data, there was a problem with data quality due to time synchronization during data saving, and the data were rejected. Microsoft Excel 2010, TopEvent FTA 2017, and Homer software's were used throughout the study.

In summary, the processing of the wind turbine failure data recorded in SCADA was examined for indices, omitted values, and black values. The collected data were processed using quality measurements of completeness, accuracy, source reputation, relevance, amount of data, usability, and conciseness.

A B

Figure 13 Adama wind farm wind turbines (a) and substation (b)

A B

Figure 14 Adama I (a) and Adama II control room (b)

A

B

Figure 15 Adama wind farm inside and maintained IGBT

Leading-edge erosion Adama wind farm I

Burnt communication cable Adama wind Farm I

Gear tooth pitting Adama wind Farm II

Figure 16 Common wind turbine failures at Adama wind Farm I and II

3.3. Fault characteristics of the wind farm

For power reliability analysis starting from the objective, both qualitative and quantitative data are gathered; therefor the methods must be the failure characterization and lifetime prediction methods. Failure characterization is mostly a qualitative approach; therefore, fault tree analysis, failure mode, and effect analysis reliability models are suitable.

Failure rates, lifetime distribution, downtime, and other necessary parameters were analyzed based on their benefit.

3.3.1. Qualitative assessments

3.3.1.1. Functional failure analysis

At this stage of the analysis, the potential failure modes of the system were identified and described. It includes the system's required function, describing the input data and conditions for the system to operate properly, in addition to how the system may malfunction.

3.3.1.2. Critical component selection

It is pointed out as a critical component that has an undeniable impact on wind turbine performance. The identification process is conducted through the application of fault tree analysis (FTA) and failure mode and effects analysis (FMEA). Additionally, it is crucial to recognize components characterized by elevated failure rates and extended downtime durations.

3.3.1.3. Failure Mode, Effect, and Criticality Analysis (FMECA)

The aim of this phase is to determine the primary failure modes that organize the FMECA, based on predefined failure causes, failure types, and associated characteristics.

3.3.1.4. Fault tree analysis (FTA)

It is used to describe the logical relationship between failures and the deduction reasoning method for identifying the subsystem from below-ground input data information.

3.3.1.5. Screening failure modes

Based on the criticality assignment in the FMECA, each failure mode of each maintenance significant item is grouped into three levels of severity:

- Less sever
- Severe
- More sever

3.3.2. Qualitative assessment

This part of the research covers the statistical analysis and qualitative assessment of the farm, as well as selecting the suitable model for the qualitative analysis by considering the available data.

3.3.2.1. Assessing the availability of wind farms considering failure and downtime

In this section the availability of wind farms is analyzed, it includes an assessment of the failure rate downtime, failure SCADA data common types of fault on assembly, and failure mode level, eventually availability data is also assessed.

1. Failure Rate and Downtime Analysis

To calculate failure rate and downtime the failure data of the SCADA system is vital, in addition, the common types of faults at the assembly and failure mode level of the Adama wind farm are analyzed.

1.1.Failure database of Adama I wind farm

The available data includes the turbine number, fault description, and fault duration time.

Table 7: Description of characteristics in the database

	Adama I and II data base
Collection period	2015-2021
Years of operation	<20 years
Number of turbines	34/16
Rotational speed	Variable
Control	Pitch
Drive train	Direct/Gearbox
Collection method	SCADA and O&M reports

1.2. Failure rate analysis

The failure rate was calculated as the total number of failures per wind turbine assembly divided by the total number of wind turbine years, for the whole set of 34 wind turbines. For that, the failure rate per assembly f_i was calculated as:

$$f_i = \frac{\sum_{t=1}^{T} n_{i,t}}{\sum_{t=1}^{T} N_t(\frac{T_t}{8760})}$$ Eq.14

Where $n_{i,t}$ is the number of failures per assembly in a period T, N_t is the total number of wind turbines, and T_t the total number of hours in the period T.

1.3.Down time analysis

Similarly, the downtime per assembly was calculated as the total downtime of an assembly i in a period, divided by the number of failures of that assembly in that period, as:

$$d_i = \frac{\sum_{t=1}^{T} d_{i,t}}{\sum_{t=1}^{T} n_{i,t}}$$ Eq.15

3.4. Availability of the wind farm

$$p = \frac{T_m - T_n}{T_m} = 1 - (\lambda/\mu)$$ Eq.16

p The average annual availability of wind turbines in a wind farm, T_m = the number of hours at a given time, T_n = the number of shutdown hours due to failure or maintenance[9].

3.5. Estimate the economic performance of the wind farm

The economic performance of the farm is investigated by the Homer software. Using cutting-edge algorithms, Homer streamlines decision-making for energy projects, such as cogeneration, energy efficiency, and renewable energy.

3.6. Homer and TopEvent FTA

Homer and TopEvent FTA are used for data analysis. Homer is used for analyzing the levelized cost of energy and TopEvent FTA is used for identifying the common faults of the components and the logical integration between the faults.

3.6.1. TopEvent FTA

TopEvent FTA is an interactive software tool designed for both qualitative and quantitative fault tree analysis. It facilitates the construction of fault trees using logic gates such as AND, OR, and NOT, to model the relationships between system failures and their causes. The general steps that used for this research are discussed below.

Step1: Define the Top Event: Identify the undesired event, such as a power outage or system failure, that aims to analyse was the first step taken.

Step 2: Basic Events identified: Determining the fundamental failures or conditions that could lead to the top event was the most time consuming stage.

Step 3: Construct the Fault Tree: Utilized logic gates to connect basic events, forming a hierarchical structure that illustrated the pathways leading to the top event.

Step 4: Qualitative Analysis: Evaluating the fault tree to identify minimal cut sets, which are combinations of basic events that can cause the top event.

Step 5: Quantitative Analysis: Calculate probabilities and importance measures, such as unavailability, reliability, and risk achievement worth, to assessing the likelihood and impact of failures.

TopEvent FTA supports both the Classical Minimal Cut Sets Method and the Binary Decision Diagram Method for fault tree evaluation.

3.6.2. Homer

HOMER (Hybrid Optimization of Multiple Energy Resources) is a simulation and optimization software designed to model and analyse hybrid power systems, including wind, solar, and storage components. It assists in determining the most cost-effective configurations by evaluating various system designs based on technical and economic criteria. The general step that used for this research is explained below.

