DESIGN AND FABRICATION OF A HYBRID WIND TURBINE AND SOLAR POWER GENERATING SYSTEM FOR ELECTRICITY

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CERTIFICATION

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DEDICATION

This project work is dedicated to God Almighty who granted us courage and patience to perform and carry out this project work, and without his help we would not have achieved what we have done so far.

Also, this project is dedicated to our parents for their great support, guidance, sacrifice and prayers throughout the duration of our course of study

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TABLE OF CONTENTS

CERTIFICATION -- II

DEDICATION -- III

ACKNOWLEDGEMENTS --- IV

TABLE OF CONTENTS --- V

LIST OF TABLES --- IX

LIST OF FIGURES -- X

NOMENCLATURE / SYMBOLS -- XI

ABSTRACT --- XIV

CHAPTER ONE -- 1

INTRODUCTION -- 1

1.1 BACKGROUND TO THE STUDY --- 1

1.1.1 WIND TURBINE --- 3

1.1.2 SOLAR SYSTEM -- 4

1.1.4 SOLAR BATTERY -- 7

1.1.5 SOLAR PANEL --- 7

1.1.6 SOLAR CHARGE CONTROLLER --- 9

1.1.7 ADVANTAGES OF WIND TURBINES: -- 10

1.1.8 ENVIRONMENTAL SUSTAINABILITY: -- 11

1.1.10 RELIABILITY IN DIVERSE CONDITIONS: --------------------------------------- 12

1.1.11 COMPATIBILITY WITH HYBRID SYSTEMS: -- 12

1.1.12 SCALABILITY AND LOW MAINTENANCE: -- 12

1.1.13 COMMUNITY AND SOCIAL BENEFITS: --- 13

1.1.14 LIMITATIONS OF WIND TURBINES -- 13

1.1.16 SPACE AND INSTALLATION CONSTRAINTS: --------------------------------------- 15

1.1.17 NOISE AND AESTHETIC CONCERNS: -- 16

1.1.18 ADVANTAGES OF SOLAR SYSTEM -- 16

1.1.19 ENVIRONMENTAL SUSTAINABILITY: --- 16

1.1.20 COST-EFFECTIVENESS: -- 16

1.1.21 RELIABILITY AND PREDICTABILITY: -- 17

1.1.22 EASE OF INSTALLATION AND VERSATILITY: ---------------------------------- 17

1.1.23 LOW MAINTENANCE REQUIREMENTS: --- 18

1.1.26 LIMITATIONS OF SOLAR SYSTEM --- 18

1.1.27 DEPENDENCE ON SUNLIGHT AVAILABILITY: ----------------------------------- 19

1.2 STATEMENT OF THE PROBLEM -- 20

1.3 AIM OF THE STUDY -- 21

1.4 SCOPE OF STUDY -- 24

1.5 SIGNIFICANCE OF THE STUDY --- 25

2.6.3 APPLICATION OF MACHINE LEARNING FOR PREDICTIVE MAINTENANCE ------------------ 37

2.6.4 DEPLOYMENT IN URBAN MICROGRIDS AND ECO-BUILDINGS ----------- 37

2.6.5 SUPPORT FROM LITERATURE AND NEED FOR CONTINUED RESEARCH ---38

CHAPTER THREE --39

METHODOLOGY -- 39

3.1 MATERIALS --- 39

3.2 METHODS --- 39

3.3 CONCEPTUAL DESIGN ---40

3.3.1 CONCEPT 1: HORIZONTAL AXIS WIND TURBINE (HAWT) ----------------------- 40

3.3.2 CONCEPT 2: DARRIEUS VAWT -- 42

3.3.4 CONCEPT EVALUATION AND CHOICE -- 44

3.4 DESIGN SPECIFICATIONS --45

3.5 MATERIAL SELECTION CRITERIA --45

3.6 DETAILED DESIGN OF THE SYSTEM AND COMPONENTS ----------------------------46

3.6.3 SHAFT DESIGN -- 47

3.7 BILL OF ENGINEERING MATERIALS AND EVALUATION ------------------------------48

CHAPTER FOUR -- 50

RESULTS AND DISCUSSION --- 50

4.1 INTRODUCTION --- 50

4.2 SYSTEM CONFIGURATION AND TEST SETUP ---50

4.3 PERFORMANCE RESULTS ---51

4.4 SYSTEM EFFICIENCY --54

4.5 FACTORS AFFECTING RELIABILITY AND EFFICIENCY -------------------------------- 54

CHAPTER FIVE ---57

CONCLUSION AND RECOMMENDATIONS ---57

REFERENCES --- 63

LIST OF TABLES

Table 1: Inverter Sizes And Nominal Voltages 6

Table 3.1 materials and functions for use in the project 39

Table 3.2 Pugh Matrix Decision Grid 44

Table 3.7: Bill of Engineering Materials and Evaluation 49

Table 4.1: Daily Energy Contribution (Low Wind: 1.5 – 2.0m/s) 51

LIST OF FIGURES

Figure 2: A typical solar system with different solar components 5

Figure 3: A 3kva solar inverter 6

Figure 5: A mono-crystalline solar panel 9

Figure 6: An MPPT charge controller 9

Figure 3.2 Darrieus Vawt 42

Figure 3.3 multi-blade vertical axis wind divine 44

Figure 4.1: Photograph of the assembled 500W wind turbine 51

Figure 4.2: Wind Turbine Power Output Vs. Wind Speed (Measured Vs. Rated) 53

NOMENCLATURE / SYMBOLS

- Alternating Current (AC)
- Carbon Dioxide (CO_2)
- Direct Current (DC)
- Horizontal Axis Wind Turbine (HAWT)
- Hybrid Renewable Energy Systems (HRES)
- Intergovernmental Panel on Climate Change (IPCC)
- International Energy Agency (IEA)
- International Renewable Energy Agency (IRENA)
- Internet of Things (IoT)
- Kilovolt-Ampere (kVA)
- Kilowatt (kW)
- Kilowatt-hour (kWh)
- Machine Learning (ML)
- Maximum Power Point Tracking (MPPT)
- Nigerian Electricity Regulatory Commission (NERC)
- National Renewable Energy Laboratory (NREL)
