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Optimal design and analysis of a grid-connected hybrid renewable energy system using homer pro: a case study of Tumbatu island, Zanzibar

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OPTIMAL DESIGN AND ANALYSIS OF A GRID-CONNECTED HYBRID RENEWABLE ENERGY SYSTEM USING HOMER PRO: A CASE STUDY OF TUMBATU ISLAND, ZANZIBAR

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

This study addresses the issue of quality electricity access on Tumbatu Island in Tanzania, with a specific focus on enhancing the high-voltage (HV) transmission line. While many studies concentrate on low-voltage (LV) transmission lines, HV lines play a crucial role and merit more attention. Therefore, the objective of the study is to improve the voltage profile of the HV transmission line through a hybrid energy system comprising solar PV, wind turbines, and batteries. This effort begins with an analysis of the total power demand and consumption, which are essential for designing an effective energy system. The study employs HOMER Pro to simulate various hybrid system configurations. The simulation findings indicate that integrating solar PV, wind turbines, and HV lines leads to a significant enhancement in the voltage profile, raising it from 29.6 kV to 31.23 kV during peak demand. This solution demonstrates the highest economic viability, boasting the lowest Net Present Cost (NPC) of USD 4 003 851 and a relatively short payback period (PB) of 3.79 years. Implementing this hybrid system not only meets the island's energy needs but also contributes to global pollution reduction and minimizes electricity costs for the population of Tumbatu Island. Furthermore, it addresses the demand for clean energy, emphasizing its role in achieving sustainable and accessible electricity in Sub-Saharan Africa and beyond.

DECLARATION

I, Thani Rashid Said, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my original work and that it has neither been submitted nor being concurrently submitted for consideration of a similar degree in any other University.

Thani Rashid Said		16/09/2024
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The above declaration is confirmed by:

Prof. Thomas Kivevele		21/08/2024
Name of Supervisor 1	**Signature**	**Date**

Dr. Baraka Kichonge		21.08.2024
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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Nelson Mandela African Institution of Science and Technology, a dissertation titled , **“Optimal design and analysis of grid-connected renewable Energy hybrid system using HOMER Pro: A case study of Tumbatu Island Zanzibar”** in partial fulfilment of the requirements for the degree of Master of Science in Sustainable Energy Science and Engineering of the Nelson Mandela African Institution of Science and Technology.

Prof. Thomas Kivevele		21/08/2024
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Dr. Baraka Kichonge		21.08.2024
Name of Supervisor 2	**Signature**	**Date**

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DEDICATION

I dedicate this work to all those who contribute to meeting the world's increasing energy demands while also mitigating the impacts of climate change. I also extend this dedication to my daughter Tahfeem Thani, my wife, and my other family members who have supported me from the outset to the completion of my studies.

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LIST OF ABBREVIATIONS AND SYMBOLS

$	Dollar
%	Percentage
A	Amperes
AC	Alternating current
COE	Cost of Electricity
DC	Direct current
DFIG	Double Fed Induction Generator
DG	Diesel Generator
DoD	Depth of Discharge
EU	European Union
FA	Factory of Activated
FF	Fill Factor
Fig	Figure
G	Solar irradiance
GW	Gig watt
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy System
HRETs	Hybrid Renewable Energy Technology
HV	High Voltage
I	Electrical Current
Imp	Panels maximum current
Io	Open Circuit Current
IRENA	International Renewable Energy Agency
IRENA	International Renewable Energy Agency
Isc	Short circuit current
Isc	Short Circuit Current
KS	Kenya Shilling
kV	Kilo Volt
kW	Kilo Watt
kWh	Kilowatt hour

LA	Lead Acid Battery
LI	Lithium Ions
LV	Low Voltage
M$	Million Dollars
MATLAB	Matrix Laboratory
MSW	Municipal Solid Waste
MW	Megawatt
MWh	Megawatt hour
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O & M	Operational and Maintenance
P	Power
PB	Payback Period
Pmp	Panels maximum power
Pmp	Maximum power
PV	Photovoltaic
RAM	Random Access Memory
RES	Renewable Energy Source
SCIG	Squirrel Cage Induction Generator
SW	Solid Waste
TMA	Tanzania meteorological Authority
TNPC	Total Net Present Cost
TWh	Terawatt hour
USA	United State of America
Voc	Open circuit voltage
W	Watts
Wp	Peak output power
WT	Wind turbines
ZECO	Zanzibar Electricity Corporation

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Energy is essential for economic development, with demand steadily rising due to factors like population growth, urbanization, and industrialization (Holechek, 2022; Ritchie, 2020). Despite advancements in resource efficiency and the adoption of renewable energy sources, fossil fuels continue to hold a predominant position in energy production (Ali, 2021; Friedemann, 2021; Heede, 2014; Li, 2021). To mitigate these challenges, there is a global push towards renewable energy sources (Mitrašinović, 2021; Opeyemi, 2021). However, integrating intermittent renewable energies, such as solar and wind power, presents grid stability challenges (Abdelkareem *et al.,* 2018; Lutyński, 2017). Tumbatu Island has plenty of renewable energy resources, but it encounters problems with the stability of its power grid because it relies on HV transmission line that experiences voltage drops (Islam, 2008).

Islands such as Tumbatu in Zanzibar have rich renewable energy resources. Utilizing various renewable energy technologies can help small islands me*et al*l their domestic energy needs. Tumbatu is the third-largest island in the Zanzibar archipelago, located northwest of Unguja Island, with a population of 26,482 and an average household size of 4.5% (National Bureau of Statistics, 2022).

A 33 kV submarine cable, running 35.3 km from Mtoni substations in Zanzibar to Mkokotoni, supplies electricity to Tumbatu. This transmission line faces several challenges, the most significant being voltage drop due to the long distance and insufficient power to meet current and growing demand. One solution to the voltage drop issue is constructing a new overhead transmission line connected by a submarine cable. However, this is financially unviable due to high costs (Acaroğlu & Márquez, 2022; De-Alegría *et al.*, 2009) and potential environmental concerns, such as maritime contamination (Al-Ghaithi *et al.*, 2017; Taormina *et al.,* 2018). The remaining feasible solution is integrating renewable energy with grid electricity (Falk *et al.,* 2021; Farghali *et al.,* 2023; Jaiswal *et al.,* 2022). Renewable sources like solar or wind power can sustainably and economically address the voltage drop issue (Ali *et al.,* 2022). This approach promotes environmental sustainability (Malik *et al.,* 2019) and offers long-term cost savings (Ababio *et al.,* 2021).

Reducing reliance on traditional energy sources and harnessing renewable resources makes the electricity grid more resilient and less prone to voltage drop issues (ENERGY5, 2023; Yadav *et al.*, 2023). This strategy aligns with the global shift toward a greener and more sustainable energy future. Therefore, focusing on renewable energy integration into the existing grid infrastructure is crucial. This approach addresses voltage drop issues and supports sustainability goals and energy independence in the region.

The HV transmission lines, as the backbone of power networks, play an indispensable role in electricity distribution. Despite their significance, the attention to quality issues in HV lines often pales in comparison to that of LV networks. This neglect is worrying considering the crucial function HV lines fulfill in maintaining the reliability and stability of the grid. Neglecting quality concerns in HV lines can lead to widespread power outages, safety hazards, and increased energy losses, posing significant risks to both infrastructure and public safety (NCSL, 2024). Furthermore, as critical components of power distribution networks, HV lines are responsible for transmitting large amounts of electricity over long distances, making them susceptible to various challenges such as insulation degradation, structural weaknesses, and environmental factors like lightning strikes and extreme weather events. These issues underscore the urgent need to prioritize quality improvement efforts in HV transmission lines to safeguard grid reliability and mitigate potential risks and disruptions to power supply (Parihar, 2018; Wu, 2017).

Addressing quality issues in HV transmission lines requires a multifaceted approach that encompasses prioritization, technological innovation, and integration of renewable energy sources. Prioritization involves identifying and assessing high-risk areas and critical infrastructure components, allowing utilities to allocate resources efficiently and effectively (Raghav *et al.*, 2022). Technological innovation plays a crucial role in improving the reliability and performance of HV lines, with advancements in materials, monitoring systems, and maintenance techniques enabling proactive identification and mitigation of potential issues (Alexopoulos *et al.*, 2021). Additionally, integrating renewable energy sources presents a promising avenue for enhancing HV line quality. By leveraging renewable energy generation located closer to consumption centers, such as solar and wind power, the strain on transmission lines can be reduced, resulting in improved grid stability and efficiency (Weiss & Tsuchida, 2015). Furthermore, the variability of renewable energy sources necessitates a more flexible and adaptive grid infrastructure, which can drive innovations in transmission line technologies and grid management practices (Karduri, 2018; Saianiruth *et al.*, 2023).

The HOMER Pro, simulation software developed by the National Renewable Energy Laboratory (NREL), stands out as a powerful tool for optimizing the integration of renewable energy sources into existing grid infrastructure. Its capabilities extend beyond traditional simulation software, allowing for the comprehensive analysis of hybrid renewable energy systems tailored to specific geographic locations and energy needs (Abdul-Wahab, 2020). HOMER Pro enables researchers and utilities to model various renewable energy sources, storage options, and system configurations, considering factors such as resource availability, energy demand profiles, and economic parameters. This versatility makes it invaluable for designing cost-effective and technically feasible solutions for integrating renewable energy into the grid, particularly in remote and isolated regions like Tumbatu Island. Additionally, HOMER Pro facilitates the assessment of the economic viability and environmental impact of different system configurations, providing valuable insights for decision-making and policy formulation related to renewable energy integration (Hassan *et al.,* 2016; Manyama, 2018; Sharma, 2022).

Despite the extensive research conducted on LV networks, there remains a noticeable gap in the literature regarding quality improvement in HV transmission lines, especially in underdeveloped regions. While much attention has been paid to enhancing the reliability and performance of LV distribution systems, HV transmission lines have often been overlooked, despite their critical role in electricity transmission and distribution infrastructure (Andersen, 2014). This research aims to address this gap by focusing on optimizing a grid-connected renewable energy hybrid system for Tumbatu Island, utilizing HOMER Pro. This involves conducting a comprehensive analysis of the economic viability, technical feasibility, and environmental impact of integrating renewable energy sources into the island's grid infrastructure. This study seeks to provide valuable insights and recommendations for improving HV line quality and enhancing overall grid resilience and sustainability. Through its unique methodology and targeted geographic focus, this research aims to contribute to the broader understanding of renewable energy integration and grid optimization in remote and isolated regions, ultimately advancing the transition towards a more sustainable and resilient energy future.

1.2 Statement of the Problem

Tumbatu Island, like other parts of Zanzibar, struggles with electricity provision. A 35.3-kilometer transmission line from the Mtoni substations in Zanzibar to Mkokotoni supplies electricity to Tumbatu Island via a 33 kV submarine cable. This line has issues, particularly a voltage drops to 29.6 kV due to the long distance and insufficient power supply for the island's growing energy needs. Previous efforts, including the use of a submarine cable, sporadic maintenance, and Reactive Power Compensation Devices to enhance voltage stability, have failed to ensure reliable electricity. Equipment failures and rising demand necessitate urgent solutions to prevent further disruptions. Despite extensive research on LV networks, there is a notable lack of literature on quality improvement in HV transmission lines, especially in underdeveloped regions.

Furthermore, while renewable energy sources offer potential solutions, there is a noteworthy absence of detailed studies focusing on the design and analysis of renewable energy systems tailored to Tumbatu Island's unique characteristics (Manyama, 2018). Moreover, the feasibility of integrating renewable energy systems with the existing HV electricity grid remains largely unexplored. This research gap underscores the critical need for a targeted investigation into the optimal design and analysis of renewable energy systems within the context of Tumbatu Island, Zanzibar.

In response to these challenges, this study aims to address the research gap by examining the design and analysis of renewable energy systems on Tumbatu Island. Specifically, the research seeks to identify the most effective technical and economic solutions for a renewable energy system integrating solar and wind power sources. By integrating these renewable energy systems with the existing HV electricity grid, the study aims to enhance reliability and sustainability while mitigating the challenges posed by the current infrastructure. Utilizing simulation modeling and optimization techniques with HOMER Pro software, the research aims to gain insights into efficiently harnessing the island's natural resources. Ultimately, this study aims to provide practical guidance for policymakers and stakeholders in formulating sustainable energy policies and strategies for Tumbatu Island (Al Ghaithi, 2017).

1.3 Rationale of the Study

The island's geographical and climatic conditions offer significant potential for renewable energy sources. Solar, wind, and biomass energy can be harnessed to create a hybrid system that complements existing grid infrastructure.

A well-designed hybrid system can enhance energy security by reducing reliance on external energy sources and mitigating the risks associated with fuel price volatility and supply disruptions. This contributes to a more stable and resilient energy supply for the island's residents.

The research explores innovative solutions by integrating various renewable energy sources and advanced optimization tools. This approach not only addresses the unique challenges faced by Tumbatu Island but also advances the field of renewable energy system design and analysis.

1.4 Research Objectives

1.4.1 General Objective

To determine the optimal combination of renewable energy sources along with high voltage transmission line (grid) to meet Tumbatu Island's energy demand while minimizing costs and maximizing reliability by conducting simulation, optimization and sensitivity analysis using HOMER Pro.

1.4.2 Specific Objectives

The study aimed to achieve the following specific objectives:

(i) To conduct optimization of the hybrid renewable energy system using HOMER software, focusing on solar photovoltaic (PV), battery storage, converters, wind turbines, and grid integration for the study area.

(ii) To enhance the voltage profile of the high-voltage transmission line in Tumbatu Island by integrating renewable energy sources, thereby improving grid stability and reliability.

(iii) To perform sensitivity analysis of the hybrid renewable energy system using HOMER software that will assess its robustness and adaptability to variations in environmental conditions and energy demand.

1.5 Research Questions

The study intended to answer the following questions:

(i) How can the hybrid renewable energy system for Tumbatu Island be optimized using HOMER software?

(ii) In what ways can the integration of renewable energy sources improve the voltage profile of the high-voltage transmission line in Tumbatu Island?

(iii) How does sensitivity analysis inform the robustness and adaptability of the hybrid system to variations in environmental conditions and energy demand?

1.6 Significance of the Study

In this section, the significance and rationale behind the research endeavor are explored, shedding light on its importance in addressing energy challenges and driving sustainable development on Tumbatu Island. By examining the socio-economic benefits, environmental impacts, and broader implications of implementing a hybrid renewable energy system, the transformative potential of renewable energy solutions in island contexts is elucidated.

(i) To establish a hybrid renewable energy system at Tumbatu Island that will generate, foster employment opportunities in sectors such as tourism and marine activities.

(ii) Hybrid renewable energy technologies (HRETs) are proposed to enhance utility company revenue by increasing grid dependability and reducing power shortages.

(iii) Implementation of HRETs reduce reliance on diesel engines, thus lowering electricity costs and mitigating environmental pollution, including greenhouse gas emissions, noise pollution and heat pollution.

(iv) Offer an alternative and sustainable solution to electrification challenges in Zanzibar.

(v) Contribute to increasing the proportion of renewable energy in Zanzibar's power generation while attracting investor interest and encouraging government investment in the renewable energy sector.

1.7 Delineation of the Study

This research will primarily concentrate on enhancing the voltage profile by assessing the optimal capacities of hybrid renewable energy system components and its economic viability for supplying electricity to Tumbatu Island. However, the scope and limitations of this study could impact the findings, including issues such as grid stability and data control. The designed system is subject to the following constraints:

(i) The hybrid system is specifically for the chosen location and may not represent the optimal configuration for another location, even if they share a similar load profile, due to differences in renewable energy potential.

(ii) Due to the lack of available data on other renewable energy resources in the chosen location, the study only took into account solar and wind energy resources.

(iii) The study does not address concerns related to grid stability and control.

CHAPTER TWO

LITERATURE REVIEW

2.1 Renewable Energy Potential in Zanzibar

2.1.1 Hydro Energy Potential

In Zanzibar, there are no suitable rivers or lakes for the generation of hydroelectric power. As a result, the islands rely on electricity supplied from the mainland of Tanzania, which has abundant opportunities for hydropower resources, totaling approximately 4.7 GW. However, only a small fraction of this potential, about 12 %, is currently utilized (African Development Bank Group, 2015; Manyama, 2018). Tanzania is endowed with numerous lakes and rivers, including Lake Victoria, River Pangani, River Rufiji, and River Ruvu. For many years, Tanzania's energy sector has heavily depended on hydropower. However, the variability in river flows has affected its reliability, leading to water shortages for hydroelectric turbine operation. This challenge has been further exacerbated by agricultural activities upstream (Manyama, 2018). Table 1 provides an overview of the various hydro resources available from different power stations.

Table 1: Tanzania large hydropower stations (Manyama, 2018)

Hydroelectric Power station	Region	Type	Capacity (MW)	Year completed	Name of reservoir	River
Mtera	Dodoma	Reservoir	80	1979	Mtera	Rufiji River
Kihansi	Morogoro	Reservoir	180	2000	Kihansi	Kihansi River
Nyumbaya Mungu	Kilimanjaro	Reservoir	8	1967	Nyumba yaMungu	Mt.Kilimanjaro Strem
Kidatu	Morogoro	Reservoir	204	1976	Kidatu Dam	Rufiji River
Pangani	Tanga	Reservoir	68	1994		Pangani River
Hale	Tanga	Reservoir	21	1964		Pangani River
Kikonge	Ruvuma	Reservoir	300	2025		Ruhuhu River

2.1.2 The Potential of Biomass Energy Resources in Zanzibar

The government and investors are eager to utilize Municipal Solid Waste (MSW) as fuel in power plants. Burning one ton of MSW generates 2.5 tons of steam, 0.5 MWh of electrical energy, and 21 kW of power, equivalent to 0.3 tons of coal or 0.2 tons of oil (Anshar *et al.,* 2014). Table 2 details the monthly solid waste generated in Zanzibar Urban Municipal for 2022. With monthly waste generation ranging from 3716 to 6609.90 tons, there are significant opportunities for electricity generation. This consistent waste production supports sustainable power generation. Investing in MSW-to-energy projects could reduce reliance on coal and oil, providing a cleaner, more reliable energy source while addressing waste management challenges.