Step 1: Define System Components: Inputting the technical and economic parameters for the wind turbines, including capacity, efficiency, capital costs, and operational costs.

Step 2: Input Load and Resource Data: Provide hourly electrical load profiles and wind resource data for the Adama Wind Farm site.

Step 3: Set Financial Parameters: Specifying the project lifetime, discount rate, and any other financial assumptions.

Step 4: Run Optimization and Analyse Results: Allow HOMER to simulate various system configurations and identify the optimal design that minimizes the LCOE, at the end assess its economic viability.

Chapter Four

4. Result and Discussion

This chapter discusses the results of all analyses performed in this thesis and interprets the results obtained from the analysis. This research aimed to assess the reliability of power generation in wind farms from different perspectives and to identify the factors influencing their overall performance. The analysis included various aspects, such as the availability of wind farms, wind turbine performance, downtime, failure rate, and levelized cost of energy. In addition, TopEvent and homer software are used.

4.1. Result of the number of failures and downtime for the direct drive system

To calculate the number of failures, and downtime's operational fault data collected from the wind farm SCADA system were analyzed. Various parameters, such as the number of turbines, fault duration, and fault description, were considered to understand the number, type, and duration of failure. This analysis enabled the identification of components with failure and long downtimes, in addition to the compression between different wind farms with the same climate but different driving systems. Key performance indicators (KPA) availability, number of failures, and downtime, were calculated to measure the reliability of each component.

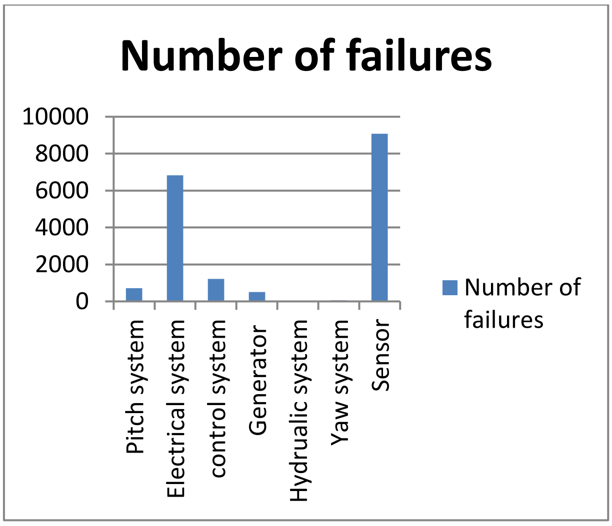


Figure 17: Number of failures for gearless wind farm

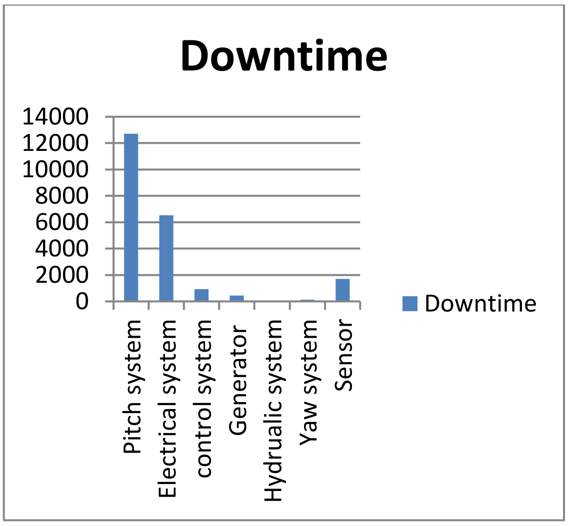


Figure 18: Downtime per subsystem for direct-drive wind farm 7 years data

4.2. Result for number of failures and downtime for geared system

Figure 19: Number of failures per sub-system for direct drive wind farm 6 years' data

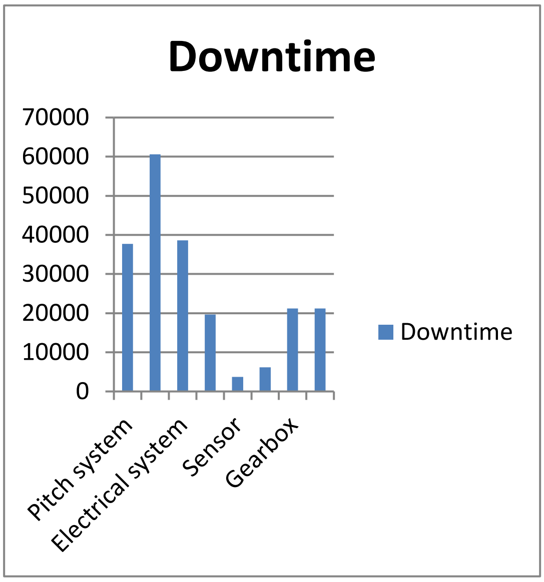


Figure 20: Downtime per subsystem for geared wind farm 6 years data

The research conducted by M.D Reder et al [18] on geared onshore wind farms indicated that the component with the longest downtime is the yaw system which is 110.8h almost 40% of the total downtime and the sensor has 30150 number of failures 25% of the total number failure. However for direct drive wind farms, the pitch system have the longest downtime 32% of the total, and the electrical system has the most number of failures 41%.

4.3. Result of common failure cause, modes, and failure effects

This study explored the common failure causes, failure modes, and their corresponding failure effects in wind turbines. The common causes of failure are environmental factors, mechanical and electrical components, and human-related factors. When it comes to failure modes mechanical, electrical, and structural failures have generally been observed. These problems have had several effects, including energy production losses, safety risks, and economic implications.