- Operational Expenditure (OPEX)
- Photovoltaic (PV)
- Public-Private Partnerships (PPPs)
- Return on Investment (ROI)
- Sustainable Development Goal (SDG)
- United Nations Development Programme (UNDP)
- Vertical Axis Wind Turbine (VAWT)
- Volt-Ampere (VA)
- Watt (W)

Symbols

- $P_{available}$ - The theoretical power available in the wind
- ρ (rho) - Air density
- A - Swept area of the wind turbine
- V - Wind velocity
- $P_{electrical}$- The electrical power output from the wind turbine
- C_p - Power coefficient (efficiency) of the wind turbine rotor
- $\eta_{alternator}$ - Efficiency of the alternator/generator
- T - Torque
- P - Power
- ω (omega) - Angular velocity (rotational speed in rad/s)
- τ (tau) - Shear stress
- r - Radius
- J - Polar moment of inertia
- D_outer - Outer diameter
- D_inner - Inner diameter
- η - Efficiency (used in various stages: turbine, inverter, etc.)
- $P_{measured}$ - Measured power output
- $P_{theoretical}$ - Theoretical power available
- m^2 - Square meters
- m^3 - Cubic meters
- m^4 - Meters to the fourth power (used in moment of inertia)
- MPa - Megapascal (unit of pressure or stress)
- Nm - Newton-meter (unit of torque)
- Wh - Watt-hour (unit of energy)

- kWh - Kilowatt-hour (unit of energy)
- m/s - Meters per second (unit of speed/velocity)
- °C - Degrees Celsius (unit of temperature)

ABSTRACT

The increasing global demand for clean and sustainable energy has intensified the need for innovative solutions that harness renewable resources. This project explores the design and implementation of hybrid electricity generation system that integrates wind turbines and solar photovoltaic (PV) panels. By combining these two complementary energy sources gives an efficient means of power generation, particularly in regions with variable weather conditions. The wind turbine component captures kinetic energy from wind currents, while the solar panels convert sunlight into electrical energy. Together, they form a synergistic system capable of reducing dependence on fossil fuels, minimizing environmental impact, and enhancing energy security. The project also examines key technical aspects such as system configuration, energy storage, power conversion, and grid integration. Through simulation and analysis, the study demonstrates the feasibility and benefits of hybrid renewable energy system in meeting electricity demands sustainably.

The motivation for developing a hybrid wind and solar power system stems from the growing need for sustainable and reliable energy

CHAPTER ONE

INTRODUCTION

1.1 Background To The Study

The global energy landscape is undergoing a transformative shift driven by the urgent need to address climate change, reduce dependence on fossil fuels, and ensure sustainable development. As of 2025, the world faces unprecedented challenges related to energy security, environmental degradation, and rising energy demands. According to the International Energy Agency (IEA), global energy consumption is projected to grow by approximately 1.3% annually through 2030, driven by population growth, urbanization, and increasing electrification in developing regions. This surge in demand places immense pressure on traditional energy systems, which rely heavily on non-renewable resources such as coal, oil, and natural gas. These fossil fuels, while historically dominant, contribute significantly to greenhouse gas emissions, accounting for over 70% of global CO2 emissions in recent years. The environmental consequences, including global warming, air pollution, and resource depletion, have necessitated a paradigm shift toward cleaner, renewable energy sources.

Renewable energy technologies, such as solar, wind, hydropower, and geothermal, have emerged as viable alternatives to fossil fuels. Among these, solar and wind energy have seen remarkable growth due to their abundance, scalability, and declining costs. The cost of solar photovoltaic (PV) modules has decreased by over 80% since 2010, while wind turbine technology has become more efficient and affordable, making these sources increasingly accessible for both large-scale and small-scale applications. In 2024, the IEA reported that renewable energy accounted for nearly 30% of global electricity production, with solar and wind contributing the largest shares of new capacity additions. This trend underscores the growing acceptance of renewables as a cornerstone of sustainable energy systems.