Table 2: Monthly Solid Waste for Zanzibar Urban Municipal (Zanzibar Urban Municipal Council, 2022)

Month	SW (tones)
January	5221.00
February	4851.90
March	4358.70
April	5221.00
May	4851.90
June	4358.70
July	6609.90
August	5097.70
September	4879.50
October	5930.00
November	3716.00
December	4462.00

2.1.3 The Potential of Solar Energy Resources in Zanzibar

Zanzibar possesses ample solar resources that remain largely untapped. According to an EU solar feasibility study conducted in 2016 at five identified solar farm sites in Zanzibar namely Michiweni, Muwambe, Matemwe, Pongwe, and Makunduchi (World bank, 2021). The average Global Horizontal Irradiation was measured at 2100 kWh/m^2/year. In response to these findings, the Zanzibar government aims to establish the primary utility-scale solar photovoltaic power facility within the Indian Ocean archipelago (Dean, 2020; World bank, 2019).

2.1.4 The Potential of Wind Energy Resources in Zanzibar

Based on an EU feasibility analysis, Zanzibar is identified as having significant wind energy potential. As part of the government's strategic initiatives, plans are underway to construct 40 MW wind farms on Unguja Island and 4 MW on Pemba Island (World bank, 2019). These developments signify a concerted effort to harness Zanzibar's abundant wind resources for sustainable energy generation and contribute to the archipelago's energy independence and environmental goals (Dean, 2020).

2.2 Hybrid Energy System

A hybrid energy setup involves utilizing two or more sources of energy, which can include both renewable and possibly non-renewable sources as primary generators, ensuring continuous power generation even in the event of capacity shortages from one source. By integrating multiple energy sources, including renewable like solar, wind, or hydro, alongside non-renewable options, the system aims to provide sustainable power solutions. This configuration not only enhances reliability but also ensures flexibility in power generation, enabling seamless adaptation to varying energy demands and environmental conditions (García, 2019). It is a suitable approach to generate electricity using energy sources available locally, particularly in areas where extending the grid is costly or where geographically isolated regions make it challenging to transmit electricity from centralized utilities.

Utilizing solely renewable sources for electricity generation in rural villages presents various advantages and disadvantages. Benefits include reduced fuel costs, although transportation expenses for fuel can be high, along with addressing concerns about global warming and climate change on a broader scale. However, relying solely on renewable sources for off-grid power systems introduces challenges due to their intermittent nature, making it difficult to regulate power output to meet demand. Combining renewable energy sources with alternatives such as diesel generators or grid generators can address reliability and affordability concerns that arise when operating individually (Al-Ghaithi *et al.*, 2017). Example of grid connected hybrid renewable energy system is shown in Fig. 1.

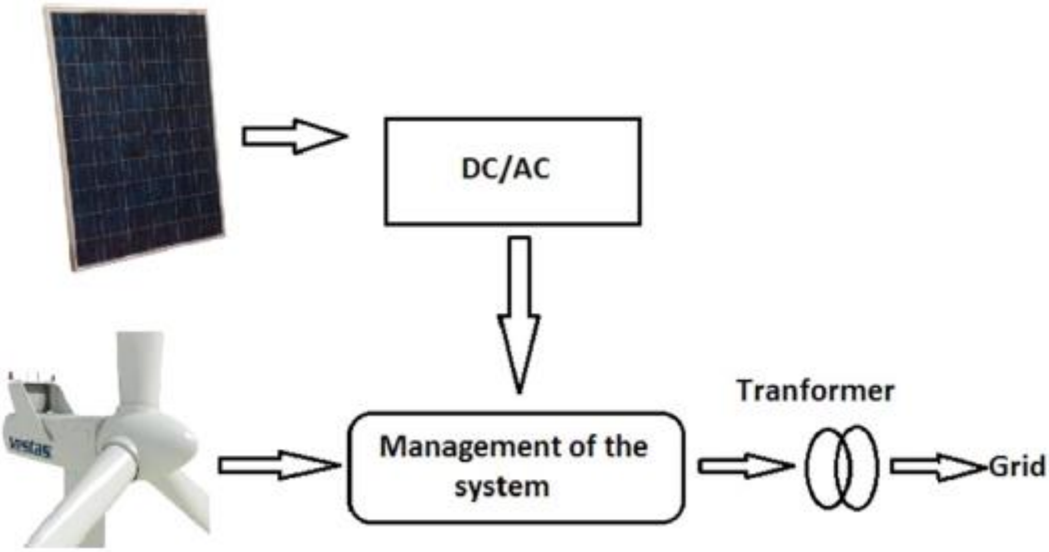

Figure 1: Grid connected hybrid renewable energy system (Koussa, 2015)

2.2.1 The ON Grid Hybrid Renewable Energy System

An on-grid hybrid renewable energy system seamlessly integrates multiple renewable energy sources, such as solar panels, wind turbines, and sometimes even small-scale hydroelectric generators, into the existing electrical grid infrastructure (Shahzad *et al.,* 2023). The system utilizes a combination of renewable energy technologies to maximize energy production and reliability while minimizing environmental impact. By harnessing the power of nature, these systems can generate electricity continuously, even during periods of low sunlight or wind. Moreover, surplus energy generated by the system can be fed back into the grid, providing clean power to surrounding communities and reducing dependence on fossil fuels. The flexibility and efficiency of on-grid hybrid renewable energy systems make them a promising solution for sustainable energy production in the face of climate change and increasing energy demands (Hassan *et al.,* 2023).

Integrating hybrid renewable energy systems into existing grids has been extensively researched to improve voltage profiles and overall grid performance. For example, Mouheb (2020) used Jpélec software to analyze data on such systems, finding a 10 % reduction in voltage drop and enhanced electrical quality during peak demand periods when PV systems were connected.

Similarly, Adel (2021) investigated the integration of a hybrid PV-wind turbine mini-power station into a rural LV network using PJ-elec software. This study highlighted the significant delivery of clean electricity and the potential of hybrid systems to support sustainable energy in remote areas. Their simulations showed less than a 10% reduction in voltage levels between 6 AM and 5 PM, demonstrating the effectiveness of hybrid renewable systems in improving grid stability and reliability, particularly in underserved regions.

Serem *et al.* (2021) found that integrating PV systems positively impacted grid stability, with multiple renewable sources slightly enhancing voltage levels. Ali *et al.* (2022) favored Double-Fed Induction Generators (DFIG) over Squirrel Cage Induction Generators (SCIG) for stability with renewable sources, noting that higher solar radiation improved solar generator output and the electrical system's voltage profile. Kumar (2018) MATLAB/SIMULINK study further emphasized better results with solar PV than wind, reinforcing the effectiveness of solar energy integration.

Following these findings, adopting an on-grid system, as suggested by Sharma (2022), is a strategic move. The integration of hybrid renewable energy systems offers multiple benefits, as demonstrated by the studies mentioned. In addition to improving voltage profiles and grid stability, these systems also contribute to environmental sustainability by reducing reliance on fossil fuels and lowering greenhouse gas emissions.

Moreover, the economic advantages of integrating renewable energy sources into the grid cannot be overlooked. By reducing energy losses and enhancing the efficiency of electricity delivery, hybrid systems can lower operational costs for utilities. Furthermore, the deployment of renewable energy technologies can stimulate local economies by creating jobs in manufacturing, installation, and maintenance sectors.

Another significant aspect is the increased energy security provided by hybrid renewable systems. By diversifying energy sources and incorporating locally available resources like solar and wind, communities can reduce their vulnerability to external energy supply disruptions. Thisis particularly crucial for remote and rural areas where traditional energy infrastructure may be lacking or unreliable.

As the demand for electricity continues to rise, especially with the growth of electric vehicles and smart technologies, the role of hybrid renewable energy systems in ensuring a stable and reliable power supply becomes even more critical. Policymakers and stakeholders should prioritize investments in these technologies to harness their full potential.

2.2.2 Components of Hybrid Renewable Energy System

(i) Solar photovoltaic systems

Solar PV energy systems comprise multiple components, each serving a distinct purpose. A basic PV-direct system consists of a solar module or array (comprising two or more modules connected) and the load it supplies energy to, which could be equipment consuming energy. Such a solar energy system produces direct current (Abdelkareem *et al.*, 2018).

The PV module and PV array

Most solar modules available in the market, including those utilized in residential and commercial solar setups, are silicon crystalline. These modules consist of multiple strings of solar cells wired in series (from positive to negative) and housed within an aluminum frame. Each solar cell can generate 0.5 volts; hence a 36-cell module is rated to produce 18 volts. Larger modules typically feature frames with 60 or 72 cells (Abdelkareem *et al.*, 2018). Figure 2 illustrates a schematic diagram depicting the connection of PV cells to create modules, as well as the connection of modules to form an array.

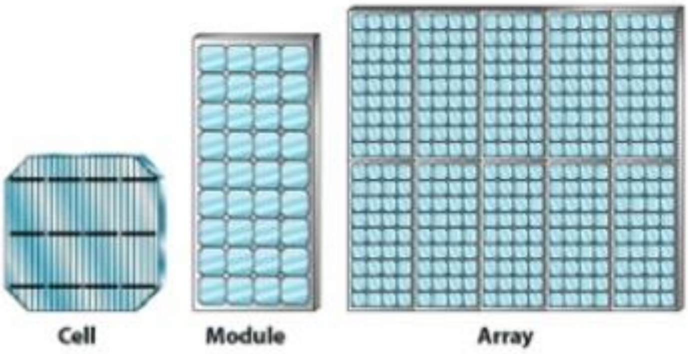

Figure 2: Relationship between solar cell, Module and Array (Abdelkareem *et al.*, 2018)

Equivalent electrical circuit and Characteristics of PV cell

Figure 3 depicts the electrical circuit representing typical characteristics of PV cells. The V-I curve demonstrates the parallel connection of solar-generated current, diode current, shunt resistance, and shunt-leakage current. These elements are also linked in series through the internal resistance that arises in the circuit during system operation.

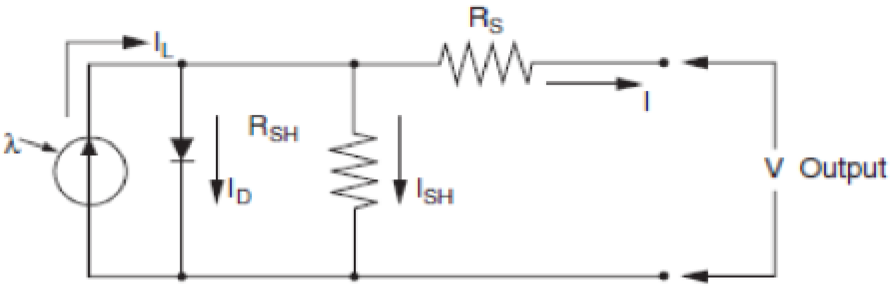

Figure 3: The equivalent electrical circuit of a PV module (Okello, 2015)

The various photovoltaic parameters represented in the equivalent circuit are denoted by the following mathematical expressions (Okello, 2015).

$$I = IL - Id - Ish \tag{1}$$

- I represent the PV output current (A),
- IL denotes the solar generated current (A),
- Id indicates the diode current (A),
- Ish represents the shunt-leakage current (A).

The efficiency of a PV panel's yield can be significantly diminished by even a minor alteration in the internal resistance developed within the cell. However, there is no variation in the output voltage for any change in the shunt resistance (Okello, 2015). Various mathematical expressions can be employed to compute the output current of the cell as follows.

$$I = D_L - I_O - \frac{V_{OC}}{R_{SH}} \tag{2}$$

During actual operation, the last term representing the shunt current is significantly smaller in comparison to the solar-generated and diode currents, making it possible to omit it. The open circuit voltage and the diode current are being determined as follows respectively.

$$V_{OC} = V + I.R_{SH} \tag{3}$$

$$I_D = I_O \, (e^{\frac{Q.V_D}{K.T}} e) - 1 \,) \tag{4}$$

Where Io represents the diode's reverse saturation current (A), Q denotes the charge of an electron (C), K signifies Boltzmann's constant (J/K), VD represents the diode voltage (V), T indicates the temperature of the cell junction point (K), and VOC denotes the open-circuit voltage of the cell (V). Similarly, determining the short-circuit current of the cell involves setting the open-circuit voltage to zero, resulted in the short-circuit and solar-generated currents retaining the same magnitude. The diode saturation current (Io) remains constant at a constant temperature (Patel, 2021) and its mathematical determination is expressed as follows.

$$Io = \frac{\boldsymbol{I_{SC}}}{(e^{Q.V_{OC}})} \tag{5}$$

If the short circuit current of the module is provided in the cell's datasheet, then the cell current at any solar irradiance can be determined accordingly.

$$I_{SC} = \left(\frac{G}{G_O}\right) I_{SC}, G0 \tag{6}$$

Where: Isc represents the short circuit current in ampere, G denotes the solar irradiance (W/m^2), Isc indicates the short circuit current at standard test in ampere and G0 represents the solar irradiance at standard test conditions (1000 W/m^2). The open circuit voltage can be determined by setting the output current to zero.

$$V_{OC} = \frac{AKT}{Q} log\,(\frac{I_L}{I_O} + 1) \tag{7}$$

The quality of a PV cell is evaluated through a parameter known as the fill factor. A high-quality PV cell typically exhibits higher values of short circuit current, open circuit voltage, and fill factor. The fill factor of a solar PV system is influenced by its design and the technology utilized in the panel. Any factor or damage that affects the fill factor will also impact the power output by reducing either the maximum current, maximum voltage or both simultaneously. The output power of a PV system can be calculated using the equation 8 (Wang, 2006).

$$Pmp = Imp * Vmp \tag{8}$$

$$FF = VoB * IscPmp \tag{9}$$

Where: Vmp: PV maximum potential voltage in volt, Imp: PV Panels’ maximum current in ampere, Pmp: PV panels maximum power in watt and FF is the fill factor.

Mathematical modeling

The mathematical modeling presents an alternative method for PV array design. It aims to optimize the power generation efficiency of solar PV systems. The outlined model below is utilized for determining the optimal attributes of power generation. By entering data such as incident solar radiation, local ambient temperature, and PV module specifications provided by manufacturers, the equations outlined below can calculate the PV power output (Diaf, 2007; Kaabeche, 2010).

$$Ppv = \eta * N * Am * G \tag{10}$$

Where Ppv represents the power output of the solar PV system (W), η denotes the generator efficiency (%). Am signifies the area of an individual module (m^2), Gt denotes the global radiation (W/m^2), and N stands for the number of modules integrated into the system. The equation illustrating the efficiency of the solar photovoltaic generator is as follows:

$$\eta g = \eta r * \eta pt[1 - \beta t(Tc - Tr)] \tag{11}$$

In this context, ηr signifies the reference efficiency (%), ηpt denotes the tracking system efficiency (%), Tc indicates the PV cell temperature (K), Tr stands for the PV cell reference temperature (K), and βt refers to the temperature coefficient efficiency, which fluctuates for silicon cells.

$$.T_C = Ta + Gt\left(\frac{\tau\alpha}{U1}\right) \tag{12}$$

$$\frac{\alpha\tau}{U1} = \frac{NOCT-20}{800} \tag{13}$$

In this scenario, Ta represents the site ambient temperature (K), Ul stands for overall heat loss (W/m^2), τ and α denote the photovoltaic transmittance and absorptance coefficients respectively. Additionally, ηpt, βt, NOCT, and Am is area parameters dependent on module type, which are obtained from solar module manufacturers.

(ii) Wind turbine

All renewable energy ultimately comes from the sun except geothermal and tidal energy. About 174.423 TWh of energy is emitted by the sun toward the earth. The amount of solar energy that is transformed into wind energy is approximately 1 to 2% (Murthy & Rahi, 2017). The wind is created by the air's natural flow across the sea or across the surface of the land. Winds are produced by the rotation of the earth and temperature differences brought on by the unequal heating and cooling of its surface. The heat received from the sun is absorbed by the land and water areas in varying amounts, as a result, warm air rises and cold air rushes to replace it and thus causing local winds. The most operationally and financially effective RES for electricity generation is wind power. The most effective and cost-effective source of energy is regarded as wind. It is widely accessible in nature, inexpensive, and evenly distributed. Therefore, the wind resources in the earth will not be exhausted, unlike oil wells and coal seams, which may eventually run dry. This resource, wind, is becoming a popular form of electricity generation and is a key component of many nations' long-term energy strategies (Murthy & Rahi, 2017).

Wind energy converters and control systems

An uneven force on the wind flow stream caused by a physical configuration causes it to rotate and oscillate, and this behavior can be used to generate power. Wind turbines are devices that use wind energy to power an electrical generator, hence producing electricity. Wind energy conversion systems utilize the kinetic energy present in wind captured by the turbine blades' swept area. This creates pressure variations across the blades, which in turn triggers the electrical generator to generate electricity. Components such as the turbine rotor control structure or yawing mechanism, tower, rotor, and nacelle comprise a wind turbine. Housed within the nacelle are the gearbox and electric generator, supported by the tower, a crucial element of the turbine. The yawing mechanism, integral to wind turbines, aligns the rotor with the wind flow to capture its kinetic energy. The torque generated by the turbine is transmitted to the gearbox, then to the electrical generator, where mechanical energy is converted into electricity (Manyama, 2018). Figure 4 illustrates the general structures of the two main types of wind turbines.