Table 8: Common failure cause, modes, and failure effects

Sub system	Components	Failure mode	Failure cause	Failure effect

Blades	Blade bolts, blade shell, and brakes	Crack, deformation,	lightning, dust, corrosion, vibration	Noise, turbine stoppage
Hub	Hub body, pitch mechanism, pitch bearings, pitch reducer, Spinner	Crack, wear, condensation,	Overwind speed, crack, loosen bolt	Turbine stoppage, vibration, feathering
Yaw system	Yaw drive, yaw motor, yaw pinion, yaw bearing, yaw brake	Shock, untwisting, linkage, Crack, abrasion	Damping force, high wind speed, bolt loosen, corrosion, dust, friction	Twisting, abnormal noise, misalignment
Hydraulic system	Pump, motor, valves, pipes, hoses, lubrication system	Linkage, blocking, braking problem	High pressure, residual	Filter problem,
Control	Relay, IGBT, module, rectifier	Burn	Over temperature, dust, error during wiring	-
Generator	Windings, brushes, stator, rotor and bearings	Rust, crack, degradation, loosen bolt,	Over temperature, lubrication, wind speed	Noise, vibration, Turbine stoppage
Electrical system	Converter, fuse, switch cables, connections	Burning	Over temperature	Connection interruption,
Sensor	Anemometer, wind vane, vibration switch….	Crack, led light vanished, burning	Over temperature	-
Structure	Lifter, nacelle cover, and cabinet, tower	Crack, Lifter break down	Fatigue, overload, lubricant linkage	-

The research studied by O. Samet et al. [21] stated that the most common failure modes are fatigue and fracture in the toothed shaft of the gearbox and loss of function in the lubricant system. In addition, the failure causes are high wind, grid failure, lighting, Icing, malfunction of control system component wear or failure, loosening of parts, and other unknown causes.

Lastly, the common failure effects are overspeed, overload, noise, vibration, reduced power causing follow-up damage, plant stoppage, and other consequences.

4.4. Result of Severity of failures

Table 9: Calculation of CCN and DCN for direct drive wind turbine

	Replacement cost	AFR	Downtime Per failure	Cost of energy production	CNN	DCN
Pitch system	46,800,000	0.1167	17.76	262000	5,723,560	2.073
Yaw system	11,700,000	0.001	2.133	270	11,970	0.00213
Hydraulic system	10,530,000	0.0002	2.73	760	2866	0.0006
Control	8,190,000	0.02	0.7714	2000	165,800	0.015428
Gear box		00	00	00	00	00
Generator	25,250,000	0.009	0.866	1000	2,526,000	0.008
Electrical system	8,190,000	0.112	0.96	13400	929,680	0.106
Sensor	234,000	0.15	0.188	3600	35,460	0.0282

Table 10: Calculation of CCN and DCN for geared system wind turbine

	Replacement cost	AFR	Downtime Per failure	Cost of energy production	CNN	DCN
Pitch system	105,808,680	0.53	1.37	81303.75	56,159,930	0.73
Yaw system	31,742,604	0.71	1.63	129,195	22,666,443	1.16
Hydraulic system	28,215,684	0.1	3.84	42,768	2,825,845	0.384
Control	14,107,824	0.07	1.8	14,033.25	1,001,580	0.126
Gear box	146,368,674	0.04	1.04	4,633.2	5,854,747	0.0416

Generator	52,904,340	0.212	1.9	44,884.125	11,260,604	0.403
Electrical system	17,634,780	0.34	2.2	83,431.25	6,079,256	0.75
Sensor	3,526,956	0.8	0.4	35,640	2,821,565	0.32

Table 11: Downtime and cost criticality comparison based on the drive concept of wind turbines

	Downtime Criticality Number (hours)		**Cost Criticality Number**					
	1.5 MW direct drive	1.5 WM geared drive	**Direct drive turbine Replacement cost**	**Cost of lost energy production**	**Direct-drive**	**Geared-drive turbine Replacement cost**	**Cost of lost energy production**	**Geared-drive**
Pitch system	2.073	0.73	46,800,000	262000	5,723,560	105,808,680	81303	56,159,930
Yaw system	0.00213	1.16	11,700,000	270	11,970	31,742,604	129195	22,666,443
Hydraulic system	0.0006	0.384	10,530,000	760	2866	28,215,684	42768	2,825,580
Control	0.015428	0.126	8,190,000	2000	165,800	14,107,824	14033.25	1,001,580
Gear box	00	0.0416	00	00	00	146,368,624	4633	5,854,747
Generator	0.008	0.403	25,250,000	1000	2,526,000	52,904,340	44884	11,260,604
Electrical system	0.106	0.75	8,120,000	13400	929,680	17,634,780	83431	6,079,256
Sensor	0.0282	0.32	234,000	3600	35,460	3,526,956	35640	2,821,565

As illustrated in the literature review chapter the primary distinctions between two wind turbine types those with gearboxes and those with direct drives are found in their generator types. Even though the other subsystems may be constructed of various materials of differing quality, they all function in the same way.

For onshore direct drive wind turbines, O. Samet et al. [21] discovered that the generator and electrical system had the highest criticalities, with 120,463 € and 59,804 € cost criticality numbers, respectively. For a geared wind farm, the gearbox ($51,750) and electrical system ($59,804) are found to be the two most critical subsystems. Although the scale of cost criticality values differs from our study, this illustrates the similar criticality order for subsystems with our study for a direct drive turbine. This discrepancy could be explained by the two studies' differing replacement cost hypotheses.

4.5. Results of fault tree analysis diagram

To investigate the reasons for the main wind turbine component failures, the fault tree analysis method is used. The minimal cut sets are the bottom reasons for the failure. This method allowed for assessing the correlation between failures.