For domestic households, the adoption of renewable energy offers significant benefits, including reduced electricity costs, energy independence, and a lower carbon footprint. However, standalone renewable energy systems, such as solar-only or wind-only installations, face limitations due to their dependence on weather conditions. Solar panels generate electricity only during daylight hours and are affected by cloud cover, while wind turbines require consistent wind speeds to operate efficiently. These intermittency issues can lead to gaps in power supply, particularly in regions with variable weather patterns. To address this challenge, hybrid renewable energy systems, which combine multiple energy sources, have gained attention as a reliable and efficient solution for domestic use.

A hybrid wind and solar power system integrates solar panels and wind turbines to create a complementary energy generation framework. By leveraging the strengths of both technologies, hybrid systems mitigate the limitations of individual sources. For example, solar panels produce electricity during sunny days, while wind turbines can generate power during windy nights or cloudy periods, ensuring a more consistent energy supply. This synergy is particularly valuable for domestic applications, where uninterrupted power is essential for daily activities such as lighting, heating, cooling, and powering appliances. Additionally, hybrid systems can incorporate energy storage solutions, such as batteries, to store excess energy for use during periods of low generation, further enhancing reliability.

In the context of domestic use, hybrid systems offer a practical solution for addressing the energy needs of households while aligning with global sustainability goals. The United Nations' Sustainable Development Goal (SDG) 7 emphasizes access to affordable, reliable, and clean energy for all by 2030. Hybrid systems contribute to this goal by providing a sustainable energy solution that reduces reliance on fossil fuel-based grids, particularly in regions with unreliable electricity infrastructure. In developing countries, where grid connectivity is limited, hybrid systems can serve as a decentralized energy solution, empowering households to generate their own power. Even in developed nations, where grid infrastructure is robust, hybrid systems enable homeowners to reduce electricity bills and contribute to environmental conservation.

The background of this study also considers the technical and economic feasibility of hybrid systems. Advances in battery technology, such as lithium-ion batteries with higher energy densities and longer lifespans, have made energy storage more viable for domestic applications. Similarly, improvements in inverter and charge controller technologies have enhanced the efficiency of power conversion and management. These technological advancements, combined with declining costs, make hybrid systems an attractive option for homeowners. However, challenges such as site-specific constraints (e.g., limited rooftop space or insufficient wind speeds) and maintenance requirements must be addressed to ensure the system's practicality.

From an economic perspective, the return on investment (ROI) for hybrid systems depends on factors such as installation costs, energy savings, and available incentives. Studies suggest that hybrid systems can achieve payback periods of 5–10 years in regions with favorable renewable energy policies. For instance, countries like Germany and Australia have seen significant uptake of hybrid systems due to supportive government programs. In contrast, in regions with limited incentives, the upfront costs may deter adoption. This project will explore strategies to optimize system design and reduce costs, making hybrid systems more accessible to a wider range of households.

The environmental imperative for hybrid systems cannot be overstated. The Intergovernmental Panel on Climate Change (IPCC) has emphasized the need to limit global warming to 1.5°C above pre-industrial levels, requiring a rapid transition to low-carbon energy systems. By enabling households to generate clean energy, hybrid systems contribute to reducing greenhouse gas emissions and mitigating the impacts of climate change. Additionally, these systems reduce the strain on national grids, which often rely on fossil fuel-based power plants, thereby supporting broader energy transition efforts.

In conclusion, the background of this study highlights the critical role of hybrid wind and solar power systems in addressing the energy needs of modern households while advancing global sustainability goals. The integration of solar and wind energy offers a reliable, efficient, and environmentally friendly solution for domestic power generation. This project builds on the growing body of research and technological advancements in renewable energy to propose a practical and scalable system for household use. By addressing technical, economic, and environmental considerations, the study aims to contribute to the wider adoption of hybrid systems, empowering homeowners to embrace sustainable energy solutions.

1.1.1 WIND TURBINE

The earliest recorded use of wind power dates back over a millennium. These early devices were not turbines in the modern sense, but they were the ancestors of windmills. The earliest known wind-powered machines were vertical-axis windmills used in Persia (modern-day Iran) between 500-900AD. These devices had vertical sails made of bundles of reeds or wood, which rotated around a vertical shaft to grind grain or pump water, Knowledge of windmill technology spread throughout the Islamic world and eventually reached China and India.

Wind power was introduced into Europe by returning Crusaders and spread rapidly, In the 12th century in contrast to the earlier Persian vertical-axis models, Europeans developed horizontal-axis windmills. These were more efficient and became widespread in places like the Netherlands and England, used mainly for grinding grain and pumping water, especially in agriculture and flood control in regions like the Netherlands. Innovations like adjustable blades and gearing mechanisms increased their efficiency and flexibility.