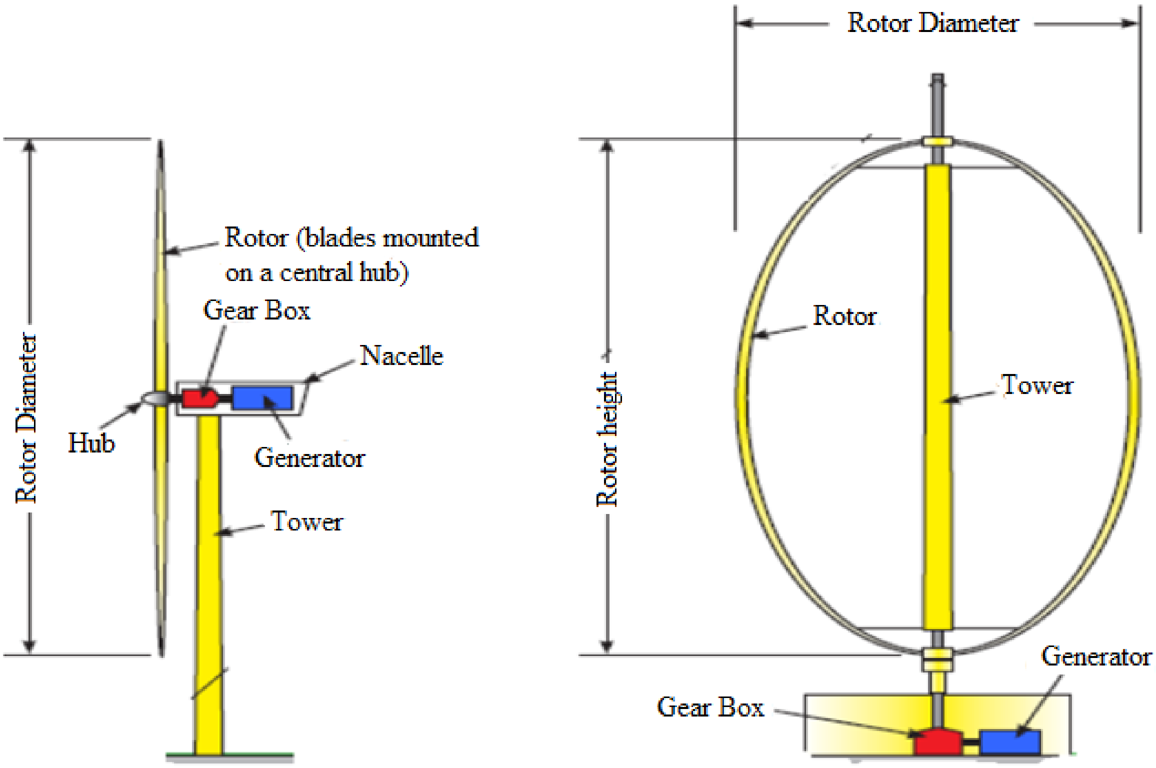

Figure 4: The design of a standard wind energy converter (Manyama, 2018)

When the wind speed surpasses the minimum threshold, known as the cut-in speed, wind turbines commence generating power. As the wind speed increases, the turbine's power output rises until it reaches its rated speed, maximizing power production. Beyond the cut-off wind speed, safety mechanisms prevent power generation to ensure turbine operation remains within safe limits. During periods of elevated wind speeds, the implementation of two over-speed or power control systems is essential to safeguard both the load and the turbine according to Murthy and Rahi (2017).

Classification of wind turbines

Wind turbine technologies can be broadly classified according to their utilization of aerodynamic lift and drag forces. Within this framework, turbines employing aerodynamic lift force can be further categorized into horizontal axis and vertical axis, such as Darrieus turbines, based on the configuration of their rotation axes. Horizontal axis wind turbines are characterized by a rotational axis aligned parallel to the direction of the wind. Typically, these turbines consist of a tower structure and a nacelle that houses the electrical generator, gearbox, and rotor. In smaller wind turbines, a tail vane is employed to align the nacelle and rotor with the wind, while larger turbines utilize a yaw system for electrical control. This mechanism allows for the adjustment of the nacelle and rotor either towards or away from the direction of the wind (Ackermann, 2012). Usually, these machines exhibit a low cut-in speed and a higher power coefficient. Depending on how they will be used, horizontal axis wind turbines are classified into single, double, three, and multi-bladed classes (Roy *et al.*, 2023). The classification of wind turbines according to several aspects is shown in Fig. 5.

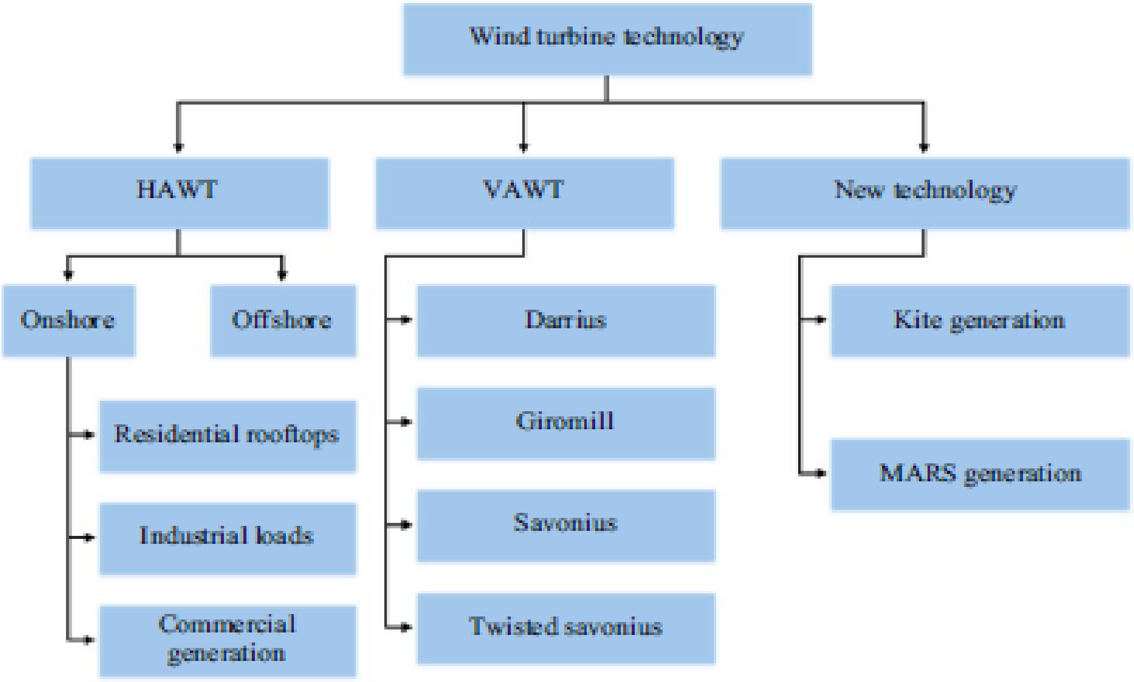

Figure 5: Classification of commonly used WT technologies (Murthy *et al.*, 2017)

The horizontal axis turbines with three blades are the most widely used for generating electrical energy (Sharma *et al.*, 2022; Wagner & Mathur, 2011).This is due to its stability, high power coefficient, easy curling, and low cut-in wind speed. Turbines with an even number of blades encounter stability challenges as the lower blade enters the wind shadow at the front of the tower while the uppermost one twists backward. Wind turbines with more than 20 blades are mainly used for pumping water rather than generating electricity due to increased aerodynamic losses (Anaya-Lara *et al.*, 2011).

(iii) Energy storage systems

The benefits of energy storage are substantial and have long been acknowledged as essential for the coordinated and dependable operation of utility grids. Energy storage plays a particularly crucial role in the integration of distributed renewable generation technologies (Zohuri, 2018). In a hybrid renewable energy system, the purpose of an energy storage device is to address the challenges posed by renewable resources. These resources are inherently intermittent, varying based on both temporal (daily and seasonal) and spatial (geographical) conditions (Potisomporn & Vogel, 2022). To manage this intermittency and uncertainty, a hybrid power system integrates variable energy sources, including conventional power generation, renewable energy generation, and energy storage. The necessity for battery energy storage becomes imperative to store surplus energy generated by renewable resources and provide it during periods of scarcity. Presently, numerous battery technologies are advancing, exhibiting improved characteristics compared to conventional battery systems, including efficiency, response time, deep cycle discharge, lifecycle, and more. In the previous decade, minimal attention was given to selecting the type of battery energy storage when constructing a grid-connected or off-grid system. Batteries can be evaluated based on factors such as price, cycling, replacement, and, importantly, safe disposal. Table 3 presents a technical comparison of three battery types: LA, LI, and FB. Table 3 provides a technical comparison of different battery types (Tharani & Dahiya, 2018). Following the comparison, the authors decide to utilize Lithium batteries for the unelectrified village area.

Table 3: Technical comparison of various types of batteries (Tharani & Dahiya, 2018)

Parameters	**Lead acid**	**Lithium**	**Flow battery**
Unit cell voltage (V)	2	3.7	1.8
Power density (W/L)	10-400	1500-10 000	< 25
Energy density (Wh/L)	50	200	35
Cycle life (cycles)	500-2000	1000-5000	> 10 000
Calendar life (years)	5-15	5-20	10-15
DoD (%)	70-80	80-90	100
Round trip efficiency (%)	85	92	75

(iv) Converter

The hybrid system comprises AC and DC components, necessitating inverters or converters to transform the power into a suitable and usable form. In instances where power generated from renewable energy systems is minimal, either the generator or the grid assumes the task of charging the batteries. Traditionally, grid-tied inverters and off-grid inverters are distinct, but technological advancements have led to their integration into a single unit when both are required. These bidirectional converters can operate as both inverters and rectifiers simultaneously. The selected inverter should ideally match the capacity of the peak load or be larger. However, given that this design incorporates both renewable and non-renewable power sources, an inverter with a capacity equal to the peak demand is chosen. Operational and maintenance costs for this equipment were disregarded, as they typically require minimal or no maintenance once installed (Fabian, 2019).

(v) Grid

The grid functions as both an auxiliary power source and a backup power supply. When power generation falls short of demand, electricity is drawn from the grid, while any excess power generated beyond the load demand is fed back into the grid through dual energy meters. It is an integral component of the schematic for hybrid power plants. Connecting to the grid eliminates the need for battery storage but necessitates a grid tie inverter (Khalil, 2021).

2.3 Application of HOMER Software in Optimizing Hybrid Energy Systems

HOMER, or Hybrid Optimization of Multiple Energy Resources, is leading software for optimizing hybrid energy systems. Developed by NREL USA in 1993, HOMER processes inputs like resource availability and technology options to create simulations. These simulations are ranked based on their NPC, helping identify feasible solutions. HOMER has been widely used in literature and case studies to optimize hybrid energy systems.

Li *et al.* (2022) used HOMER to compare the techno-economic performance of grid-integrated and off-grid hybrid systems in West China, combining solar PV, wind, biomass, and grid energy. Their study confirmed that the hybrid system was both reliable and cost-effective for rural electrification. Ali *et al.* (2024) examined an off-grid system for wetland areas in developing countries, using HOMER for optimization. They proposed a system with PV panels, wind turbines, diesel generators, and hydrokinetic turbines to meet the energy needs of three villages in Bangladesh.

Prum *et al.* (2024) analyzed hybrid energy systems for remote Asian communities, finding that a combination of PV, diesel, and batteries was most effective. This mix resulted in 89 % PV penetration, a cost of electricity of $0.257 per kWh, an initial capital cost of USD 244 277, and a net present cost of USD 476 216, with a 51 005 kg reduction in CO_2 emissions annually compared to a diesel-only system.

Ahmad *et al.* (2018) conducted a techno-economic analysis of a hybrid renewable energy system in Kallar Kahar, finding that the total cost for a peak load of 73.6 MW was 180.2 million USD, with a COE of USD 0.05744 per kWh. Similarly. Muh and Tabet (2019) evaluated hybrid systems for off-grid use in Southern Cameroons, finding that a PV/diesel/small hydro/battery system was the most economical, with a COE of USD 0.443 per kWh.

Jahangir *et al.* (2019) used HOMER to compare photovoltaic/thermal organic Rankine cycle systems with other hybrid systems in Rayen, Iran. They found that a PV, wind, diesel, and battery hybrid system was the most cost-effective, with a net cost of USD 268 592 and a COE of USD 0.197 per kWh. Al-Garni *et al.* (2018) focused on grid-connected photovoltaic systems, revealing that a two-axis tracker could produce 34% more power than a fixed system, while a vertical-axis tracker could generate up to 20% more power.

Mandal *et al.* (2018) assessed a hybrid system in northern Bangladesh using HOMER and found that the optimal setup included 73 kW of PV arrays, a 57 kW diesel generator, a 387 kWh battery bank, and 28 kW inverters. This configuration achieved a minimum COE of USD 0.37 per kWh and a net present cost of USD 357 284, with a 62% reduction in CO_2 emissions compared to kerosene and 67% compared to grid systems.

The HOMER remains a premier tool in hybrid energy system optimization due to its comprehensive approach and extensive use in various studies. For instance, Zebra *et al.* (2021) utilized HOMER to optimize a hybrid energy system for a remote island, incorporating solar PV, wind, diesel, and battery storage. Their findings highlighted the potential for significant cost savings and emissions reductions when adopting a hybrid system over a purely diesel-based one.

Similarly, Rajbongshi *et al.* (2017) optimized hybrid systems for rural electrification, highlighting that biomass gasification systems were more advantageous than photovoltaic systems. Their study found a COE of USD 0.145 per kWh for an off-grid system and USD 0.91 per kWh for a grid-connected system. Zebra *et al.* (2021) reviewed off-grid hybrid systems in developing countries, noting that success depends on government support and community organization. Their analysis showed diesel systems had the highest COE (USD 0.92 to USD 1.30 per kWh), while solar PV systems ranged from USD 0.40 to USD 0.61 per kWh, and hybrid solar PV/diesel systems ranged from USD 0.54 to USD 0.77 per kWh.

Inconsistent load data and sensitivity analysis were common issues in the literature. Many studies used limited data or only a single year of load data, affecting future projections. This study improves accuracy by collecting and forecasting six years of load data up to 2030. It also addresses sensitivity analysis by evaluating how changes in system parameters impact future outcomes. The nominal discount rate, crucial for calculating NPC, varies by country. For example, Tanzania's discount rate was 7% in 2018 and decreased to 5% in 2022. This study incorporates such scenarios and aims to improve voltage profiles in high-voltage transmission lines using renewable sources in Tumbatu Island, with HOMER Pro for analysis.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted on Tumbatu Island, located within the Zanzibar archipelago. Tumbatu Island characterized by its remote location and limited access to conventional energy infrastructure, presents a compelling case for exploring sustainable energy solutions. With a focus on enhancing HV line (grid)-connected hybrid renewable energy systems, the study examines the island's renewable energy potential, including solar irradiance, wind speed, and existing electric load. By leveraging HOMER Pro's simulation capabilities, the research aims to propose an optimal energy solution that enhances energy reliability, reduces dependency on fossil fuels, and fosters socio-economic development on Tumbatu Island. The Island is located at northwest of Unguja Island, it has an area of about 7 miles long and 5 miles wide (Sheha, 2007). The Island has a geographical location of latitude: 5°49.1’S and longitude: 39°13.4’E with a time zone of GMT+3:00. Figure 6 depicts the map for Tumbatu Island.

Figure 6: Location of Tumbatu Island

3.2 Renewable Energy Resources

In this study, renewable energy sources (solar and wind) are focal points for the development of sustainable energy solutions on Tumbatu Island. The methodology involves a multifaceted approach that begins with a thorough assessment of the island's solar irradiance and wind speed patterns to gauge the feasibility and potential of harnessing these resources. Solar PV panels are identified as a primary renewable energy technology, given Tumbatu Island's ample sunlight exposure throughout the year. Additionally, wind turbines are evaluated for their suitability in capturing the island's wind energy resources, especially when solar generation is limited. Through detailed modeling and simulation using HOMER Pro, optimal configurations of hybrid renewable energy systems comprising solar and wind components are explored. This approach ensures that the energy needs of Tumbatu Island are met reliably and sustainably, while also reducing reliance on fossil fuels and mitigating environmental impact.

3.3 Hybrid Components

In this section, a hybrid energy system, incorporating HV line from the utility grid, solar cells, a wind turbine, a battery bank, a bidirectional converter, and DC and AC buses were designed as illustrated in Fig. 7.