4.7.1. Fault analysis diagram for pitch and hub system

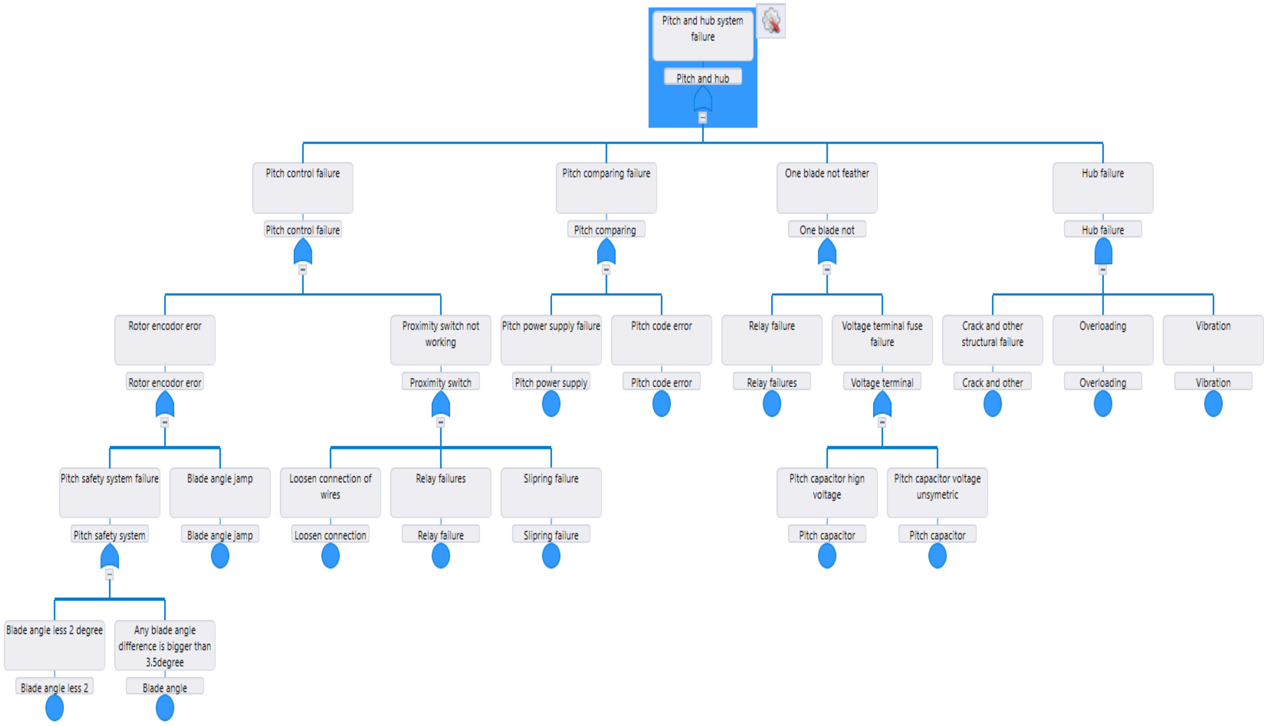
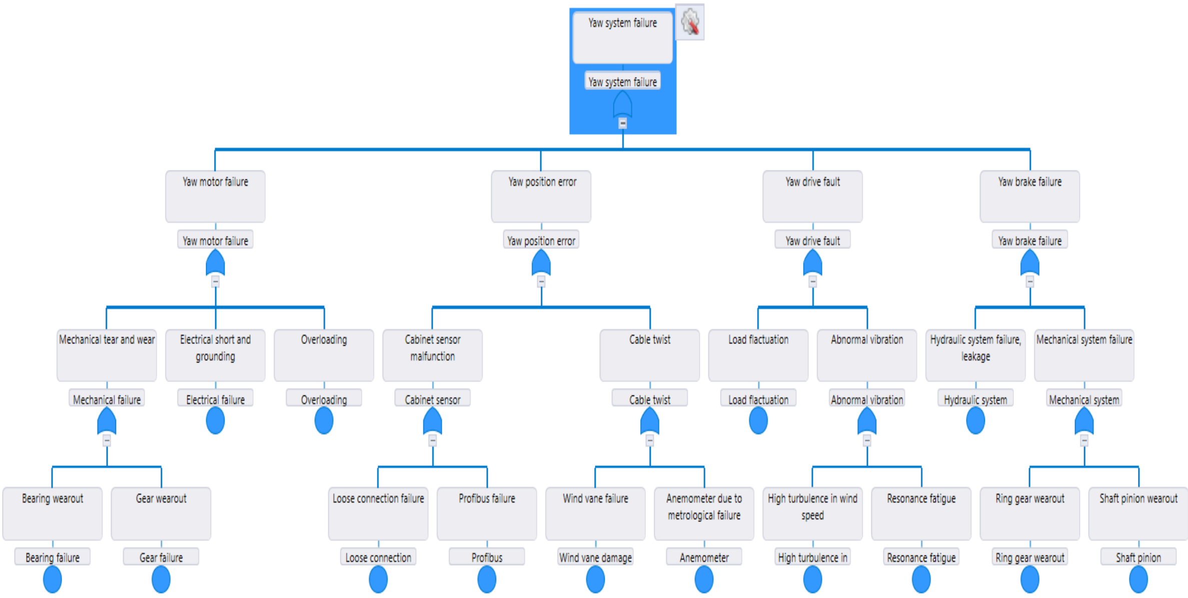


Figure 21: Fault analysis diagram for pitch and hub system

Table 12: Summary of pitch and hub system



tem FTA

Fault Tree: Pitch and hub system failure Fault Tree Node: Pitch and hub system failure Search...

	Minimal Cut Set	Order	Unavailability	Contribution
1	Blade angle less 2 degree	1	0.001	0.0909091
2	Blade angle	1	0.001	0.0909091
3	Blade angle jamp	1	0.001	0.0909091
4	Loosen connection	1	0.001	0.0909091
5	Relay failure	1	0.001	0.0909091
6	Slipring failure	1	0.001	0.0909091
7	Pitch power supply	1	0.001	0.0909091
8	Pitch code error	1	0.001	0.0909091
9	Relay failures	1	0.001	0.0909091
10	Pitch capacitor hign voltage	1	0.001	0.0909091
11	Pitch capacitor voltage unsymetric	1	0.001	0.0909091
12	Crack and other structural failure.Overloading.Vibration	3	1E-09	9.09091E-08

4.7.2 Fault analysis diagram for yaw system

Figure 22: Fault analysis diagram for yaw system

Table 13: Summery for yaw system FTA

Fault Tree: Yaw system failure | Fault Tree Node: Yaw system failure | Search...

	Minimal Cut Set	Order	Unavailability	Contribution
1	Bearing failure	1	0.001	0.0714286
2	Gear failure	1	0.001	0.0714286
3	Electrical failure	1	0.001	0.0714286
4	Overloading	1	0.001	0.0714286
5	Loose connection	1	0.001	0.0714286
6	Profibus	1	0.001	0.0714286
7	Wind vane damage	1	0.001	0.0714286
8	Anemometer	1	0.001	0.0714286
9	Load fluctuation	1	0.001	0.0714286
10	High turbulence in wind speed	1	0.001	0.0714286
11	Resonance fatigue	1	0.001	0.0714286
12	Hydraulic system failure	1	0.001	0.0714286
13	Ring gear wearout	1	0.001	0.0714286
14	Shaft pinion wearout	1	0.001	0.0714286