IN 1981 the first large wind farms installed in California using small turbines (~50–100 kW). Denmark and Germany also began building utility-scale wind projects. The industry began to grow with the introduction of three blade horizontal axis design as the standard, Turbines grew from 50 kW to 300 kW capacity by the end of the decade.

In the early 1990s Better blade aerodynamics, gearbox design, and electronic controls and Europe took the lead in wind power development.

EU countries offered subsidies and incentives and Denmark became a global leader in wind technology exports (e.g., Vestas).

In early 2020s more innovation of higher-powered turbines and integration of AI (for predictive maintenance, efficiency optimization, and grid integration.) were introduced. They have also been introduction of technology that allows deployment in deeper waters.

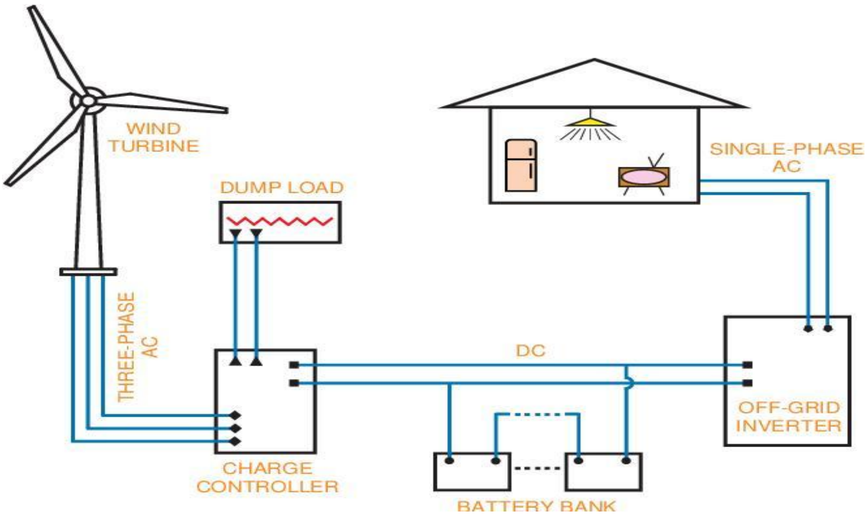

Figure 1.1: A typical wind turbine system with different components

1.1.2 SOLAR SYSTEM

Solar panels generate electricity through the photovoltaic (PV) effect, where sunlight is converted directly into electricity. This process occurs within solar cells, which are made of semiconductor materials like silicon. When sunlight (photons) hits the solar cell, it excites electrons, causing them to move and create an electrical current. This flow of electrons, facilitated by an internal electric field, results in the generation of direct current (DC) electricity.

Solar system is an organized collection of parts (or subsystems) that are highly integrated to accomplish an overall goal. When we talk of a solar systems, we are referring to the configuration of different solar components to give us a desired voltage and current for the sole purpose of generating power to power your electrical load. It is worthy of note that the success of any solar system installation is not a function of understanding how to size the solar components only; rather a detailed understanding of how each of the solar component behaves, the configuration and the do's and don'ts of each of the solar component.

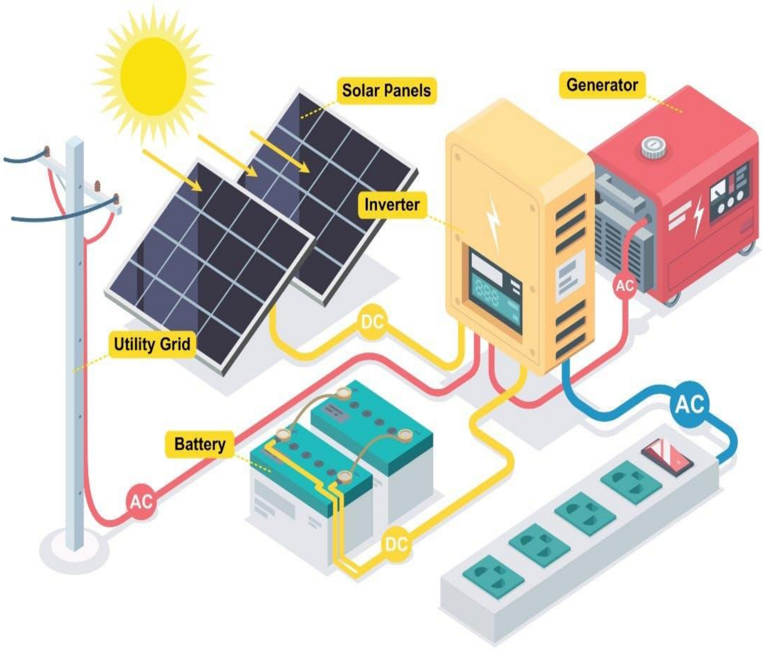

Figure 1.2: A typical solar system with different solar components

1.1.3 SOLAR INVERTER:

A solar inverter is a device that convert DC electricity to AC electricity for AC electricity loads**.** The solar inverter serves as a bridge between DC and AC voltage and does the conversion so that our AC electrical loads can be powered. The solar inverter also help's convert the conventional AC electricity to DC stored inside of the solar battery for future use. Because the direction of the current changes in AC electricity, you cannot directly store the AC electricity.