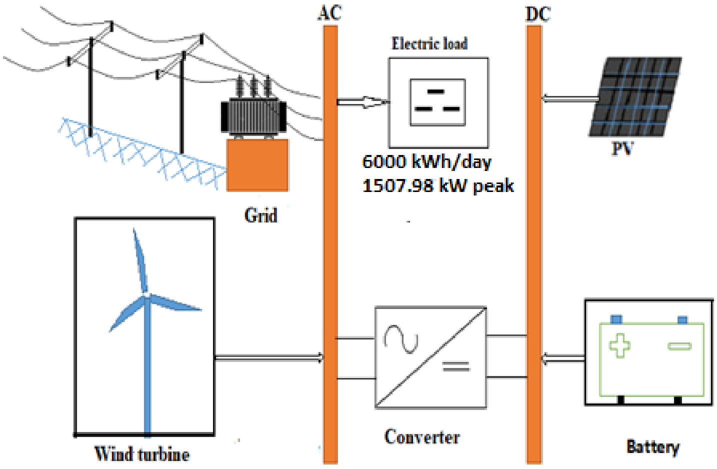

Figure 7: Schematic design of designed hybrid renewable energy system

3.4 Economics of the Proposed Hybrid System

The economics of the proposed hybrid system include operational, maintenance, capital, and the replacement cost value of solar panels, wind turbines, batteries, bidirectional converters, grid, and electrical load. Several factors, like labor costs, land costs, etc., have been considered in the designing of a complete hybrid renewable energy system. The following subsections discuss in detail the economics of the hybrid components, which are summarized in Table 4.

3.4.1 Size and Cost of Solar PV

A generic flat-plate solar PV with an efficiency of 17.3% has been used to generate electricity from solar energy. The solar panel under consideration had a capacity of 1 kW, comprising four solar modules each with a capacity of 250 W. Their inexpensive delivery and excellent output efficiency played a significant role in the choice to incorporate these goods into the design. The HOMER Pro will estimate the system's energy production with greater precision, leading to more reliable results. In this study, estimated PV cost of USD 883 per kW (IRENA, 2021) was considered. The replacement cost was set at 60% of the PV price after a 25-year service life in this study, as proposed by Manyama (2018). As suggested by Xu (2020), an annual operation and maintenance cost of 1% per year was also adopted.

3.4.2 Size and Cost of Wind Turbine

The turbine needs to generate a substantial amount of energy depending on wind speed sources to make a significant contribution to renewable energy. This can be achieved either through a single large wind turbine or multiple smaller ones. Factors such as the number of turbines, maintenance duration, hub height, component costs, type of electricity produced, and the cut-in wind speed are critical in choosing the appropriate wind turbine. The selected turbines are capable of generating AC electricity to fulfill the AC power needs of consumers. A Generic wind turbine with rated capacity of 3 kW has been selected to convert wind energy to electrical energy for the proposed hybrid energy system as proposed by Topham (2017). The criteria of selecting this model of wind turbine are due to turbine Efficiency and good power curve that it can efficiently convert wind energy into electrical energy across a range of wind speeds. The global estimated cost is around USD 1355 per kW of wind turbine (IRENA, 2021). The operation and maintenance costs of a wind turbine has been estimated to be 2% of its initial capital cost as adopted from Duman (2018) and Nsafon *et al.* (2020), while replacement cost is taken as 70% of capital cost as proposed by Smith (2015).

3.4.3 Cost and Size of Batteries

To determine the suitable size of the battery bank for the Hybrid Energy System, a thorough analysis is necessary. This analysis involves a detailed assessment of the battery's charging and discharging modes, considering factors like the load profile and the output energy from the renewable energy sources (Suresh & Meenakumari, 2021). Like other components in the power system, the software requires input parameters such as the cost and quantity of batteries. It's essential to understand the following definitions: the rated or nominal capacity of the battery indicates the amount of energy it can discharge. The minimum state of charge of batteries represents the level below which the battery should never be discharged to avoid damage, typically recommended to be within a range of 30-50%. Round-trip battery efficiency refers to the energy flow into the battery that can later be extracted for use. Lifetime throughput denotes the total energy circulated through the battery during its lifespan.

One unique advantage of lithium batteries over other types is their high energy density. Compared to traditional battery chemistries like lead-acid or nickel-cadmium, lithium batteries can store significantly more energy per unit volume or weight. This makes them ideal for applications where space and weight are critical factors, such as in portable electronics, electric vehicles, and aerospace technologies. Additionally, lithium batteries offer excellent charge retention when not in use, with lower self-discharge rates compared to other types of batteries. This means they can hold their charge for longer periods, making them suitable for devices that may be used intermittently or stored for extended periods between uses. Moreover, lithium batteries typically have longer cycle life, allowing them to endure a larger number of charge-discharge cycles before experiencing significant degradation. This longevity makes them cost-effective over the long term, especially in applications where frequent cycling is required, such as in renewable energy storage systems or electric vehicles. Furthermore, lithium batteries usually have faster charging times compared to other battery chemistries, enabling quick recharging for devices or vehicles, thus improving overall efficiency and convenience.

According to adoption from Kashem and Arefin (2017), the energy from the PV panel is stored in this study utilizing a Surrette S-260 storage device, which can offer energy retained at a nominal voltage of 12 V. The selected battery has a capacity of 3.123 kWh, 83.4 Ah with maximum charge current of 16.7 A and minimum discharge current of 24.3A. According to Mongird *et al.* (2019), lithium-ion batteries costed $271/kWh in 2018 and shall vary to USD 189/kWh in 2025. Based on the provided data, the installation cost for the battery stands at

USD 256 per kWh with a battery capacity of 3.123 kWh. Additionally, each battery replacement incurs a fixed cost of USD 560, while O & M require an USD 8 per battery.

3.4.4 Size and Cost of Power Converters

A bidirectional converter has been adopted to convert DC power to AC power or vice versa because the solar PV and battery bank generate DC power while the load operates in AC mode. Despite the load being sourced from both the grid and RES, the inverter's rated power would be installed below, equal to, or exceeding the peak load. The current study takes into account a 1 kW bi-directional converter with a 95% efficiency as adopted by Das (2020). The converter's capital cost is $800, the replacement cost is USD 560, or 70% of the capital cost, O & M cost is taken as USD 8 as proposed by Manyama (2018).

3.4.5 Cost of Electricity (COE)

In this study, the grid plays a vital role as an electrical backup and acts as an absorber when electricity is generated by renewable sources. The main objective of utilizing the grid as an electrical backup is to ensure a dependable and consistent supply of electricity, especially when the quantity of electricity produced from renewable sources is insufficient to meet the demand of consumers. This insufficiency can be caused by various factors, such as irregular power generation from renewable sources or unexpected fluctuations in energy production. To bridge the gap between supply and demand, electricity is procured from the grid. This allows for the continuous fulfillment of consumers' electricity needs, even during periods when RES are unable to generate the desired amount. By integrating the grid as a reliable backup, the study aims to provide uninterrupted power supply and improve the overall stability and reliability of the electricity system. Zanzibar Electricity Corporation (ZECO) estimates that the cost of grid power is USD 0.114 per kWh, while the cost of returning power to the grid is USD 0.05 per kWh. Table 8 provides a summary of the technical details and assumed parameters used in the study.

3.5 Constraints

The minimum renewable fraction of 40% was set to ensure a significant proportion of the energy produced originates from renewable sources, aligning with the goal of promoting sustainability and reducing greenhouse gas emissions. By mandating a substantial portion of renewable energy in the energy mix, the study aims to drive the transition towards cleaner and more environmentally friendly power generation. Simultaneously, the maximum annual capacity shortage of 10% was imposed to enhance grid reliability and stability. By limiting the capacity shortage to this threshold, the study seeks to mitigate the risk of power shortages and disruptions, thus safeguarding the energy supply and avoiding adverse impacts on consumers, industries, and critical services.

3.6 Hybrid Optimization of Multiple Energy Resources Simulation

Hybrid Optimization of Multiple Energy (HOMER) simulation serves as a pivotal methodology for designing and analyzing a grid-connected hybrid renewable energy system tailored to the specific needs and constraints of Tumbatu Island. The simulation process involves inputting data such as energy demand profiles, solar irradiance, wind speed, size of battery, size of converter and economic parameters into the HOMER Pro software. The HOMER Pro micro grid analysis tool was utilized to assess the most economically viable option of hybrid energy sources in this study. It simulates, optimizes, and sensitizes various parameters inputted during the design process. The software requires a computer for execution. Specifically, HOMER Pro version 3.14.2 was employed in conjunction with an HP Intel Laptop computer equipped with an 8GB processor and 64-bit architecture. The complete methodology is explained below in steps and summarized in Fig. 8.

Step 1: Designing Hybrid Optimization Model using HOMER Pro.

Step 2: Perform simulation and optimization using HOMER Pro.

Step 3: Analysis of voltage profile using optimized results from HOMER Pro.

Step 4: Perform Techno-economic and Sensitivity analysis using HOMER Pro.

Step 5: Results, Discussion, Conclusion and Recommendations of the work.

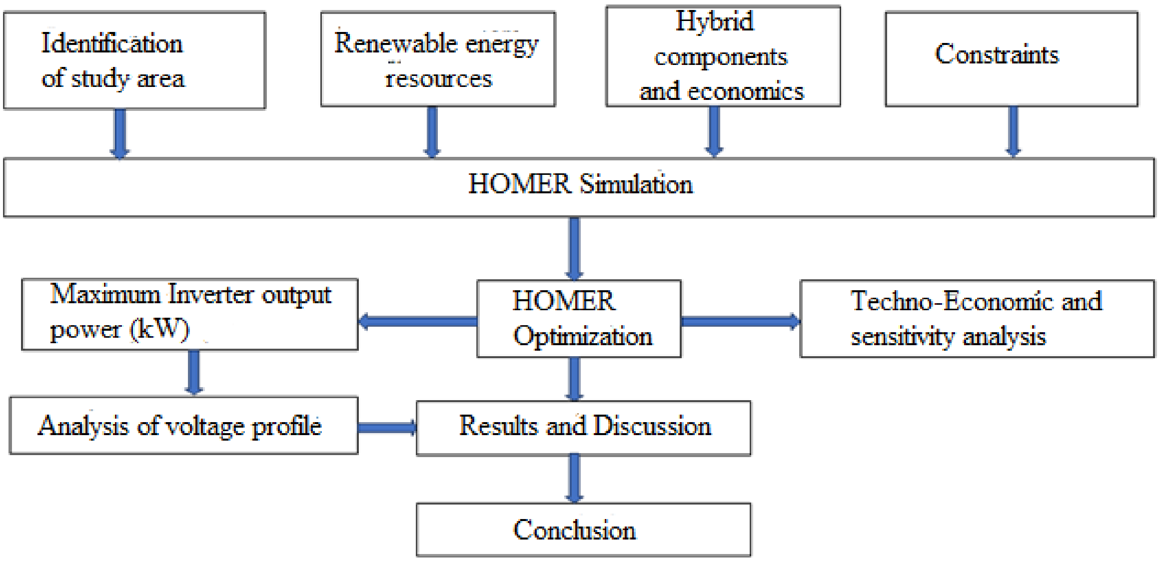

Figure 8: **Summary of the methodology**

Table 4: **Specification of system components**

Component	Size	Capital cost (USD)	Replacement cost (USD)	O&M cost (USD)	Life Time (year)
Solar PV	1 kW	883	529.8	8.83	25
Wind Turbine	3 kW	4065	2844.5	81.3	20
Battery	3.123 kWh	800	560	8.0	4
Converter	1 kW	800	560	8.0	15

3.7 Key Assumption

In this section, the key assumptions underlying the research methodology and analysis are outlined, providing insights into the foundational principles and considerations guiding the study. These assumptions serve as fundamental premises upon which the research framework is built, influencing various aspects of project planning, data interpretation, and decision-making processes. The assumptions made in this study are listed while the technical parameters are shown in Table 5.

(i) The inflation rate for all costs remains constant throughout the project's lifespan. Forecasting inflation rates can be complex and uncertain over long periods. Assuming a constant inflation rate simplifies financial projections and makes the analysis more straightforward.

(ii) Data from the TMA and NASA meteorology database are deemed sufficiently accurate for estimating PV and wind systems.

(iii) The estimated deferred load is considered accurate. Pricing strategies or investment planning can be influenced by the estimated deferred loads. Assuming accuracy aids in making informed decisions.

(iv) The mean annual variations in solar irradiation and wind speeds throughout the project's lifespan remain consistent. The design and sizing of solar panels, wind turbines, and other related equipment are based on expected average conditions over the project's lifespan. Assuming consistent annual variations in solar irradiation and wind speed helps in determining the appropriate capacity and configuration to maximize energy production efficiency.

Table 5: Different technical details and assumptions parameters used in the study

Parameters	Value
System Lifetime (Year)	25
Annual Discount Rate (%)	5
Homer pro software version	3.14.2
Minimum Renewable Fraction (%)	40
Maximum annual capacity shortage (%)	10
Simulation time step (minutes)	60
Load factor	0.17
Random variability of load day to day (%)	10
Random variability of load time step to time step (%)	20
Currency	USD
Cost of electricity ($)	0.114
Cost of returning power to the grid ($)	0.05
Operating system type (bits)	64
Processor (GHz)	1.99
Random Access Memory (RAM) (GB)	8.0
hp, Intel Laptop (piece)	1
Core	i7
Generation	8

3.8 Sensitivity Analysis

In the sensitivity analysis, various optimizations are carried out using different inputs to assess the impact of uncontrollable variables like solar radiation and wind speed (Bastholm, 2018; Lau *et al.,* 2018). This analysis helps understand how optimization results vary with changes in input variables (Koo *et al.,* 2020). It is a vital technique used in fields such as engineering, economics, and environmental science to evaluate how changes in input parameters affect model or system outputs (Saltelli *et al.*, 2019). Sensitivity analysis systematically varies one or more input variables while keeping others constant to gauge the model's or system's sensitivity to these changes. This approach allows researchers to identify which parameters most significantly influence outcomes, offering insights into the model’s robustness, reliability, and uncertainty. Consequently, stakeholders can make better-informed decisions by understanding potential scenario impacts and uncertainties. Sensitivity analysis is especially useful in complex systems like renewable energy projects, where factors such as resource availability, technology costs, and policy dynamics impact outcomes. Conducting this analysis improves understanding of key drivers and risks, enhancing project planning, risk management, and decision-making.

In this study, a thorough sensitivity analysis was conducted to examine how various sensitive variables affect the cost parameters of the HRES. Table 6 outlines the evaluated sensitive parameters and their values. Wind speeds of 6.24 m/s, 6.5 m/s, and 7 m/s were considered, reflecting typical conditions for the study area. Specifically, 6.24 m/s represents lower-than-average wind speeds within the operational range for Tumbatu Island, 6.5 m/s is an average value, and 7 m/s signifies higher-than-average wind conditions, all within safe operational limits.

Solar radiation parameters included 5.57 kWh/m^2/day, 5.8 kWh/m^2/day, 6 kWh/m^2/day and 6.6 kWh/m^2/day, covering a range from lower to higher levels. 5.57 kWh/m^2/day represents lower solar radiation, while 5.8 kWh/m^2/day is an average level. The 6 kWh/m^2/day parameter indicates slightly better conditions, and 6.6 kWh/m^2/day reflects higher solar radiation typical of clear or summer conditions.

The analysis also considered annual average electric loads of 6000 kWh, 9000 kWh, 10 000 kWh, and 11 000 kWh. The base load is set at 6000 kWh. A 9000 kWh load represents minimal load scenarios, 10 000 kWh is a mid-range value, and 11 000 kWh indicates higher load conditions. Additionally, nominal discount rates of 5% and 4% were evaluated. In Tanzania, the standard discount rate is 5% and a 4% rate was chosen to assess the impact of a 1% decrease.

This comprehensive sensitivity analysis allows for a detailed examination of how varying wind speeds, solar radiation levels, electric loads, and discount rates influence the cost parameters of the HRES. By analyzing these variables, the study provides valuable insights into how changes in these factors affect system performance and cost efficiency, aiding in better decision-making and risk management for renewable energy projects.

Table 6: Various sensitivity variables with various values

Parameter	**Wind**	**Solar**	**Load**	**Nominal Discount Rate**
Sensitivity Parameter	**Speed (m/s)**	**Radiation (kWh/m²/day)**	**Scaled Annual Average Electric Load (kWh)**	**Percentage of Discount Rate (%)**
Values	6.24	5.57	6000	5%
	6.5	5.8	9000	4%
	7	6.0	10 000	-
	-	6.6	11 000	-

3.8.1 Techno-economic Analysis

A techno-economic analysis is a tool for determining the economic effectiveness of a process, product, or service (Mahmud, 2021; Zimmermann, 2020). In general, the profitability of a project is determined by analyzing economic indicators such as NPC, COE and PB. These economic indicators, which are crucial decision-making tools (Veilleux, 2020), for investors, governments, and donors, were analyzed in the current study.

(i) Total Net Present Cost (TNPC)

The TNPC of a system refers to the present value of all expenses incurred throughout the system's lifespan subtracted from the present value of all revenues generated over the same period (Beza, 2021). Costs include capital costs, replacement costs, O and M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Salvage value and grid sales revenue are included. The HOMER calculates the total NPC by summing the total discounted cash flows in each year of the project lifetime using Equation 14.

$$NPC = CF_0 + \left\{\frac{CF_1}{(1+i)^1} + \frac{CF_2}{(1+i)^2} + \frac{CF_3}{(1+i)^3} + \cdots + \frac{CF_N}{(1+i)^N}\right\}$$

$$NPC = CF0 + \sum_{i=1}^{N} \frac{CF_1}{(i+i)^i} \quad (14)$$

Where CF_0 is initial capital cost in USD, CF_t is the cash flow of t-year in USD, t is the number of years, i is the annual real interest rate in % and N is project duration in years.