4.5.1. Fault analysis diagram for hydraulic system

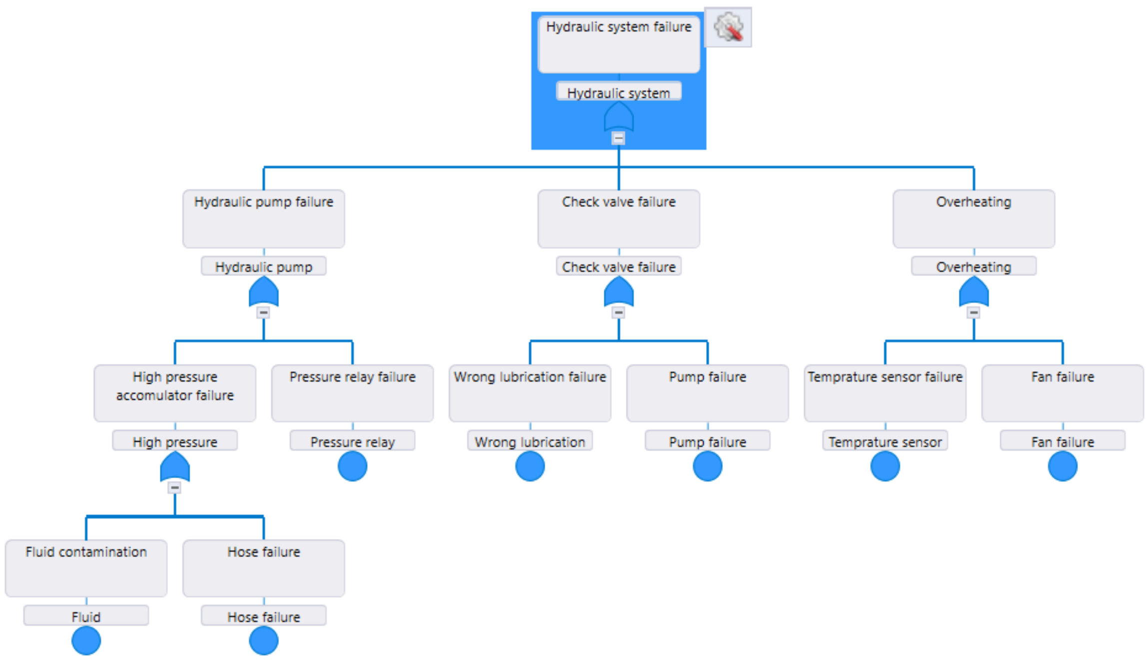


Figure 23: Fault analysis diagram for hydraulic system

Table 14: Summery of hydraulic system FTA

	Minimal Cut Set	Order	Unavailability	Contribution
1	Fluid contamination	1	0.001	0.142857
2	Hose failure	1	0.001	0.142857
3	Pressure relay failure	1	0.001	0.142857
4	Wrong lubrication failure	1	0.001	0.142857
5	Pump failure	1	0.001	0.142857
6	Temprature sensor failure	1	0.001	0.142857
7	Fan failure	1	0.001	0.142857

4.7.3. Fault analysis diagram for gearbox

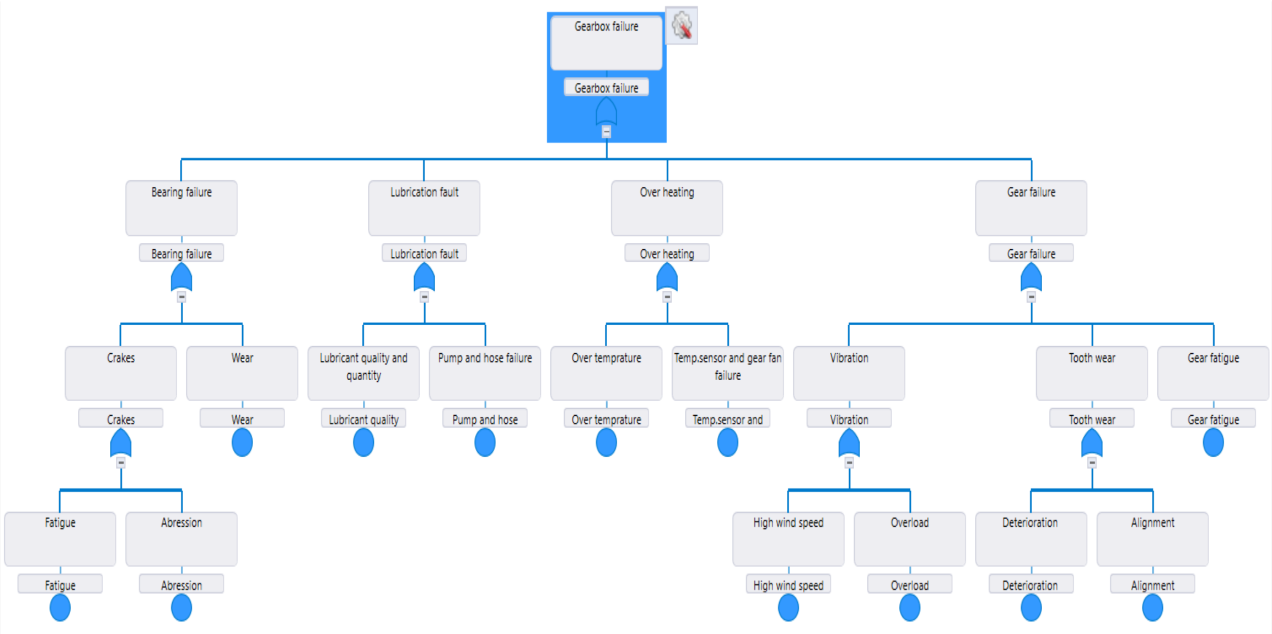


Figure 24: Fault analysis diagram for gearbox system

Table 15: Summery for gearbox system FTA

	Minimal Cut Set	Order	Unavailability	Contribution
2	Abression	1	0.001	0.0833333
3	Wear	1	0.001	0.0833333
4	Lubricant quality and quantity	1	0.001	0.0833333
5	Pump and hose failure	1	0.001	0.0833333
6	Over temprature	1	0.001	0.0833333
7	Temp.sensor and gear fan failure	1	0.001	0.0833333
8	High wind speed	1	0.001	0.0833333
9	Overload	1	0.001	0.0833333
10	Deterioration	1	0.001	0.0833333
11	Alignment	1	0.001	0.0833333
12	Gear fatigue	1	0.001	0.0833333