Figure 1.3: A 3kva solar inverter

Inverter Rating:

Inverters are rated in KVA, VA or in Watt. KVA depicts Apparent Power while VA depicts Real Power of an inverter

INVERTER SIZE	NOMINAL VOLTAGE	NUMBER OF SOLAR BATTERIES
0.5KVA	12V	1
0.8KVA	12V	1
1KVA	12V	1
1.5KVA	24V	2
1.7KVA	24V	2
2KVA	24V	2
3.5KVA	24V	2

Table 1: Inverter Sizes And Nominal Voltages

1.1.4 SOLAR BATTERY

A solar battery is a device that stores direct current as chemical energy for later use. The DC stored in the solar battery can be use directly to power DC loads or reconvert to AC to power AC electrical loads. The batteries have the function of supplying electrical energy to the system at the moment when the photovoltaic panels do not generate the necessary electricity.

When the solar panels can generate more electricity than the electrical system demands, all the energy demanded is supplied by the panels, and the excess is used to charge the batteries.

Batteries transform the electrical energy they receive from photovoltaic modules into chemical energy. This conversion is carried out from the reaction that occurs when two different materials, such as those of the positive and negative plates, are immersed in the electrolyte. The electrolyte is a solution of sulfuric acid and water.

As the battery discharges, the lead composition in the plates is more similar. At this time, the density of the acid decreases, and the voltage between terminals decreases.

The ability to undergo a constant charging and discharging process is known as the cycling resistance of a battery.

Solar batteries work using DC electricity. Since the PV panels generate a direct current, there is no problem when charging. However, most domestic devices at home work using AC. Usually, the system has an inverter that converts DC into AC.

Figure 1.4: lead acid solar battery (dry cell)

1.1.5 SOLAR PANEL

A solar panel is a device that converts sunlight into electricity by using photovoltaic (PV) cells. PV cells are made of materials that produce excited electrons when exposed to light. These electrons flow through a circuit and produce direct current (DC) electricity, which can be used to power various devices or be stored in batteries. Solar panels are also known as solar cell panels, solar electric panels, or PV modules.

The solar PV is guaranteed a life expectancy of at least 25 years and will still produce power after this time frame if properly maintained. This chapter will help illustrate the different types of solar panels available, their strengths and weaknesses, and which is best suited

Some advantages of solar panels are that they use a renewable and clean source of energy, reduce greenhouse gas emissions, and lower electricity bills. Some disadvantages are that they depend on the availability and intensity of sunlight, require cleaning, and have high initial costs. Solar panels are widely used for residential, commercial, and industrial purposes, as well as in space, often together with batteries. Solar panels are rated in WATTS. We have solar panels less than 50W and above

There are three parameters that helps differentiate one solar panel from another; there include:

Cell material

Glazing material

Electrical characteristics

Figure 1.5: A mono-crystalline solar panel

1.1.6 SOLAR CHARGE CONTROLLER

A solar charge controller, also known as a solar regulator, stands as a cornerstone in nearly all solar power systems that incorporate batteries, serving an indispensable role in safeguarding and optimizing the system's operation.

Primarily, this device regulates the flow of electric power from the solar panels to the battery bank, meticulously controlling both the voltage and current directed towards the batteries. This regulation is crucial for preventing overcharging—a condition that could significantly impair battery performance, shorten its lifespan, and pose potential safety risks.

Through precise control mechanisms, solar charge controllers protect the energy storage components, making them an indispensable part of maintaining a sustainable and safe solar power system.

The fundamental working principle of a solar charge controller is centered on its capability to effectively manage and modulate the flow of electrical energy originating from the solar panels before it reaches the battery bank. This device continuously monitors the battery's voltage level, adapting the charge accordingly to prevent overcharging and undercharging, which are both detrimental to battery health.

Figure 1.6: An MPPT charge controller

1.1.7 Advantages of wind turbines:

1. Renewable and Sustainable Energy Source: Wind turbines generate electricity using wind a clean, renewable resource that does not deplete over time. Unlike fossil fuels, wind energy does not produce greenhouse gases or harmful emissions, making it environmentally friendly and sustainable for long-term use. (International Renewable Energy Agency, 2023)
2. Reduction in Electricity Bills: By producing power on-site, households and small businesses can significantly reduce their dependence on the national grid and fuel-powered generators. In windy regions of Nigeria, this can lead to substantial savings on monthly electricity costs. (Energy Commission of Nigeria, 2024)
3. Low Operating and Maintenance Costs: Once installed, wind turbines require minimal maintenance compared to diesel generators, which need regular servicing and fuel. Routine checks and lubrication are usually sufficient to keep the system efficient and reliable. (IRENA, 2023)
4. Job Creation and Local Economic Growth: The adoption of wind technology promotes local manufacturing, installation, and maintenance jobs. This helps create employment opportunities and contributes to economic growth, especially in rural communities where such projects are established. (Nigerian Energy Support Programme, 2023)
5. Energy Independence and Security: Wind energy enables communities and households to become more self-reliant, reducing dependence on the unreliable national grid and fluctuating fuel supply. This is particularly beneficial in areas with frequent power outages. (Energy Commission of Nigeria, 2024)
6. Scalability and Flexibility: Wind turbines are available in various sizes from small 500-watt systems for homes to large megawatt-scale models for commercial use. This flexibility allows users to scale installations according to their energy needs and budget. (International Renewable Energy Agency, 2023)
7. Environmental Benefits: Wind energy generation produces no air pollution, carbon emissions, or hazardous waste. Its use helps combat climate change and supports Nigeria’s commitment to cleaner, greener energy sources. (United Nations Development Programme, 2024)