(ii) Cost of electricity (COE)

The Homer software defines the COE as the system's average cost per kWh of useful electrical energy generate (Vendoti, 2021). It is determined by dividing the total annualized cost (TAC) by the total annualized useful electrical energy generated, as illustrated in Equation 15.

$$\text{COE}=\frac{\text{TAC}}{\text{E}_{\text{Served}}} = \frac{\text{Total Annualised Cost}\left(\frac{\$}{\text{year}}\right)}{\text{Annual Load Served (kWh /year))}} \quad (15)$$

$$\text{Total Annualised Cost (TAC)} = \text{NPC} \times \text{CRF} \quad (16)$$

$$\text{Annual Load Served}(\text{E}_{\text{served}}) = \text{E}_{\text{primary}} + \text{D}_{\text{efferer}} + \text{E}_{\text{grid,sales}} \quad (17)$$

Where: TAC is the annualized value of the NPC in USD/year, E_{served} is the total electrical load served (primary load, deferred load, and energy sales to the grid) in kWh/year, CRF is the capital recovery factor, i is the real interest rate (%) and N is the project lifetime (years).

(iii) PB

The duration required to recoup the investment made in the installation of a plant is termed as the PB (Anbazhagan *et al.*, 2023). The payback is an indication of how long it would take to repay the difference in investment costs between the optimized and basic case systems (Fabian, 2019; Riayatsyah, 2022) as presented in Equation 18.

$$\text{PB} = \frac{InitialInvestment}{Cashflowperperiod} \quad (18)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Analysis of Electrical Load

Electricity consumption data from Zanzibar Electricity Corporation (ZECO) for the years 2016 to 2021 were collected for analysis as depicted in Appendix 3. Using a linear forecast function in Microsoft Excel, the data was projected into the future and the detailed results can be seen in Table 7. Given that the load on Tumbatu Island is primarily residential, the daily load demand can be categorized into three parts: low, medium, and high consumption. The low consumption represents approximately 2%, 3%, and 4% of the total daily demand, the medium consumption covers around 5% to 6% of the total daily demand, and the high consumption constitutes approximately 10%, 13%, and 15 % of the total daily demand. These percentages are based on the findings proposed by Alayan (2016) and Kashem and Arefin (2017). In the context of a power system, a load profile or load curve is a graphical depiction that illustrates the variations in electrical demand or load throughout a designated period (Suresh *et al.*, 2022). The load profile for Tumbatu Island is found in Fig. 9.

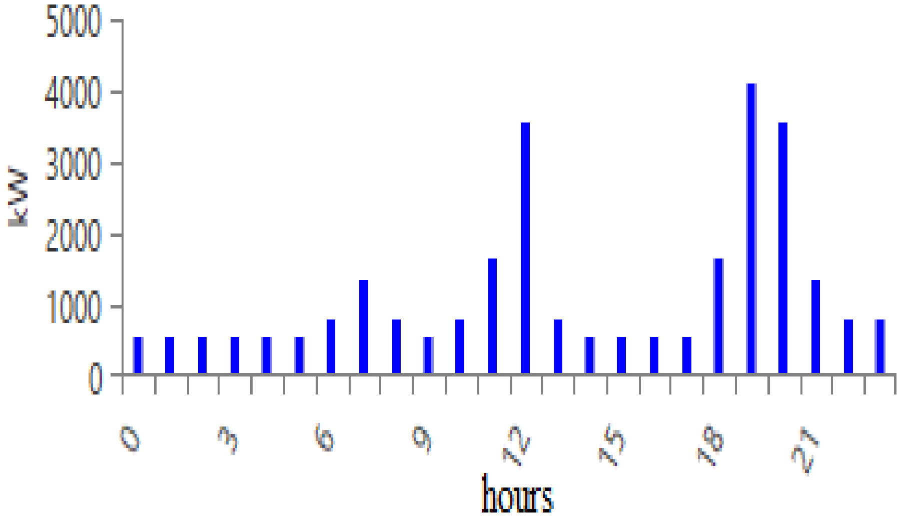

Figure 9: **Daily load profile forecast for 2030**

4.2 Analysis of Renewable Energy Resources

Figures 10 and 11 provide a comprehensive analysis of solar radiation, clearness index, and wind data for Tumbatu Island, crucial components in understanding the renewable energy potential of the region. Solar radiation data, sourced from the Tanzania Meteorological Authority (TMA), offers insights into the intensity and variability of solar irradiance throughout the year. By examining this data, patterns in solar availability can be discerned, aiding in the design and optimization of solar photovoltaic systems. The clearness index, derived from solar radiation data, provides further granularity by indicating the atmospheric conditions affecting solar energy generation, such as cloud cover and air pollution. Meanwhile, wind data sourced from the NASA within the HOMER software offer valuable information on wind speed, essential for assessing the feasibility of wind energy projects on Tumbatu Island.

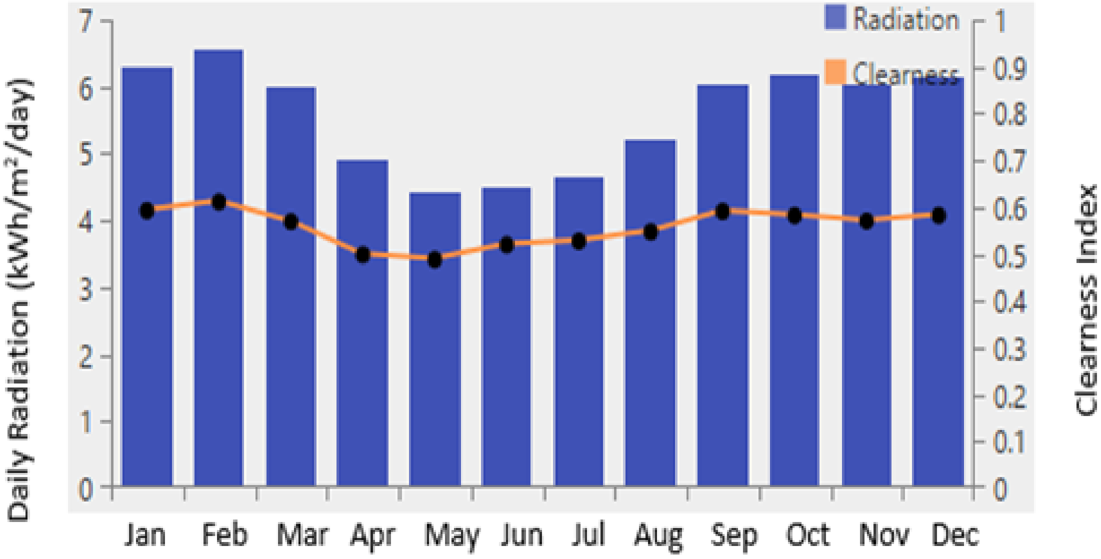

Figure 10: Average solar radiation (TMA, 2022)

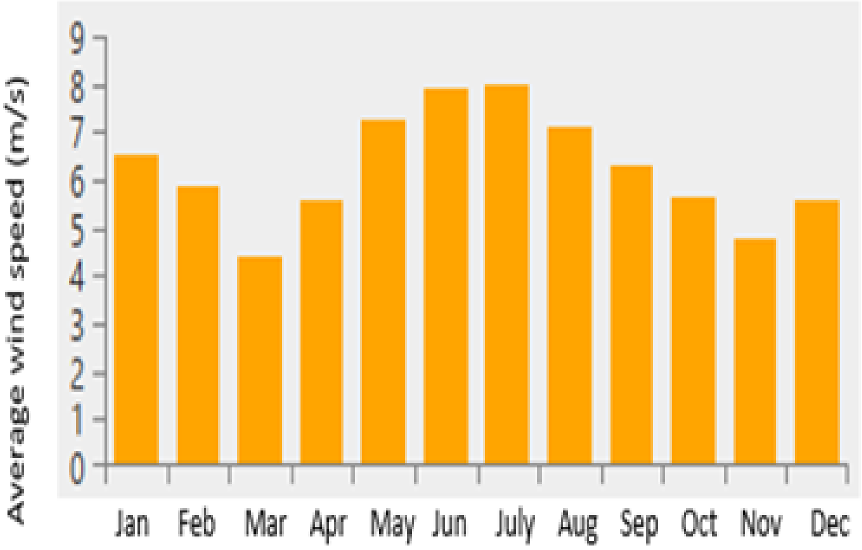

Figure 11: Average wind speed (NASA)

4.3 Simulation and Optimization of Various Hybrid Energy Systems

Total of 7208 solutions were simulated by HOMER Pro, of which 1536 were feasible. The HOMER then optimized the possible options and ranked them into the top six solutions, which are shown in Table 8. The results obtained from Table 8 indicate that Configuration A is the most favorable choice among the analyzed hybrid renewable energy setups. Configuration A, which includes PV, wind, and grid components, stands out due to its highly competitive NPC of USD 4 003 851 making it a cost-effective solution. Furthermore, Configuration A boasts a short PB of 3.79 years, indicating a quick return on the initial investment. Although its COE is slightly higher at USD 0.09 per kWh compared to Configuration B, the overall balance of cost-effectiveness and a swift payback establishes Configuration A as the optimal choice. The inclusion of both PV and wind sources, along with grid connectivity, ensures a reliable and consistent energy supply. Decision-makers can utilize these findings to prioritize Configuration A when seeking an economically efficient and promptly rewarding hybrid renewable energy solution. While Configuration A emerges as the best choice among the analyzed hybrid renewable energy setups, Configuration B, consisting solely of PV panels with grid connectivity, also presents notable attributes. With a NPC of USD 4 005 868 and a slightly longer PB of 4.88 years, Configuration B represents a competitive option. The absence of wind or battery components simplifies the system design, which may be appealing in scenarios where simplicity and reduced upfront investment are prioritized.

Table 7: Tumbatu hourly load demand forecast (kW) for 2030

Month		**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
		Daily load (kWh)											
Hours	**Variation of Hourly electricity consumption**	**27499**	**28202**	**27903**	**24036**	**26949**	**27248**	**27015**	**28395**	**28687**	**27786**	**28617**	**30145**
0	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
1	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
2	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
3	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
4	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
5	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
6	3.00%	824.97	846.06	837.09	721.08	808.47	817.44	810.45	851.85	860.61	833.58	858.51	904.35
7	5.00%	1374.95	1410.1	1395.15	1201.8	1347.45	1362.4	1350.75	1419.75	1434.35	1389.3	1430.85	1507.25
8	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
9	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
10	3.00%	824.97	846.06	837.09	721.08	808.47	817.44	810.45	851.85	860.61	833.58	858.51	904.35
11	3.00%	824.97	846.06	837.09	721.08	808.47	817.44	810.45	851.85	860.61	833.58	858.51	904.35
12	6.00%	1649.94	1692.12	1674.18	1442.16	1616.94	1634.88	1620.9	1703.7	1721.22	1667.16	1717.02	1808.7
13	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
14	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
15	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
16	2.00%	549.98	564.04	558.06	480.72	538.98	544.96	540.3	567.9	573.74	555.72	572.34	602.9
17	4.00%	1099.96	1128.08	1116.12	961.44	1077.96	1089.92	1080.6	1135.8	1147.48	1111.44	1144.68	1205.8
18	6.00%	1649.94	1692.12	1674.18	1442.16	1616.94	1634.88	1620.9	1703.7	1721.22	1667.16	1717.02	1808.7
19	10.00%	2749.9	2820.2	2790.3	2403.6	2694.9	2724.8	2701/.5	2839.5	2868.7	2778.6	2861.7	3014.5
20	13.00%	3574.87	3666.26	3627,39	3124.68	3503.37	3542.24	3511.95	3691.35	3729.31	3612.18	3720.21	3918.85
21	15.00%	4124.85	4230.3	4185.45	3605.4	4042.35	4087.2	4052.25	4259.25	4303.05	4167.9	4292.55	4521.75
22	5.00%	1374.95	1410.1	1395.15	1201.8	1347.45	1362.4	1350.75	1419.75	1434.35	1389.3	1430.85	1507.25
23	3%	824.97	846.06	837.09	721.08	808.47	817.44	810.45	851.85	860.61	833.58	858.51	904.35

Table 8: Optimization results

		Sizes of various components					NPC ($)	COE ($)	PB (Year)
		PV (kW)	**WT (Quantity)**	**CONVERTER (kW)**	**BATTERY (kW)**	**GRID**			
A	PV/WIND/GRID	685	10	376	-	ON	4 003 851	0.09	3.79
B	PV/GRID	750	-	424	-	ON	4 005 868	0.088	4.88
C	PV/WIND/BATTERY/GRID	731	5	392	1	ON	4 007 771	0.089	4.52
D	PV/BATTERY/GRID	743	-	409	17	ON	4 028 774	0.089	4.2
E	WIND/GRID	-	200	-	-	ON	4 491 925	0.091	n/a
F	WIND/BATTERY/GRID		200	12	17	ON	4 529 434	0.092	n/a

Table 9: **Simulation results**

Month	Energy Purchased (kWh	Energy Sold (kWh)	Net Energy Purchased (kWh)	Inverter output power per day(kW)		
				Case 1	Case 2	Case 3
January	126 540	34 931	91 609	376.03	200.00	194.00
February	113 774	33 355	80 419	368.12	195.53	191.42
March	135 314	30 776	104 539	373.44	198.88	192.80
April	107 119	29 114	78 005	373.00	197.32	192.20
May	123 863	25 088	98 775	372.00	196.74	191.77
June	123 910	24 020	99 890	364.71	195.00	188.00
July	124 540	27 049	97 491	367.23	196.40	189.50
August	136 937	27 570	109 367	372.83	196.21	190.63
September	130 550	31 211	99 340	373.00	196.00	190.33
October	122 927	34 184	88 743	375.58	198.90	190.00
November	131 118	30 005	101 113	372.37	195.30	191.32
December	141 093	29 861	111 233	374.80	198.00	193.88
Annual	**1 517 686**	**357 163**	**1 160 522**	**4463.11**	**2 364.28**	**2 295.85**

4.4 Analysis of Voltage Profile

The stability of the electric grid plays a crucial role in effectively incorporating renewable energy systems. This section focuses on verifying and analyzing the voltage profile in a grid-connected HRES. Three different scenarios (Case 1, Case 2, and Case 3) are investigated, with each case representing different ranges of inverter output power. Validation of the results was conducted using three different cases. In Case 1, the inverter output power ranged from 376.03 kW to 364.7 kW. In Case 2, the power varied from 200 kW to 194 kW. Case 3 had a power range of 193 kW to 188 kW, as indicated in Table 9. The inverter capacity of 376 kW was presented in Table 8, and the number of inverters per phase was calculated using Equation 19. Detailed specifications of the inverters can be found in Appendix 1.

$$\text{Inverters per phase} = \frac{Invertercapacity}{3 \times Inverterrating} = \frac{376}{3 \times 25} = 5 \text{ Inverters per phase} \qquad (19)$$

$$Currentperphase(I_P) = NumberofInverterperphase \times Maximumcurrent \qquad (20)$$

Total power in three phase balanced load is demonstrated in Equation 21 (Abdulganiyu, 2017).

$$\mathrm{P} = 3I_pV_p\mathrm{Cos}\,\theta \qquad (21)$$

Where: P is the power per phase, Ip is the phase current, Vpis the phase voltage and cosθ is the power factor = 0.8. Equation 8 was employed to derive the output voltage profile of renewable energy sources pre-integration into the grid, as presented in Tables 10 -12. Upon integration of PV and wind on the LV side of the transformer, the transformer characteristic transitions from step-down to step-up. The elevated voltage on the HV side is computed using the transformer ratio in Equation 21, yielding results shown in Tables 10 – 12.

$$\frac{N_H}{N_L} = \frac{V_H}{V_L} = k \qquad (22)$$

Where: N_H and N_L are the number of turns of high voltage and low voltage side respectively

V_H and V_L are the phase voltage at high voltage and low voltage side respectively obtained in Table 13. The standard voltage in Tanzania is 230 volts, alternating at 50 cycles (Hertz) per second (Mnyanghwalo *et al.,* 2020), this is the same as or similar to most countries throughout the world. The HV is calculated using Equation 24, and the results are displayed in Tables 10-12. The inverter ensures that the grid receives the standard voltage, even in cases where the voltage is higher. The voltage from solar PV and wind turbine will be synchronized at a common bus bar (230 V). Due to the high potential of the voltage generated by solar PV, it will be fed back into the grid, as depicted in Tables 10-12.

$$V_E = V_I k \qquad (23)$$

Where: V_I is the Inverter output voltage and V_E is the elevated voltage on the HV side of the transformer.

Table 10 provides a comprehensive summary of the voltage profile of the proposed renewable energy system on Tumbatu Island for Case 1, while Figs. 12 and 13 depict the voltage profile of renewable energy both before and after integration with the grid on the LV side, respectively. Table 10 reveals the variations in combined output voltage from renewable energy sources observed across different months, ranging from 0.844 kV in June to 0.870 kV in January. Additionally, the feeding voltage on Tumbatu Island remains stable at 0.23 kV. Fluctuations in the remaining voltage after feeding, ranging from 0.626 kV to 0.655 kV, indicate dynamic changes occurring within the local grid. The voltage from the inverter to the low-voltage side remains constant at 0.23 kV, ensuring a reliable conversion process. Furthermore, the stepped-up voltage to the high-voltage side improved to 31.23 kV at peak load, indicating efficient long-distance power transmission. It can be concluded that the higher the renewable generation the higher the power output of hybrid system and the greater the improvement in the voltage profile of the grid. This finding is concurred with Ali (2022) who stated that the higher the solar radiation, the higher the power output of the solar generator and the greater the improvement in the voltage profile of the electrical system. These findings offer valuable insights into energy generation patterns, system stability, and the potential for sustainable electricity supply on Tumbatu Island as reported by Utilities (2024).