4.6. Result of availability for direct drive system

The availability of a wind farm can be calculated by dividing the total amount of time the wind turbines were available and producing electricity by the total amount of time in a given period, such as a year.

$$p = \frac{T_m - T_n}{T_m} = 1 - (\lambda/\mu) \quad \text{Eq.17}$$

p The average annual availability of wind turbines in a wind farm, T_m = the number of hours at a given time, T_n the number of shutdown hours due to failure or maintenance

$$p = 78\%$$

4.7. Result of availability for geared system

$$p = \frac{T_m - T_n}{T_m} = 1 - (\lambda/\mu) \quad \text{Eq.18}$$

p The average annual availability of wind turbines in a wind farm, T_m = the number of hours at a given time, T_n the number of shutdown hours due to failure or maintenance

$$p = 83\%$$

The above results reveal certain key facts that most wind farm availability is 80% to 99% so the result of direct drive 78% is a little bit strange because the paper published by Y. Zheng et al. [9] shows 98% availability. There is also research conducted by D. Cevasco et al.[63] different availability results for different wind farms and mean ratings 99%, 96%, 98.6%, 99.4%, 99.1%, 96.2%, 84.41%, and 80.2%. The unexpected result from this research is from the alarm and downtime mixing and unable to sort out.

4.8. Results of Levelized cost of energy for direct drive system

Here, the research presented the results of analysis on the levelized cost of energy (LCOE) for a direct drive system wind turbine. It represents the cost of producing one unit of electricity from a particular source over the asset's lifetime. So, 0.119// 6.93 ETB euro LCOE means that the cost of producing one unit of electricity from a particular source equals 0.119 euro/ 6.93 ETB over the life cycle of the generating asset. This cost includes all expenses such as installation, maintenance, fuel, and other operational costs.

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Architecture			Cost				System		G1500			Grid	
G1500	Grid (kW)	Dispatch	COE (£)	NPC (£)	Operating cost (£/yr)	Initial capital (£)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (£)	Production (kWh/yr)	O&M Cost (£)	Energy Purchased (kWh)	Energy Sold (kWh)
	999,999	CC	£0.100	£39.5M	£3.05M	£0.00	0	0				30,527,872	0

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture			Cost				System		G1500			Grid	
G1500	Grid (kW)	Dispatch	COE (£)	NPC (£)	Operating cost (£/yr)	Initial capital (£)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (£)	Production (kWh/yr)	O&M Cost (£)	Energy Purchased (kWh)	Energy Sold (kWh)
	999,999	CC	£0.100	£39.5M	£3.05M	£0.00	0	0				30,527,872	0
1	999,999	CC	£0.119	£47.8M	£3.02M	£8.80M	4.62	0	8,804,613	1,433,329	24,655	29,565,678	471,134

4.9. Results of Levelized cost of energy for geared system

It represents the cost of producing one unit of electricity from a particular source over the asset's lifetime. As a result, 0.102 euro/5.94 ETB LCOE means that the cost of producing one unit of electricity from a particular source equals 0.102 euro/5.94 ETB over the life cycle of the generating asset. This cost includes all expenses such as installation, maintenance, fuel, and other operational costs. This calculation is useful for comparing the costs of different types of electricity-generating technologies.

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Architecture			Cost						System		G1500			Grid
G1500	Grid (kW)	Dispatch	COE (£)	NPC (£)	Operating cost (£/yr)	Initial capital (£)	Fuel cost (£/yr)	O&M (£/yr)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (£)	Production (kWh/yr)	O&M Cost (£)	Energy Purcha (kWh)
	999,999	CC	£0.100	£145M	£11.2M	£0.00	£0.00	£11.2M	0	0				112,078,768

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture		Cost						System		G1500			Grid	
Grid (kW)	Dispatch	COE (£)	NPC (£)	Operating cost (£/yr)	Initial capital (£)	Fuel cost (£/yr)	O&M (£/yr)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (£)	Production (kWh/yr)	O&M Cost (£)	Energy Purchased (kWh)	Energy Sold (kWh)
999,999	CC	£0.100	£145M	£11.2M	£0.00	£0.00	£11.2M	0	0				112,078,768	0
999,999	CC	£0.102	£147M	£11.1M	£3.21M	£0.00	£11.1M	0.893	0	3,205,919	1,001,708	9,395	111,231,240	154,179

From the research conducted by **Yuqiao Zheng** the main weak subsystem is the pitch system and from the paper studied by **P.J. Tavner** yaw system causes long downtime for the turbine is yaw system and availability 87% levelized cost of energy becomes 11 ETB.

Chapter Five

5. Conclusion and Recommendation

This chapter discusses the conclusions and outlines every important finding under the study's objective. It also notes the thesis recommendations for further research.

5.1. Conclusion

Assessing the reliability of power plants is necessary because growth depends on power quality and is highly exposed to unreliability owing to its complex nature. The wind farm industry is currently booming. Owing to the complex nature of wind turbines, both qualitative and quantitative approaches are mandatory to obtain a full picture of the situation.

Comparing the two technologies with the increase in power demand, more power plants are installed, and their technological advancement has a significant effect on power reliability. In addition, wind turbines are complex machines with many components because of repeated faults and downtime. This affects the reliability of harnessed power.

For Gearless wind turbines from the fault tree analysis, the main root causes for the failure of the turbine are the yaw system and electrical component next sensor component has a high failure rate when compared to the downtime pitch system has an 1800-hour downtime. Its levelized cost of energy becomes 3.19 birr.

For geared type wind turbines from the fault tree analysis the main root cause for the failure of the turbine is yaw twisting component next to the pitch system component has a high failure rate when comparing the down time yaw system has 3200 hours down time. Its levelized cost of energy becomes 3.20 birr.

The gearless wind farm was expected to harness 157.4 GWH per year and the geared type was 479 GWH. But from the plant's availability, there is a big difference compared to the SCADA availability mostly 98 to 99 because it counts the availability of the WTG without considering the wind speed.

5.2. Recommendation

This research revealed that power reliability is affected by long downtime, failure rate, and technology differences. Future research should examine power quality related to harmony and how to reduce unreliability and power quality loss due to transmission lines.