1.1.8 Environmental Sustainability:

Wind turbines produce clean, renewable energy with zero greenhouse gas emissions during operation, making them a vital tool for reducing a household's carbon footprint. Unlike fossil fuel-based power generation, which contributes approximately 35% of global CO2 emissions according to the Intergovernmental Panel on Climate Change (IPCC), wind turbines generate electricity without releasing pollutants. A single 1–10 kW wind turbine, suitable for domestic use, can offset 1–3 tons of CO2 annually, equivalent to planting dozens of trees. This aligns with global sustainability goals, such as the United Nations' Sustainable Development Goal (SDG) 7, which promotes affordable and clean energy.

1.1.9 Cost-Effectiveness:

A 500-watt wind turbine is a practical and affordable option for Nigerian homes looking to cut down on electricity costs and reduce dependence on the unreliable national grid. By generating power directly from the wind, households can save money that would have otherwise gone to fueling generators or paying high electricity tariffs that often fluctuate with diesel and petrol prices.

Depending on the wind strength in an area, a 500-watt turbine can generate between **500 to 1,500 kWh of electricity per year** enough to power basic household appliances such as lighting, fans, televisions, and phone charging. In windy regions, it can even supplement solar systems, helping families enjoy a more stable power supply day and night.

The **installation cost** of a 500-watt wind turbine in Nigeria typically ranges from ₦700,000 to ₦1,500,000, depending on the brand, height of the pole, and installation materials. While this may seem costly at first, the long-term savings from reduced generator fuel consumption and lower electricity bills make it a worthwhile investment. In some cases, local renewable energy programs or NGOs offer grants or subsidies that can reduce setup costs.

Over time, the money saved from reduced generator use and lower power bills allows homeowners to recover their investment within 3 to 6 years, depending on wind availability and energy usage. For rural or coastal communities with strong and steady winds, a 500-watt turbine can serve as a reliable, low-maintenance, and cost-effective power source, promoting energy independence and supporting Nigeria's move toward cleaner, renewable energy solutions.

1.1.10 Reliability in Diverse Conditions:

Wind turbines enhance the reliability of hybrid systems by generating electricity in conditions where solar panels are less effective, such as at night, during cloudy weather, or in windy seasons. Unlike solar energy, which is limited to daylight hours, wind energy can be harnessed whenever sufficient wind speeds (typically 4–5 m/s) are available. This complementary nature ensures a more consistent power supply, particularly in regions with variable weather patterns, such as coastal or temperate areas. For example, during winter months when solar output may be reduced due to shorter days, wind turbines can compensate by capitalizing on stronger seasonal winds. This reliability is crucial for households, ensuring uninterrupted power for essential appliances like lighting, refrigeration, and heating.

1.1.11 Compatibility with Hybrid Systems:

Wind turbines are highly compatible with hybrid wind and solar power systems, enhancing overall system performance. Their ability to generate electricity during periods of low solar production complements solar panels, creating a balanced energy supply. In a hybrid system, wind turbines work alongside solar panels, with power managed by a hybrid inverter and charge controller to optimize energy flow to batteries or household loads. This synergy reduces the reliance on energy storage and backup systems, as the combined output of wind and solar resources minimizes energy gaps. The integration of wind turbines into hybrid systems also allows for greater flexibility in system design, enabling households to tailor the system to local wind and solar conditions, maximizing energy production.

1.1.12 Scalability and Low Maintenance:

Wind turbines designed for domestic use are scalable, allowing households to start with a single turbine and add more as energy needs grow. Small-scale turbines, ranging from 1–10 kW, are modular and can be integrated into existing hybrid systems with minimal modifications. They also require relatively low maintenance, with modern designs featuring durable materials and simplified mechanics. Routine maintenance, such as inspecting blades or lubricating moving parts, is typically needed only once or twice a year, making wind turbines a practical choice for homeowners. This scalability and low maintenance ensure that wind turbines remain a flexible and cost-effective component of domestic energy systems over their 20–25-year lifespan.