In Table 11, the voltage profile of the proposed renewable energy system on Tumbatu Island (Case 2) is presented for a period of twelve months. Solar and wind generation exhibit slight fluctuations, ranging from 0.450 kV to 0.463 kV. The feeding voltage remains constant at 0.23 kV, showing consistent power input. The overall voltage level after feeding experiences minimal impact, ranging from 0.220 kV to 0.233 kV, indicating a stable grid. The transmission voltage to the low-voltage side remains consistent at 0.220 kV to 0.230 kV, ensuring reliable power flow. The stepping up of voltage to the high-voltage side is efficient, ranging from 29.8 7kV to 31.36 kV. In Case 2, the system demonstrates stable and dependable performance, which is vital for maintaining a consistent power supply to Tumbatu Island. In Table 12, a comprehensive monthly breakdown of the voltage profile for the proposed renewable energy system on Tumbatu Island (Case 3) is presented. Notable aspects include a consistent feeding voltage of 0.23 kV, indicating stability at the point of renewable energy entry. The remaining voltage after feeding provides valuable insights into the available grid capacity, while the voltage from the inverter to the LV side and the stepped-up voltage to the high-voltage (HV) side highlight the operational efficiency of the system. Monthly variations in the combined output voltage from renewable energy sources are also clearly visible.

Among the three cases, Case 2 emerges as the most stable and reliable option. It exhibits minimal fluctuations in output voltage, maintains a steady feeding voltage, and consistently delivers dependable power to both LV and HV sides. The efficient stepping up of voltage enhances the effectiveness of the long-distance power transmission system. Overall, the system in Case 2 appears to be well-suited for ensuring a consistent and reliable power supply to

Tumbatu Island, making it the preferred option. However, despite Case 3 demonstrating operational efficiency in terms of maintaining voltage stability and increasing voltage, the monthly fluctuations observed in the combined output voltage could potentially affect the overall efficiency of the system. In situations where predictability is of utmost importance as is the case of Tumbatu Island, this variability may present difficulties in effectively managing the power supply. Similarly, despite the variations in combined output voltage in Case 1 falling within an acceptable range, the monthly fluctuations (ranging from 0.844 kV to 0.870 kV) have the potential to introduce uncertainties in energy generation patterns. This variability may impact the consistency of the power supply and potentially pose challenges in meeting demand during specific months (Benti, 2023). It is clear from the results that ensuring system stability and efficiency is key in the creation of sustainable renewable energy solutions (Mathiesen *et al.*, 2015; Uduma, 2010) for remote areas like Tumbatu Island.

Table 10: Voltage profile of proposed system in Tumbatu Island (Case 1)

Month	Renewable energy (kV)	Tumbatu feeding voltage (kV)	Remaining voltage after feeding (kV)	Voltage from the Inverter to the LV side of the Grid (kV)	Stepped up the voltage to the HV side (kV)
January	0.870	0.23	0.655	0.23	31.19
February	0.852	0.23	0.637	0.23	31.19
March	0.864	0.23	0.646	0.23	31.36
April	0.863	0.23	0.645	0.23	31.36
May	0.861	0.23	0.643	0.23	31.36
June	0.844	0.23	0.626	0.23	31.36
July	0.850	0.23	0.632	0.23	31.36
August	0.863	0.23	0.645	0.23	31.36
September	0.863	0.23	0.645	0.23	31.36
October	0.869	0.23	0.651	0.23	31.36
November	0.862	0.23	0.647	0.23	31.23
December	0.868	0.23	0.653	0.23	31.23

Table 11: Voltage profile of proposed system in Tumbatu Island (Case 2)

Month	Renewable energy (kV)	Tumbatu feeding voltage (kV)	Remaining voltage after feeding (kV)	Voltage from the Inverter to the LV side of the Grid (kV)	Stepped up the voltage to the HV side (kV)
January	0.463	0.23	0.233	0.230	31.19
February	0.453	0.23	0.223	0.223	30.24
March	0.460	0.23	0.230	0.230	31.36
April	0.457	0.23	0.227	0.227	30.95
May	0.455	0.23	0.225	0.225	30.68
June	0.451	0.23	0.221	0.221	30.14
July	0.454	0.23	0.224	0.224	30.54
August	0.454	0.23	0.224	0.224	30.54
September	0.454	0.23	0.224	0.224	30.54
October	0.460	0.23	0.230	0.230	31.36
November	0.452	0.23	0.222	0.222	29.87
December	0.458	0.23	0.228	0.228	29.87

Table 12: Voltage profile of proposed system in Tumbatu Island (Case 3)

Month	Renewable energy (kV)	Tumbatu feeding voltage (kV)	Remaining voltage after feeding (kV)	Voltage from the Inverter to the LV side of the Grid (kV)	Stepped up the voltage to the HV side (kV)
January	0.449	0.23	0.219	0.219	29.70
February	0.443	0.23	0.213	0.213	28.89
March	0.446	0.23	0.216	0.216	29.45
April	0.445	0.23	0.215	0.215	29.32
May	0.444	0.23	0.214	0.214	29.18
June	0.435	0.23	0.205	0.205	27.95
July	0.439	0.23	0.209	0.209	28.50
August	0.441	0.23	0.211	0.211	28.77
September	0.441	0.23	0.210	0.210	28.64
October	0.440	0.23	0.210	0.210	28.64
November	0.443	0.23	0.213	0.213	29.92
December	0.449	0.23	0.219	0.219	29.74

Table 13: Monthly existing voltage profile per phase per day

Month	HV side (kV)	LV side (kV)
January	29.7	0.219
February	29.7	0.219
March	30	0.22
April	30	0.22
May	30	0.22
June	30	0.22
July	30	0.22
August	30	0.22
September	30	0.22
October	30	0.22
November	29.6	0.218
December	29.6	0.218

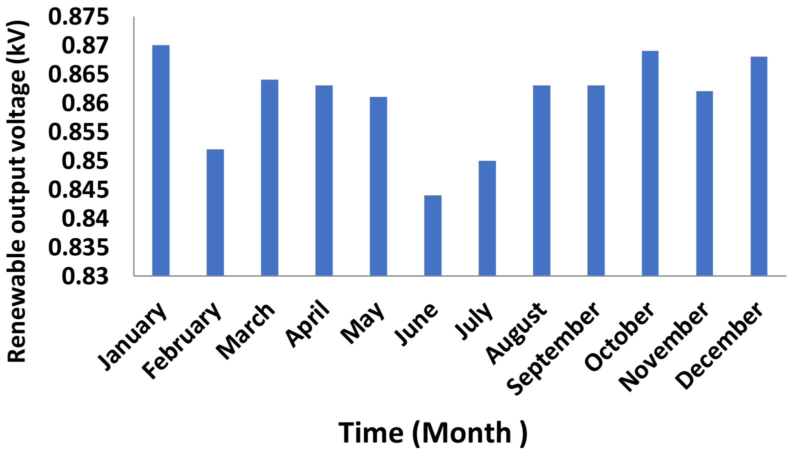

Figure 12: Voltage profile of renewable energy before integrated to the grid on the LV side

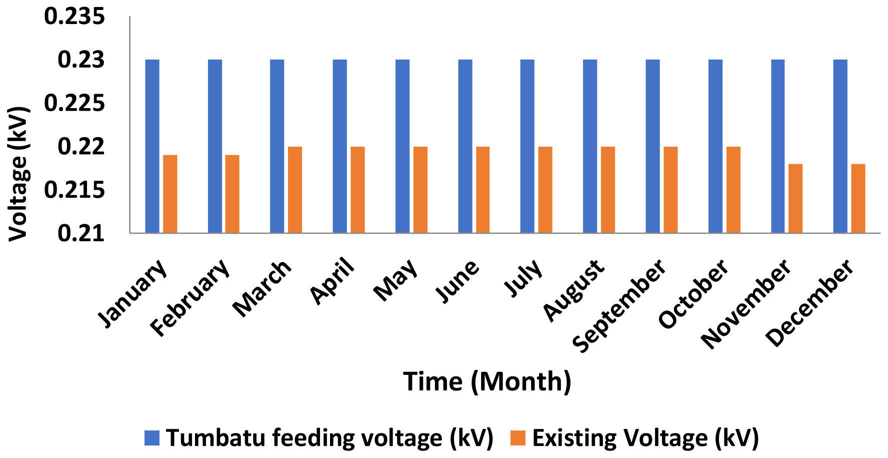

Figure 13: Voltage profile of renewable energy when integrated to the Grid on the LV side

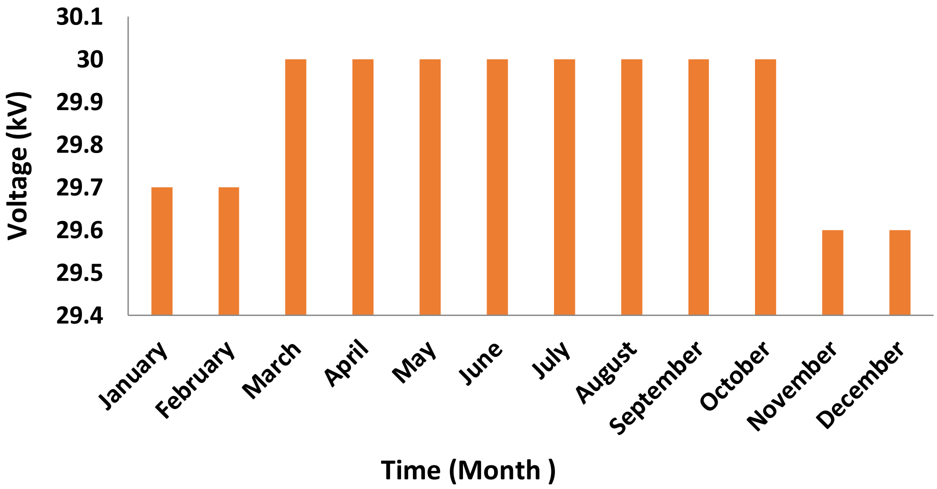

Figure 14: Existing Voltage profile for Tumbatu Island on the HV side

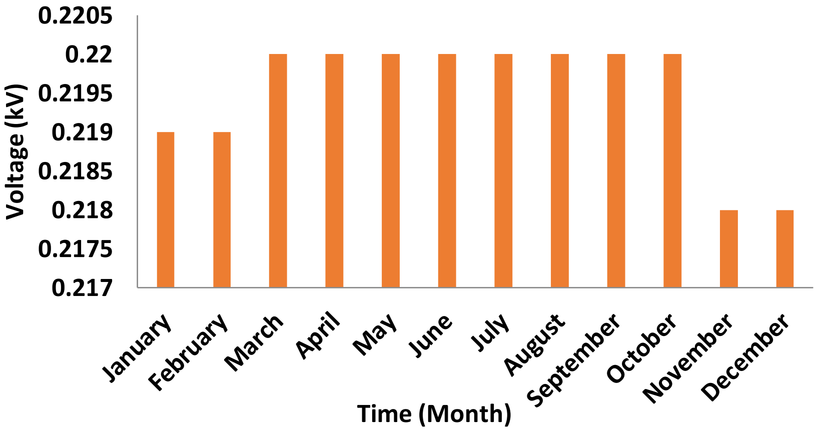

Figure 15: Existing Voltage profile for Tumbatu Island on LV side

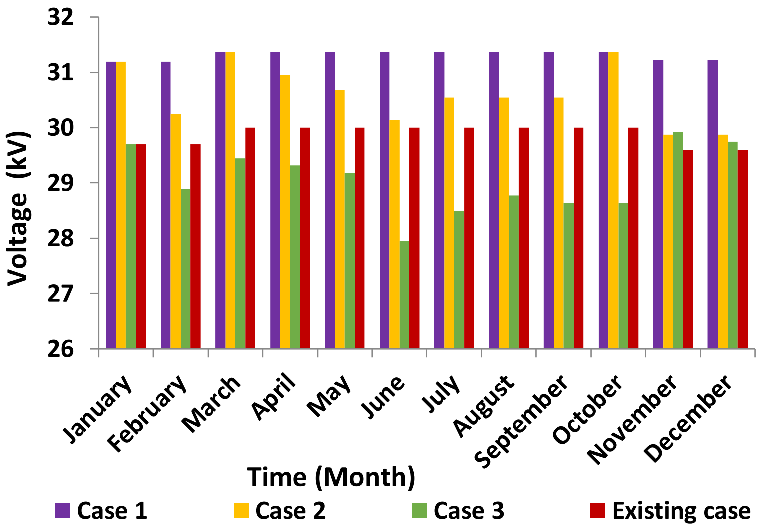

Figure 16: Voltage profile of existing and proposed on the HV side

4.5 Voltage Profile Improvement Results

To improve the voltage profile of the transmission line, the PV/Wind/Battery/Converter system and the utility grid were designed using the HOMER Pro software. Through simulation, it was determined that the optimal solution involved the combination of PV/Wind and the grid. This solution resulted in an improved voltage profile, as evidenced by the data presented in Table 8 and Table 9. The results of the simulation and optimization for various configurations of a renewable energy system, consisting of PV panels, wind turbines (WT), converters, batteries, and grid connection, are summarized in Table 8. The results in Table 8 for different renewable energy configurations are summarized, presenting information on component sizes, NPC, COE, and PB. It is important to highlight that configuration B (PV/GRID) stands out as an economical option, with the lowest NPC, favorable COE, and a reasonable PB of 4.88 years. This particular configuration, which relies on photovoltaic panels and grid connectivity, emphasizes a well-balanced and economically viable approach to maintaining a consistent electricity supply (Sharma, 2022).

Table 9 presents the simulation results for three different cases (Case 1, Case 2, and Case 3) across various months. In all cases and months, the net energy purchased is positive, indicating a consistent trend of buying more energy than selling. This suggests a reliance on external sources to meet energy demands which for this study it is the grid. The inverter output power per day for each case varies across the months. Case 1 consistently has the highest output, followed by Case 2 and Case 3. This suggests that the system in Case 1 is designed to generate more power, while Case 3 has the lowest output. In terms of electricity availability, the positive values in the net energy purchased column signify a dependence on the grid, to fulfill energy requirements. This implies that the PV/Wind system is not entirely self-sufficient and relies on purchasing additional energy from the grid to meet the demand. The differences in inverter output power per day between the cases indicate varying levels of energy generation capacity, with Case 1 being the most productive.

The simulation results in Table 9 indicate a consistent pattern of relying on purchased energy from the grid, with variations in inverter output power per day across different cases. The results exhibit higher performance of renewable energy sources in stabilizing the grid when there is insufficiency in terms of electricity supplied by the grid. In comparison with previous studies, Al-Shetwi (2022) and Ehteshami (2014) conducted a comprehensive study on renewable energy systems and concluded that ensuring system stability and improving efficiency are vital for the long-term sustainability of renewable energy integration. In a research paper by Hoang (2021), they examined the relationship between system stability, efficiency, and sustainable renewable energy. Their findings align with the importance of maintaining stable and efficient systems for achieving sustainable energy goals. When comparing the three scenarios for grid integration, it can be concluded that Case 2 is the most preferable. It achieves a good balance by providing a reasonable output power from the inverter each day while reducing the amount of energy purchased from external sources. This indicates a higher capacity for generating energy while minimizing dependency on outside suppliers. Therefore, it can be inferred that Case 2 is a potentially more sustainable option for grid integration when compared to the other cases.

Furthermore, the integration of renewable energy led to an increase in harvested voltage, a reduced reliance on the grid, and an enhanced capacity for integration into the grid, as indicated in Table 10. Before to the integration of renewable energy sources, there was a noticeable decline in voltage levels, as illustrated in Table 13, Figs. 14 and 15. This decline was observed in both the LV and HV sides of the transformer, indicating an overall improvement in voltage levels. These findings remained consistent across different inverter outputs, ranging from 376.03 kW to 364.7 kW (Case 1), 200 kW to 195 kW (Case 2), and specifically in the months of December and January, 194 kW to 188 kW in Case 3, as depicted in Fig. 16. When comparing the findings with existing literature, some studies, such as Elshahed (2016), achieved an improvement in voltage profile by 6.3%, while Ababio *et al.* (2021) improved voltage profile by 1.97%. Additionally, Chukwulobe (2022) enhanced the voltage profile by 8%. In the present study, the voltage profile improved from 29.6 kV to 31.32 kV out of 33 kV, representing a 5.36% improvement. This improvement of voltage falls within the acceptable range of ±5% of the nominal voltage for voltages up to 33 kV, as reported by Kanan *et al.* (2019). The different of findings depends on the size of load, availability of resources in different climatic conditions and area (Jing, 2022). These findings are essential for assessing system stability, efficiency, and guiding decision-making processes to ensure a sustainable and reliable energy supply on Tumbatu Island as concluded by Dudi and Sharma (2024).

4.6 Economic Details of the Optimized System

Table 8 illustrates that for the selected system A, the annual energy purchased from the grid amounts to 1517.686 MWh, while the annual energy sold back to the grid is 357.163 MWh. Additionally, the minimum electrical energy sold to the grid in June is 24.020 MWh, whereas the maximum electrical energy sold to the grid in January is 34.931 MWh. These results indicate that renewable energy, especially solar PV, produced the least amount of electricity in June and the highest amount in January. Variations in electricity production by solar PV and the wind turbine are depicted in Fig. 17 and Fig. 18, respectively, while Fig. 19 displays the variation in output power via the system converter throughout the year. Figure 20 illustrates the fluctuations in primary load, electricity sales to the grid, and electricity purchases from the utility grid for selected days in January, providing a clear visual representation of the energy transactions. The red lines represent the primary load, black lines depict electricity purchases from the utility grid, and blue lines show the electricity sold back to the grid.