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Appendices

Appendix A: Data requesting letter for EEP

ቀን 16/04/2015

ለኢትዮጵያ ኤሌክትሪክ ኃይል
ለጀነሬሽን ኦፐሬሽን ስራ አስፈፃሚ
አዲስ አበባ

<u>ጉዳዩ</u>፡- መረጃ ስለመጠየቅ

ለ2ተኛ ዲግሪ መመረቂያ ጥናታዊ ጹሁፍ መስሪያ የአዳማ 2 ን/ኃ/ማምንጫ SCADA fault history data ስለሚያስፈልገኝ መርጃው ይሰጠኝ ዘንድ በትህትና እጠይቃለሁ።

ከሠላምታ ጋር
ሀያት ኢብራሂም (701311)

ጀነሬሽን ኦፐሬሽን ሥራ
አስፈፃሚ

Appendix B: Fault history data sample

	Name	Code	LastOccurTime	LastClearTime	Duration	Times	Level
2	Yaw sensor defect	1413	6/30/2014 3:08:01 PM	6/30/2014 3:16:54 PM	00:08:53	1	4
3	Yaw motor MCB FB	1201	6/29/2014 4:51:01 PM	6/30/2014 2:54:25 AM	10:18:26	3	4
4	Yaw motor MCB FB	1200	7/23/2014 3:53:39 AM	7/23/2014 3:48:39 AM	193.05:19:08	14	4
5	Yaw CW feedback	1025	7/2/2014 2:54:55 AM	7/2/2014 3:56:55 AM	3.01:27:04	11	4
6	Yaw CW FB err.	1157	7/23/2014 3:48:41 AM	7/23/2014 3:48:39 AM	195.07:27:30	18	4
7	Yaw CCW feedback	935	6/30/2014 2:54:52 AM	6/30/2014 3:01:05 AM	11.12:28:25	12	4
8	Yaw CCW FB err.	1023	7/23/2014 3:48:41 AM	7/23/2014 3:48:39 AM	172.08:36:21	422	4
9	Yaw brake MCB FB	1305	7/23/2014 5:05:02 AM	7/23/2014 3:48:39 AM	169.06:10:46	23	4
10	Yaw brake MCB FB	1239	7/23/2014 3:48:44 AM	7/23/2014 3:48:39 AM	185.07:01:05	23	4
11	Yaw (M) FB	1430	7/2/2014 2:54:53 AM	7/2/2014 2:58:32 AM	01:37:16	8	4
12	Wind > maxmax	507	6/30/2014 5:44:00 AM		183.06:16:02	1	4
13	Wind > maxmax	417	7/23/2014 3:48:39 AM	7/23/2014 3:48:39 AM	183.19:51:09	14	4
14	Twisted limit	1332	6/18/2014 4:01:30 AM		195.07:58:32	1	1
15	Tower resonance	236	6/18/2014 5:10:42 AM	6/18/2014 5:19:23 AM	00:14:22	2	4
16	Rotor locked	2636	6/8/2014 7:00:36 AM	6/8/2014 7:01:25 AM	00:00:49	1	1
17	Pitch ctrl.communic.defect	2136	6/19/2014 4:35:10 PM	6/29/2014 4:00:46 PM	15.01:33:00	2	4
18	Outdoor temp.low stop	415	6/18/2014 4:11:24 AM		195.07:48:38	1	4
19	Nacelle temp. low stop	92	6/30/2014 2:54:47 AM	6/30/2014 3:01:05 AM	5.02:29:21	4	4
20	Manual Stop	13	6/30/2014 3:01:13 AM	6/30/2014 3:03:16 AM	9.21:10:24	6	4
21	Main bear.temp. low stop	3010	6/30/2014 5:43:59 AM	6/30/2014 5:45:59 AM	00:02:00	1	4
22	Inverter tripped	2622	6/8/2014 7:00:36 AM	6/8/2014 7:01:25 AM	00:00:49	1	1
23	Inverter CANopen defect	1946	6/8/2014 7:00:36 AM	6/8/2014 7:01:25 AM	00:00:49	1	4
24	Inverter canopen comm. failure Rep	2073	6/30/2014 2:54:47 AM	6/30/2014 3:01:05 AM	10:26:18	4	4

	Time	Code	Name	ClearTime	Duration	Level
2	12/30/2015 8:16:06 AM	1157	Pitch3 24V loop MCB	12/30/2015 8:16:13 AM	00:00:07	1
3	12/30/2015 8:15:53 AM	1157	Pitch3 24V loop MCB	12/30/2015 8:16:03 AM	00:00:10	1
4	12/30/2015 8:15:45 AM	1157	Pitch3 24V loop MCB	12/30/2015 8:15:45 AM	00:00:00	1
5	12/25/2015 8:32:59 AM	111	Axis 1 2F3、2F10、7k6 state		6.03:27:31	1
6	12/25/2015 8:32:59 AM	1961	Axis 3 breaker 1F1 state	12/25/2015 8:33:01 AM	00:00:02	1
7	12/25/2015 8:05:35 AM	2436	Axis 1 charger state	12/25/2015 8:32:59 AM	00:27:24	1
8	12/25/2015 4:34:46 AM	1157	Pitch3 24V loop MCB	12/25/2015 8:05:32 AM	03:30:46	1
9	12/25/2015 4:34:21 AM	2468	tower 230V heat-protection feedback slip brake	12/25/2015 8:05:32 AM	03:31:11	4
10	12/25/2015 4:34:19 AM	2436	Axis 1 charger state	12/25/2015 8:05:32 AM	03:31:13	1
11	12/25/2015 4:34:15 AM	111	Axis 1 2F3、2F10、7k6 state	12/25/2015 8:32:59 AM	03:58:44	1
12	12/25/2015 4:34:15 AM	121	0	12/25/2015 8:32:59 AM	03:58:44	0
13	12/25/2015 4:34:15 AM	1443	Emer.Stop nacelle	12/25/2015 8:05:32 AM	03:31:17	1
14	12/25/2015 4:34:14 AM	1420	(TB) emer. Stop	12/25/2015 8:05:32 AM	03:31:18	1
15	12/22/2015 6:14:09 PM	111	Axis 1 2F3、2F10、7k6 state	12/25/2015 4:34:15 AM	2.10:20:06	1
16	12/22/2015 5:33:52 PM	2436	Axis 1 charger state	12/22/2015 6:14:09 PM	00:40:17	1
17	12/22/2015 3:09:26 PM	1157	Pitch3 24V loop MCB	12/22/2015 5:33:49 PM	02:24:23	1
18	12/22/2015 3:08:59 PM	2436	Axis 1 charger state	12/22/2015 5:33:49 PM	02:24:50	1
19	12/22/2015 3:08:57 PM	2468	tower 230V heat-protection feedback slip brake	12/22/2015 5:33:49 PM	02:24:52	4
20	12/22/2015 3:08:55 PM	111	Axis 1 2F3、2F10、7k6 state	12/22/2015 6:14:09 PM	03:05:14	1
21	12/22/2015 3:08:55 PM	121	0	12/22/2015 6:14:09 PM	03:05:14	0
22	12/22/2015 3:08:54 PM	1444	MCB reday fault(ABB)	12/22/2015 5:33:49 PM	02:24:55	1
23	12/22/2015 3:08:54 PM	1418	Axis 1 Super capacitance state	12/22/2015 5:33:49 PM	02:24:55	1
24	12/22/2015 3:08:54 PM	1420	(TB) emer. Stop	12/22/2015 5:33:49 PM	02:24:55	1