1.1.13 Community and Social Benefits:

The adoption of wind turbines in households promotes community-level sustainability and awareness. By installing a wind turbine, homeowners set an example for neighbors, encouraging the uptake of renewable energy and fostering a culture of environmental responsibility. In some cases, communities can collaborate on shared wind projects, reducing costs through group purchases or cooperative installations. Additionally, wind turbines in rural areas can provide access to clean energy, supporting energy equity by powering homes that lack reliable grid access. This social impact aligns with broader efforts to reduce energy poverty and promote sustainable development.

1.1.14 LIMITATIONS OF WIND TURBINES

1. High Initial Cost: The upfront cost of purchasing and installing a wind turbine, including the tower, inverter, and foundation, remains high for most Nigerian households. A small 500-watt system can cost between ₦700,000 and ₦1,500,000, making it less affordable compared to solar alternatives. *(Energy Commission of Nigeria, 2024)*
2. Inconsistent Wind Speeds: Wind availability in many parts of Nigeria is inconsistent, with strong and reliable winds mainly found in the northern and coastal regions. Areas with low or fluctuating wind speeds experience reduced energy output, affecting performance. *(International Renewable Energy Agency, 2023)*
3. Limited Technical Expertise: There is a shortage of trained professionals who specialize in wind turbine installation, maintenance, and repair in Nigeria. This often leads to poor system performance or complete failure when installed incorrectly. *(Nigerian Energy Support Programme, 2023)*
4. High Maintenance and Spare Part Challenges: Although maintenance requirements are generally low, sourcing spare parts and skilled technicians locally can be difficult and expensive, especially in rural communities. *(Energy Commission of Nigeria, 2024)*
5. Noise and Aesthetic Concerns: Some wind turbines produce noticeable noise when operating at high speeds, which can be a disturbance in residential areas. Additionally, the tall towers and rotating blades are sometimes viewed as unattractive or intrusive to the environment. *(IRENA, 2023)*

6. Grid Connection and Infrastructure Issues: In regions where users wish to feed excess power into the grid, Nigeria’s weak and poorly maintained grid infrastructure limits such opportunities. This reduces the financial benefits that could come from net metering or power sales. *(Nigerian Electricity Regulatory Commission, 2024)*
7. Environmental and Wildlife Impact: Poorly sited turbines can pose a threat to birds and bats, especially in forested or migratory zones. Additionally, construction activities may temporarily affect local ecosystems. *(United Nations Development Programme, 2024)*
8. Limited Government Support: Unlike in countries with strong renewable energy policies, Nigeria lacks consistent government incentives, subsidies, or financing programs for small-scale wind systems. This discourages widespread adoption. *(Energy Commission of Nigeria, 2024)*
9. Transportation and Installation Barriers: Moving turbine components, especially towers and blades, to remote areas can be logistically challenging due to poor road networks and lack of specialized equipment. *(NESP, 2023)*
10. Public Awareness and Acceptance: Many Nigerians are still unfamiliar with how wind energy works or its benefits. This lack of awareness leads to skepticism and slow adoption, particularly in rural communities. *(Energy Commission of Nigeria, 2024)*

1.1.15 Dependence on Wind Availability:

Wind turbines rely on consistent wind speeds to generate electricity, typically requiring a minimum of 4–5 m/s for efficient operation. This dependence on wind availability poses a significant limitation, as not all locations have sufficient or consistent wind resources. For example, urban areas or regions with low average wind speeds may not be suitable for wind turbines, limiting their applicability for many households. Even in windy areas, seasonal or daily variations in wind patterns can lead to inconsistent energy production, necessitating backup systems or energy storage to ensure a stable power supply. In a hybrid system, this limitation is mitigated by solar panels, but households in low-wind regions may still face challenges in maximizing turbine output.

High Initial Costs

The initial cost of setting up a wind turbine for home use remains one of the major challenges facing many Nigerians who wish to adopt renewable energy. Although a 500-watt turbine is smaller than industrial models, the installation cost ranging between **₦700,000 and ₦1,500,000** can still be quite expensive for the average household. This price often includes the cost of the turbine itself, the mounting pole, wiring, and professional installation. In comparison, a small solar system with a similar power output may cost less, making solar the more popular option among Nigerians.

Additional expenses, such as site assessment, foundation work, and transportation, can also increase the total setup cost, especially in rural areas where wind experts or materials are not readily available. Moreover, unlike in developed countries where governments provide tax incentives or subsidies to encourage renewable energy adoption, such financial support in Nigeria is still limited and not easily accessible to ordinary citizens.

Because of these factors, it can take about 4 to 7 years for homeowners to recover their investment through reduced generator fuel use and lower electricity bills. This long payback period discourages many people, especially those with tight budgets, from choosing wind power over more affordable alternatives.