As the proposed hybrid renewable energy system does not incorporate storage technologies, excess electricity generated by solar PV and the wind turbine can be efficiently sold back to the utility grid. The chosen hybrid renewable energy configuration A, encompasses components such as solar PV, wind turbine, grid, and converter, all contributing to its economic viability. Each component in the system incurs costs related to capital, operational, maintenance, and replacement expenses. The electricity production of the HRES stems from these diverse components. To visually illustrate the cost parameters of the components within optimized system A. Figure 21 provides a clear representation.

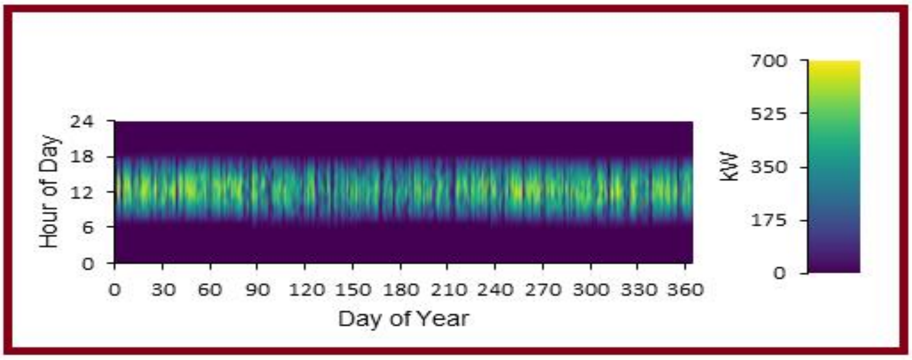

Figure 17: Solar PV output power production throughout the year

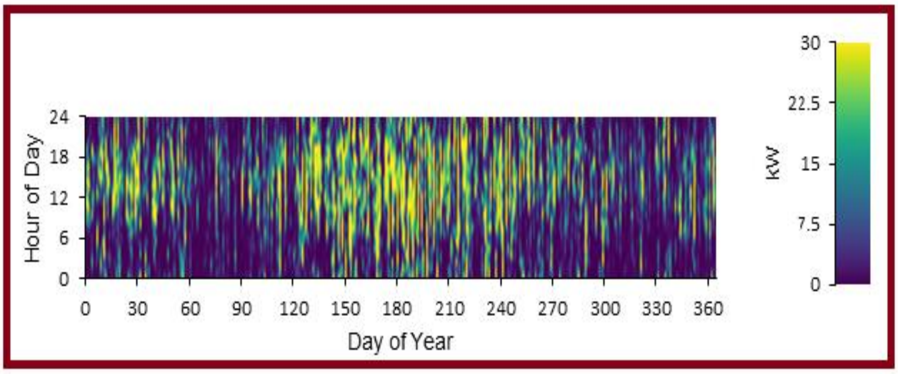

Figure 18 : Wind turbine output power production throughout the year

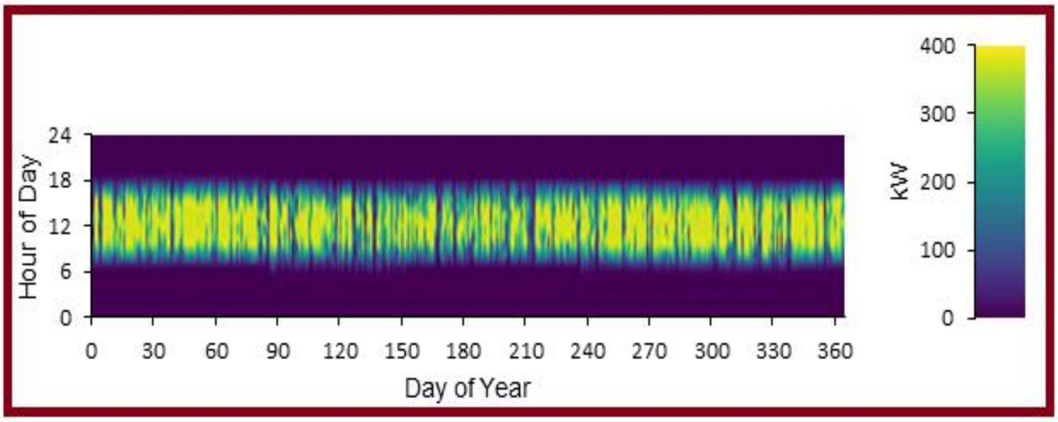

Figure 19: System converter variation of output power throughout the year

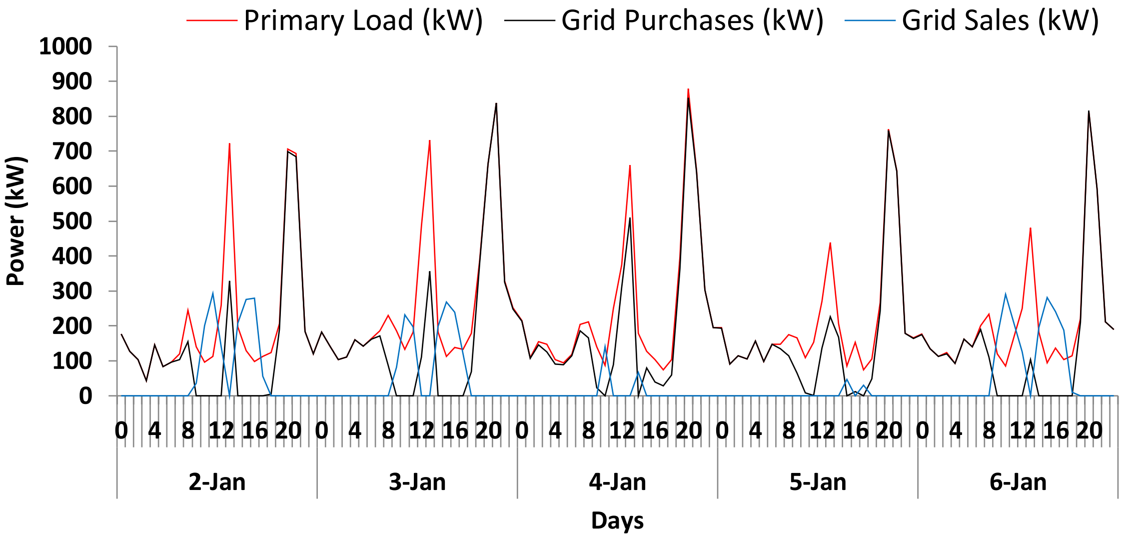

Figure 20: **Variations of power output from scenario A with grid purchase and sales**

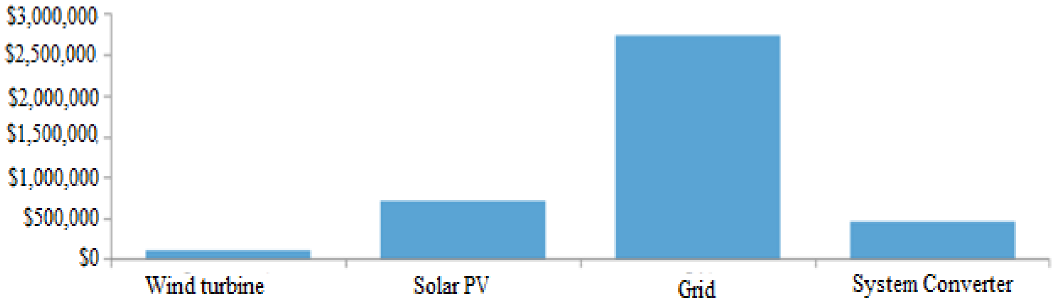

Figure 21: **Summary of system cost by component**

4.7 Sensitivity Analysis

4.7.1 Sensitivity Analysis of Solar Radiation on Cost Parameters

The variation in solar radiation levels plays a significant role in determining the electrical energy output from the solar PV system. To investigate this impact, three distinct solar radiation sensitivity values were input into the Homer Pro software, allowing for a comprehensive assessment of how solar radiation influences the cost parameters. The information regarding radiation, COE, and TNPC is presented in a graphical format in Fig. 22. As the radiation levels increase from 5.57 to 6.6 kWh/m^2/day, a noticeable pattern emerges in both the COE and TNPC columns. The COE decreases from 0.0897 to USD 0.0785 kWh, indicating a reduction in the cost of electricity. Simultaneously, the TNPC decreases from USD 4 million to USD 3.88 million suggesting a decrease in the TNPC. In terms of electricity availability, interpreting results in Fig. 23 reveals that higher radiation levels contribute to more favorable economic outcomes. The decreasing trend in both COE and TNPC implies that as radiation increases, the cost of generating electricity decreases, leading to an improvement in overall economic feasibility (Kaur, 2020; Malik *et al.*, 2019). This could be attributed to increased efficiency or higher energy output associated with greater radiation levels, resulting in electricity being more readily available at a lower cost. Figure 23 provides a visual representation of this relationship, highlighting how changes in solar radiation levels can influence the overall cost parameters of the hybrid renewable energy system.

In previous studies, several researchers have concurred with the findings of this study based on solar radiation on cost parameters (COE and TNPC). For example, Daus (2019) reported similar cost reductions in their research, stating, As radiation levels increase, a noticeable decrease in the COE is observed. In line with this, Kaur (2020) conducted a study where they observed a decrease in the overall cost of the HRES with higher radiation levels, affirming that 'increased radiation levels contribute to more favorable economic outcomes. In a separate study, Sharma (2022) emphasized the positive relationship between radiation levels and economic feasibility, stating that higher radiation levels lead to improved economic viability. Similarly, Haidar (2020) found that as radiation increases, there is a decrease in the COE. They stated, 'The trend indicates that as radiation levels rise, the cost of electricity decreases. Lastly, Buni (2018) highlighted the positive impact of higher radiation levels on energy production, stating that 'increased radiation levels result in higher energy output and improved efficiency. These various studies align with the findings presented in this study, further supporting the significance of solar radiation levels in determining the electrical energy output and cost parameters of solar PV systems.

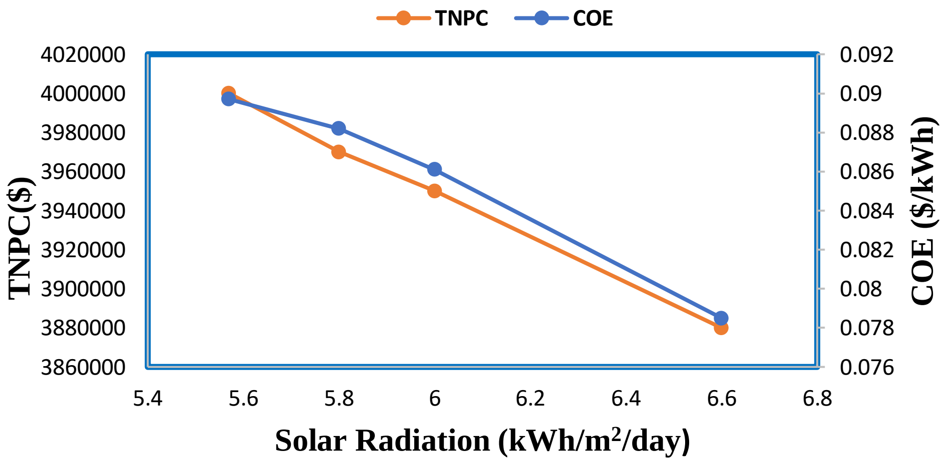

Figure 22: Impact of solar radiation on TNC and COE

4.7.2 Sensitivity Analysis of Electric Load on Cost Parameters

The sensitivity analysis conducted in this study also examined the impact of electric load variations on the optimized hybrid system's TNPC and COE. The investigation revealed interesting findings regarding the behavior of these cost parameters in response to changes in electrical load. As illustrated in Fig. 23, it was observed that as the electrical load increases, the NPC values also increase. However, the COE initially decreases from 6000 kWh/day to 10 000 kWh/day and then starts increasing again from 10 000 kWh/day to 11 000 kWh/day. Furthermore, the sensitivity analysis allowed us to examine the effect of electric load changes on the individual components of the hybrid system. It was noted that while the quantity of wind turbines remained constant at 10 units in the original design, the capacity of solar panels increased in correlation with the increase in electric load, as depicted in Fig. 24. This result indicates that the solar panel capacity is directly affected by variations in the electrical load in this particular scenario. The findings from this sensitivity analysis shed light on the dynamic relationship between electric load, cost parameters, and the sizing of renewable energy components in the optimized hybrid system. This finding aligns with the findings of a study conducted by Malik *et al.* (2019) who investigated on decrease of COE and rise of TNPC as electric load increases. Similarly, Sharma (2022) observed when electrical load increases COE and TNPC increases. Furthermore, Manyama (2018) observed the consistence wind turbine quantity as the electric load rises.

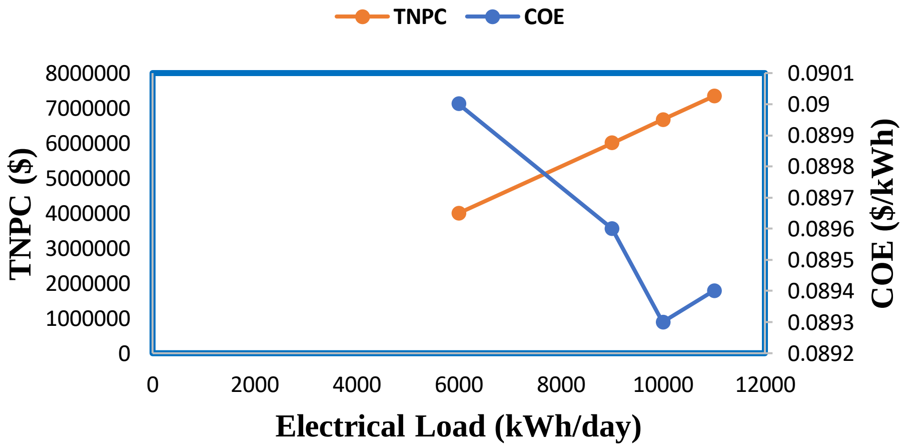

Figure 23: Variation of electric load on cost parameter

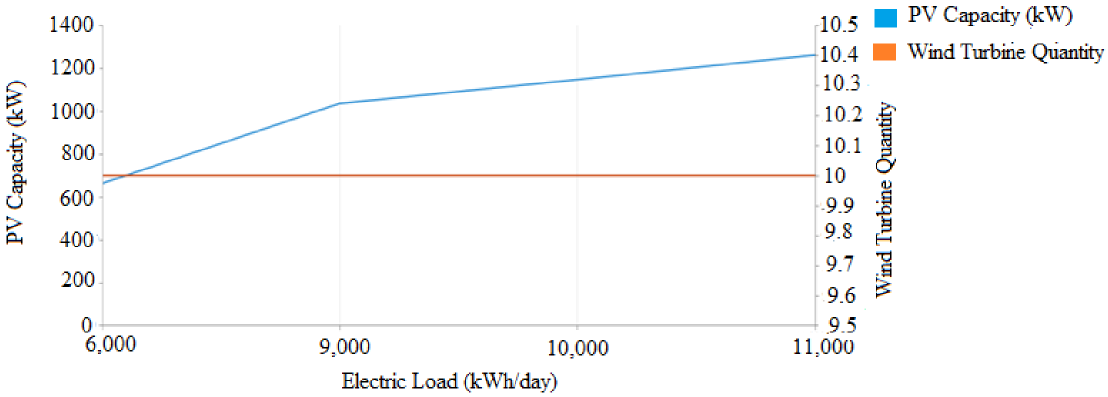

Figure 24: Variation of electric load on PV cost and wind turbine quantity

4.7.3 Sensitivity Analysis of Wind Speed on Cost Parameter

Wind speed is the most important aspect of producing electricity using wind turbines. In this case, the wind speeds tested were 6.24 m/s, 6.5 m/s, and 7 m/s. The result revealed that both TNPC and COE decrease as wind speed increases as presented in Fig. 25. This finding is consistent with the findings of a study conducted by Malik *et al.* (2019) stated if the wind speed is increased COE and TNPC is decline. In a separate study, Alavi (2024) emphasized the positive relationship between wind speed levels and economic feasibility, stating that increasing average wind speed levels lead to decrease system costs.

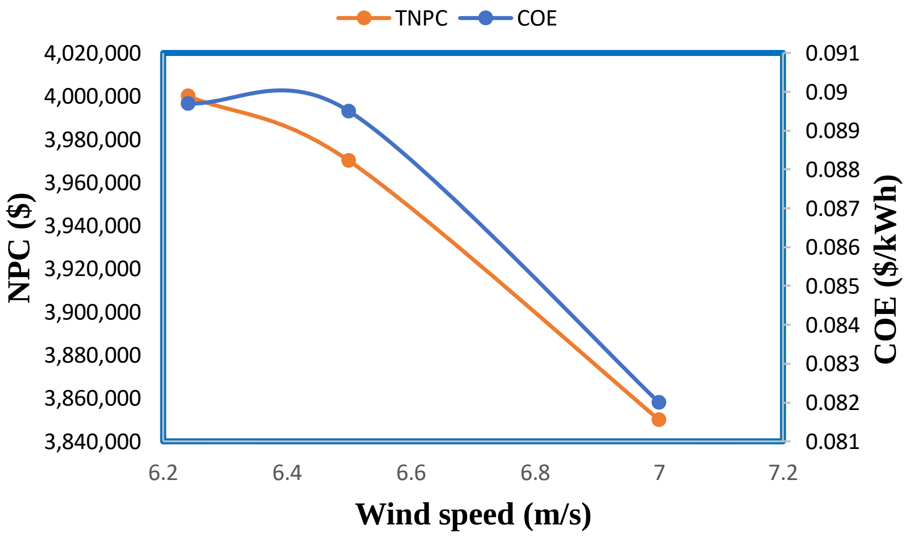

Figure 25: Impact of wind speed on cost parameter

4.7.4 Sensitivity Analysis of Nominal Discount Rate on Cost Parameters

In Tanzania, the nominal discount rate holds significant importance in economic evaluations and investment decisions. To comprehensively assess its impact on the cost parameters of optimized hybrid renewable energy system, a sensitivity analysis is conducted using two different discount rates: 5% and 4%. The findings, depicted in Fig. 26, provide valuable insights into how variations in the nominal discount rate influence the cost parameters. As the discount rate decreases from 5% to 4%, the NPC experiences a corresponding increase, while it decreases as the discount rate rises. This phenomenon can be attributed to the time value of money; lower discount rates place greater emphasis on future cash flows, thus leading to higher present costs. On the other hand, higher discount rates place more weight on present cash flows, resulting in lower present costs.