Appendix B: Total Expenditure Sample

	A	B	C	D	E	F
1	Account	Account (T)	System	System (T)	Period	Amount
2	5101	Materials for repair and Maintenance	1141	Adama I Wind Power Plant	200712	41,106.15
3	5102	Vehicles repair and maintenance	1141	Adama I Wind Power Plant	200712	266,366.25
4	5103	Office Equipment maintenance	1141	Adama I Wind Power Plant	200712	640.56
5	5108	Stationery & supplies	1141	Adama I Wind Power Plant	200712	66,432.32
6	5109	Computer Stationery	1141	Adama I Wind Power Plant	200712	6,159.15
7	5110	Benzine	1141	Adama I Wind Power Plant	200712	433,832.84
8	5111	Gas oil	1141	Adama I Wind Power Plant	200712	114,384.16
9	5112	Grease	1141	Adama I Wind Power Plant	200712	13,688.80
10	5113	Oil	1141	Adama I Wind Power Plant	200712	927.39
11	5201	Basic Salary	1141	Adama I Wind Power Plant	200712	2,960,361.37
12	5202	Salary For Contract employees	1141	Adama I Wind Power Plant	200712	105,383.50
13	5204	Overtime	1141	Adama I Wind Power Plant	200712	448,293.15
14	5206	Hardship Allowance	1141	Adama I Wind Power Plant	200712	787,099.14
15	5207	Rent allowance	1141	Adama I Wind Power Plant	200712	12,150.00
16	5208	Transport allowance	1141	Adama I Wind Power Plant	200712	54,909.26
17	5209	Cash Shortage Allowance	1141	Adama I Wind Power Plant	200712	840
18	5210	Management Allowance	1141	Adama I Wind Power Plant	200712	69,050.00
19	5211	Special Allowance	1141	Adama I Wind Power Plant	200712	24,015.88
20	5212	Wages	1141	Adama I Wind Power Plant	200712	282,516.23
21	5213	Special Allowance - Hydro & Geothermal	1141	Adama I Wind Power Plant	200712	1,330,260.32
22	5214	Work shop labour recovery	1141	Adama I Wind Power Plant	200712	2,000.00
23	5217	?	1141	Adama I Wind Power Plant	200712	28,400.00
24	5303	Medical	1141	Adama I Wind Power Plant	200712	39,385.15
25	5304	EEPCO Pension Contribution (6%)	1141	Adama I Wind Power Plant	200712	410,683.68
26	5306	Safety equipment	1141	Adama I Wind Power Plant	200712	42,878.06
27	5307	Transfer and transpotation	1141	Adama I Wind Power Plant	200712	2,065.22
28	5431	Rent	1141	Adama I Wind Power Plant	200712	147,570.00

	A	B	C	D	E	F
1	Account	Account (T)	System	System (T)	Period	Amount
2	5101	Materials for repair and Maintenance	1142	Adama II Wind Power Plant	200712	10,328.74
3	5108	Stationery & supplies	1142	Adama II Wind Power Plant	200712	557.98
4	5110	Benzine	1142	Adama II Wind Power Plant	200712	433,475.44
5	5111	Gas oil	1142	Adama II Wind Power Plant	200712	10,411.65
6	5201	Basic Salary	1142	Adama II Wind Power Plant	200712	12,218.56
7	5208	Transport allowance	1142	Adama II Wind Power Plant	200712	3,125.77
8	5210	Management Allowance	1142	Adama II Wind Power Plant	200712	750
9	5211	Special Allowance	1142	Adama II Wind Power Plant	200712	1,200.00
10	5213	Special Allowance - Hydro & Geothermal	1142	Adama II Wind Power Plant	200712	1,000.00
11	5217	?	1142	Adama II Wind Power Plant	200712	600
12	5303	Medical	1142	Adama II Wind Power Plant	200712	273.45
13	5306	Safety equipment	1142	Adama II Wind Power Plant	200712	16,516.06
14	5461	Travel and Subsistance allowance -Local	1142	Adama II Wind Power Plant	200712	2,078.24
15						492,535.89
16	Account	Account (T)	System	System (T)	Period	Amount
17	5101	Materials for repair and Maintenance	1142	Adama II Wind Power Plant	200812	5,913.04
18	5102	Vehicles repair and maintenance	1142	Adama II Wind Power Plant	200812	1,113.50
19	5103	Office Equipment maintenance	1142	Adama II Wind Power Plant	200812	479.99
20	5108	Stationery & supplies	1142	Adama II Wind Power Plant	200810	14,949.45
21	5108	Stationery & supplies	1142	Adama II Wind Power Plant	200812	22,189.66
22	5110	Benzine	1142	Adama II Wind Power Plant	200812	661.3
23	5111	Gas oil	1142	Adama II Wind Power Plant	200809	3,050.25
24	5111	Gas oil	1142	Adama II Wind Power Plant	200810	7,320.60
25	5111	Gas oil	1142	Adama II Wind Power Plant	200812	70,776.66
26	5112	Grease	1142	Adama II Wind Power Plant	200812	780
27	5201	Basic Salary	1142	Adama II Wind Power Plant	200808	8,300.00
28	5201	Basic Salary	1142	Adama II Wind Power Plant	200809	16,980.00