The COE, on the other hand, exhibits an inverse relationship with the nominal discount rate. As the discount rate decreases, the COE decreases as well, and vice versa. This outcome is a direct consequence of the interplay between the discount rate and the COE. A lower discount rate reduces the cost of financing, leading to lower COE, while a higher discount rate has the opposite effect, raising the COE. Based on these findings, it is evident that the choice of discount rate has a profound impact on the economic evaluation of renewable energy projects. The selection of an appropriate discount rate is crucial for accurately assessing the viability and attractiveness of investment opportunities. A lower discount rate may be favored when evaluating long-term and sustainable energy projects, as it values future benefits more highly and encourages the development of renewable energy infrastructure.

The optimization results, as presented in Table 14, provide a comprehensive overview of the sensitivity analysis with the 4% discount rate. It is essential to consider such variations in the discount rate during project planning and decision-making processes to ensure sound economic evaluations and foster the sustainable growth of renewable energy initiatives in Tanzania. The nominal discount rate significantly impacts the cost parameters of HRES. Understanding the dynamics between the discount rate, NPC, and COE is vital for making informed investment decisions and maximizing the economic benefits of renewable energy projects. With a clear understanding of these relationships, stakeholders can chart a path towards a greener, more sustainable, and economically viable future for Tanzania's energy landscape. The findings of nominal discount rate on cost parameters (COE and TNPC) for this study concurred by different researchers. For instance, Kirim *et al.* (2021) revealed that when nominal discount rate increases , the COE increases while TNPC decreases. Also, this finding regarding the nominal discount rate is consistent with the study by Khan (2022) , which states that the COE is proportional to the nominal discount rate, while it is inversely proportional to the TNPC.

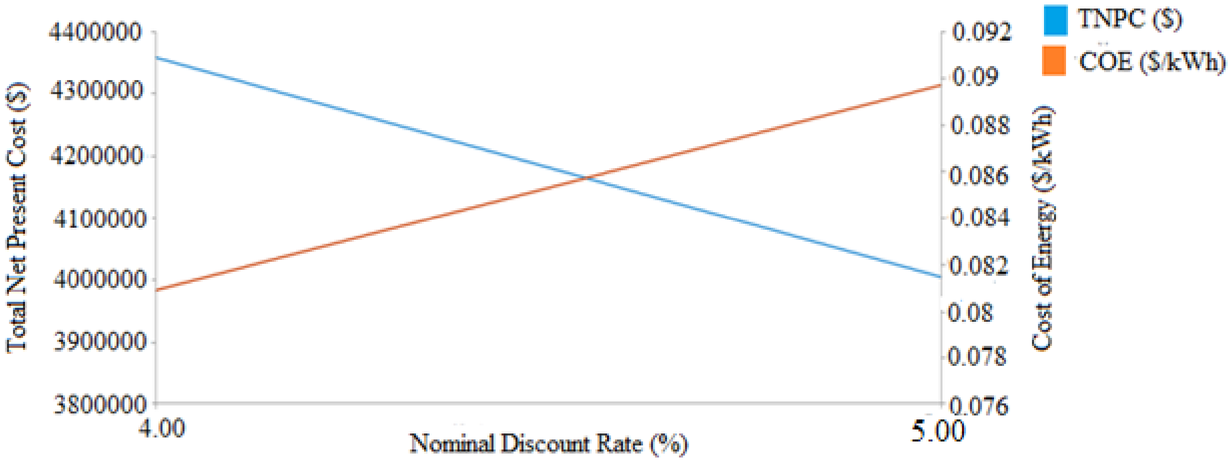

Figure 26: Impact of nominal discount rate on cost parameters

Table 14: Sensitivity analysis of nominal discount rate

SENSITIVITY	ARCHITECTURE					COST	
NOMINAL DISCOUNT RATE (%)	PV	WIND	BATTERY	GRID	CONVERTER	NPC ($)	COE ($/kWh)
4.00	✓	✓	-	✓	✓	4.36M	0.0809
5.00	✓	✓	-	✓	✓	4.00M	0.0897

4.7.5 Economic Comparison Between the Available Hybrid Renewable Energy Systems in the Literature and the Suggested One

In the context of the optimally designed HRES for Tumbatu Island, Table 15 provides a comparison with various system configurations previously studied in the literature for other islands by different authors. The comparison is based on the costs associated with each system. While the TNPC value may differ among the proposed HRESs due to variations in initial component costs, average energy demand, and element sizes, the Cost of COE value serves as an alternative measure for comparing different combinations of RES (Seedahmed, 2022). The table reveals that Hong Kong exhibits a significantly higher COE compared to the other territories, followed by Koh Samui islands. On the other hand, Masirah, Bozcaada, Bozcaada and Tumbatu Islands have recorded the lowest energy prices in comparison to the mentioned islands. Notably, incorporating a combination of renewable resources and non-renewable resources, such as diesel and the grid, contributes to decreasing the cost of energy. Conversely, relying solely on renewable systems may result in higher costs, or conversely, depending on the potential and economic parameters of the available renewable sources. Through the results obtained in this techno-economic analysis, satisfactory outcomes have been achieved with low costs compared to the proposed survey, making it an affordable solution for the inhabitants of Tumbatu Island.

Table 15: Comparison between the available hybrid renewable energy systems in the Literature and the suggested one

Island	Country	Studied Energy type	TNPC (USD M)	COE (USD (kWh)	References
Ras Musherib	Abu Dhabi Emirates	PV/Wind/Diesel	14.5	0.2	Rohani (2014)
Koh Samui	Thailand	PV/Wind/Fuel cell/Battery	542	0.385	Chaichan *et al.* (2022)
Deokjeok-do	South Korea	PV/Wind	11.3	0.159	Baek (2015)
Hong Kong	China	PV/Wind	0.69	0.595	Ma (2014)
Bozcaada	Turkey	Wind/Grid	2.34	0.103	Kalinci (2015)
Masirah	Oman	Wind/Diesel/Natural Gas	129	0.0724	Abdul-Wahab (2020)
Biaro	Indonesia	PV/Wind	3.87	0.204	Aisyah *et al.* (2020)
Kibran Gabriel	Ethiopia	PV/Battery	1.19	0.175	Beza (2021)
Tumbatu	Tanzania	PV/WIND/GRID	4.00	0.09	This study

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigated the voltage profile improvement in an HV line and assesses the economic viability of a grid-connected renewable energy hybrid system at Tumbatu Island as a case study area over a 25-year period. The optimization and analysis of HRES comprising solar PV, wind turbine, battery, and the HV line from utility grid was conducted using HOMER software. The findings of this study shows that solar PV and Wind when injected to the grid can produce great improvement of the voltage profile from 29.6 kV to 31.23 kV on HV side and from 0.219 kV to 0.23 kV on LV side during maximum demand. Among the configurations analyzed, the HRES incorporating solar PV, wind turbine, and the grid emerged as the most economically viable solution for electricity generation on Tumbatu Island. The integration of RES resulted in a substantial decrease in the COE, dropping from USD 0.114 kWh when relying solely on the grid to USD 0.09 kWh. This reduction represents a significant decrease of approximately 21%. However, when the results were tested for validation, they showed that the improvement in the voltage profile is valid for the inverter output, which ranges from 376 kW to 191.32 kW. The proposed hybrid system has the capacity to meet the growing electricity demand on the island, producing an excess of 104.387 MWh per year.

Moreover, the HRES stands out for its environmental friendliness, mitigating techno-economic challenges related to diesel engine emissions and the cost of transporting oil to remote areas. The sensitivity analysis highlighted the impact of solar radiation and wind speed on the cost of energy and total net present cost, with higher solar radiation and wind speed resulting in decreased costs. Additionally, the electric load variations were found to affect the solar panel capacity in the system, while the wind turbine capacity remained unaffected. Wind speed was identified as the most sensitive parameter in the study. In conclusion, the proposed grid-connected hybrid renewable energy system improves the voltage profile. With its cost-effectiveness, environmental benefits, and capacity to generate excess electricity, this optimized system presents a promising solution to address the energy needs of the island's inhabitants in a sustainable and eco-friendly manner. However, setting up a hybrid power system on Tumbatu Island, which uses solar panels, wind turbines, and HV transmission lines, comes with several challenges and risks. Combining these different energy sources is technically complex and requires advanced control systems and ongoing maintenance, which can be costly. The high initial investment and the need for specialized training also add to the financial load.

5.2 Recommendations

(i) Conducting research on the Island of Tumbatu is a great start, but expanding the studies to other islands with different climatic conditions would indeed provide valuable comparative data. By comparing the results across various islands, researchers can gain insights into how different climates impact various aspects such as ecosystem resilience, and vulnerability to environmental changes.

(ii) Further studies could focus on integrating offshore wind turbines, tidal energy, and wave energy to the HV transmission line.

(iii) The current study has achieved a 21% reduction in the cost of electricity COE. To achieve even greater reductions in COE, further research is recommended.

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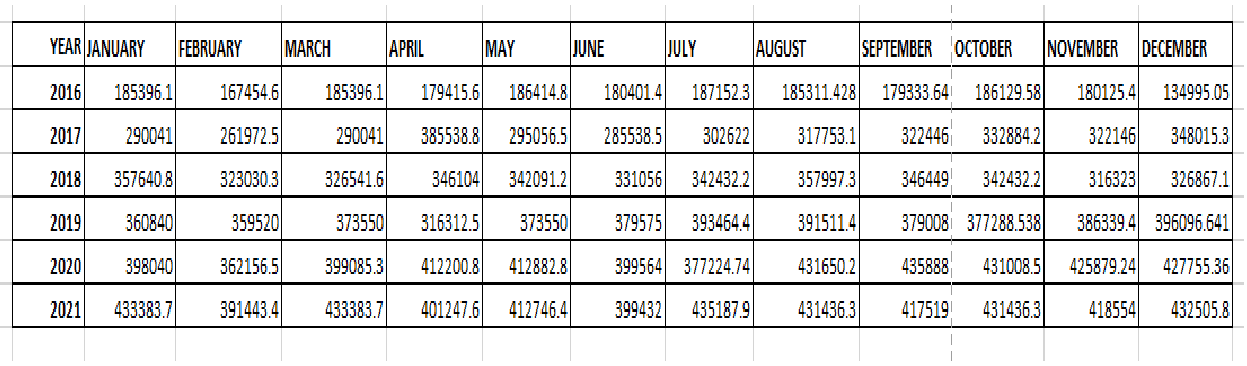
APPENDICES

Appendix 1: Inverter specifications

Item	Specifications
Input (DC)	
Max Dc Power(W)	28000
Max Dc voltage (V)	1000
Min working Voltage(V)	250
Output (A.C)	
AC nominal power(W)	25000
Max output Current(A)	36
Nominal AC output	50/60 HZ; 400 Vac
Power factor	0. 8 leading/lagging
Grid type	3W/N/PE
Max efficiency (%)	98.6
Safety and Protection	
DC reverse-polarity protection	Yes
DC breaker	Yes
Leakage Current protection	Yes
Insulation Impedance Detection	Yes
Residual Current protection	Yes

Appendix 2: Electric load data for Tumbatu Island



YEAR	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
2016	185396.1	167454.6	185396.1	179415.6	186414.8	180401.4	187152.3	185311.428	179333.64	186129.58	180125.4	134995.05
2017	290041	261972.5	290041	385538.8	295056.5	285538.5	302622	317753.1	322446	332884.2	322146	348015.3
2018	357640.8	323030.3	326541.6	346104	342091.2	331056	342432.2	357997.3	346449	342432.2	316323	326867.1
2019	360840	359520	373550	316312.5	373550	379575	393464.4	391511.4	379008	377288.538	386339.4	396096.641
2020	398040	362156.5	399085.3	412200.8	412882.8	399564	377224.74	431650.2	435888	431008.5	425879.24	427755.36
2021	433383.7	391443.4	433383.7	401247.6	412746.4	399432	435187.9	431436.3	417519	431436.3	418554	432505.8

RESEARCH OUTPUTS

(i) Research Paper

Said, T. R., Kichonge, B., & Kivevele, T. (2024). Optimal design and analysis of a grid-connected hybrid renewable energy system using HOMER Pro: A case study of Tumbatu Island, Zanzibar. *Energy Science & Engineering*, *12*(5), 2137-2163.

(ii) Poster Presentation

Poster Presentation

Optimal Design and Analysis of a Grid-Connected Hybrid Renewable Energy System Using HOMER Pro: A Case Study of Tumbatu Island, Zanzibar

Thani R. Said[1], **Baraka Kichonge**[2] **and Thomas Kivevele**[1]
[1]School of Materials Energy Water and Environmental Sciences (MEWES), The Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania
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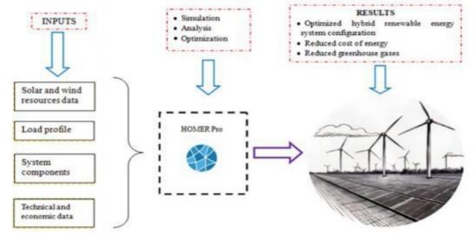
Abstract


INPUTS
- Solar and wind resources data
- Load profile
- System components
- Technical and economic data

HOMER Pro

- Simulation
- Analysis
- Optimization

RESULTS
- Optimized hybrid renewable energy system configuration
- Reduced cost of energy
- Reduced greenhouse gases

Introduction

Energy demand rising due to population growth, urbanization and industrialization. Fossil fuels remain predominant despite advancements in renewable energy sources. Global push towards renewable energy aims to address the problems associated with fossil fuels. However a major challenge of using a renewable energy source is their intermittent nature, which affects energy production. This issue can be mitigated through hybridization.

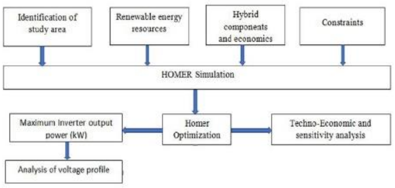
Main Objective

To determine the optimal combination of renewable energy sources along with high voltage transmission line (grid) to meet Tumbatu Island's energy demand while minimizing costs and maximizing reliability by conducting simulation, optimization and sensitivity analysis using HOMER Pro.

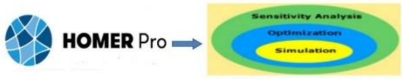
Specific Objectives

- To conduct optimization of the hybrid renewable energy system using HOMER software, focusing on solar photovoltaic (PV), battery storage, converters, wind turbines, and grid integration for the study area.
- To enhance the voltage profile of the high-voltage transmission line in Tumbatu Island by integrating renewable energy sources, thereby improving grid stability and reliability.
- To perform sensitivity analysis of the hybrid renewable energy system using HOMER software that will assess its robustness and adaptability to variations in environmental conditions and energy demand.

Research Frame work


Identification of study area
Renewable energy resources
Hybrid components and economics
Constraints
HOMER Simulation
Maximum Inverter output power (kW)
Homer Optimization
Techno-Economic and sensitivity analysis
Analysis of voltage profile

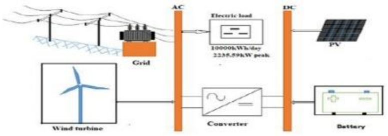
Designing tool


HOMER Pro
Sensitivity Analysis
Optimization
Simulation

Study Area

The study was conducted on Tumbatu Island, located within the Zanzibar archipelago. Tumbatu Island characterized by its remote location and limited access to conventional energy infrastructure, presents a compelling case for exploring sustainable energy solutions. With a focus on enhancing HV line (grid)-connected hybrid renewable energy systems, the study examines the island's renewable energy potential, including solar irradiance, wind speed, and existing electric load. By leveraging HOMER Pro's simulation capabilities, the research aims to propose an optimal energy solution that enhances energy reliability, reduces dependency on fossil fuels, and fosters socio-economic development on Tumbatu Island.

Hybrid Components



Optimal Configuration and Results

Power system Configurations		Sizes of various components					NPC ($)	COE ($)	PBP (Year)
		PV (kW)	WT (Quantity)	CONVERTER (kW)	BATTERY (kW)	GRID			
A	PV/WIND/GRID	685	10	376	-	ON	4,003,851	0.09	3.79
B	PV/GRID	750	-	424	-	ON	4,005,868	0.088	4.88
C	PV/WIND/BATTERY/GRID	731	5	392	1	ON	4,007,771	0.089	4.52
D	PV/BATTERY/GRID	743	-	409	17	ON	4,028,774	0.089	4.2
E	WIND/GRID	-	200	-	-	ON	4,491,925	0.091	n/a
F	WIND/BATTERY/GRID		200	12	17	ON	4,529,434	0.092	n/a