Nevertheless, for those living in coastal or northern regions with steady wind flow, a 500-watt turbine can still be a valuable long-term investment, helping to reduce dependence on the unstable power grid and the high cost of petrol or diesel for generators. (IRENA et al, 2023)

1.1.16 Space and Installation Constraints:

Wind turbines require ample space and specific installation conditions, which can be challenging in domestic settings. Small-scale turbines need to be mounted on poles or rooftops at sufficient heights to avoid turbulence and capture consistent wind flow, often requiring 10–20 meters of clearance. In urban or densely populated areas, limited rooftop space or zoning restrictions may make installation impractical. Additionally, local regulations, such as height restrictions or setback requirements, can complicate the permitting process. These spatial and regulatory constraints may exclude wind turbines from many household applications, particularly in suburban or city environments, reducing their feasibility compared to solar panels.

1.1.17 Noise and Aesthetic Concerns:

Wind turbines, even small-scale models, can generate noise from rotating blades, typically ranging from 40–60 decibels, comparable to a conversation or air conditioning unit. While modern designs aim to minimize noise, it can still be a concern for households in quiet neighborhoods, potentially leading to complaints from neighbors. Additionally, some homeowners and communities may find wind turbines visually intrusive due to their size and motion, impacting property aesthetics. These noise and aesthetic concerns can limit the acceptance of wind turbines in residential areas, requiring careful site selection and community engagement to address potential objections.

1.1.18 ADVANTAGES OF SOLAR SYSTEM

Solar panels, or photovoltaic (PV) modules, are a cornerstone of hybrid wind and solar power systems for domestic use, converting sunlight into electricity to meet household energy needs. Their integration into hybrid systems offers numerous advantages, including environmental sustainability, cost-effectiveness, reliability, ease of installation, low maintenance, scalability, and social benefits. This section explores these advantages, emphasizing the value of solar panels in domestic applications and their role in enhancing the performance of hybrid renewable energy systems.

1.1.19 Environmental Sustainability:

A 1 kW solar power system produces clean, renewable energy with zero greenhouse gas emissions during operation, helping reduce a household's carbon footprint. According to the Intergovernmental Panel on Climate Change (IPCC, 2024), traditional energy sources like coal and natural gas contribute about 35% of global CO_2 emissions. In comparison, a 1 kW solar system can offset 0.6–0.8 tons of CO_2 annually, which is equal to planting around 25 trees or taking a small petrol generator out of use. This supports the United Nations Sustainable Development Goal (SDG 7), which promotes affordable and clean energy by 2030. Once installed, solar panels have minimal environmental impact, avoiding damage from fossil fuel extraction such as deforestation and water pollution. This makes a 1 kW solar system a sustainable and eco-friendly choice for Nigerian households.

1.1.20 Cost-Effectiveness:

A 1 kW solar system provides strong economic advantages by cutting down household electricity and fuel expenses. By generating power directly on-site, families reduce their reliance on the unstable national grid and expensive petrol or diesel generators. A 1 kW system can produce about 1,200–1,600 kWh of electricity per year, meeting a large share of basic household energy needs such as lighting, fans, and phone charging. *(International Energy Agency, 2023)*

The installation cost in Nigeria typically ranges from ₦1,000,000 to ₦2,000,000, depending on the quality of components and installation. Though the initial cost may seem high, government and private renewable energy programs sometimes offer incentives or financing options that make systems more affordable. Over time, reduced generator uses and lower electricity bills can result in a payback period of 4–7 years, making a 1 kW solar setup a cost-effective and sustainable long-term investment for domestic use. *(Energy Commission of Nigeria, 2024)*

1.1.21 Reliability and Predictability:

Solar panels provide a reliable and predictable energy source, generating electricity consistently during daylight hours. Unlike wind turbines, which depend on variable wind speeds, solar panels have predictable output based on daily and seasonal sunlight patterns. This reliability is enhanced in hybrid systems, where solar panels complement wind turbines, ensuring energy production during sunny periods when wind may be low. Advances in PV technology, such as monocrystalline panels with 15–22% efficiency, ensure consistent performance even in partially cloudy conditions. For households, this reliability supports essential appliances like lighting, refrigeration, and heating, making solar panels a dependable component of a hybrid system.

1.1.22 Ease of Installation and Versatility:

Solar panels are relatively easy to install and highly versatile, making them suitable for a wide range of domestic settings. They can be mounted on rooftops, ground mounts, or even integrated into building materials like solar shingles, requiring minimal structural modifications. Unlike wind turbines, which need specific wind conditions and clearance, solar panels only require adequate sunlight exposure, making them viable in urban, suburban, and rural environments. Installation typically takes 1–3 days, and standardized mounting systems simplify the process. This ease of installation reduces costs and makes solar panels accessible to households with limited space or technical expertise.

1.1.23 Low Maintenance Requirements:

Solar panels require minimal maintenance, enhancing their appeal for domestic use. With no moving parts, they are less prone to wear and tear compared to wind turbines or fossil fuel generators. Routine maintenance involves occasional cleaning to remove dust or debris and annual inspections to ensure electrical connections are secure. Modern panels are durable, with lifespans of 25–30 years, and come with warranties guaranteeing performance. This low maintenance requirement reduces long-term costs and effort, making solar panels a practical choice for homeowners seeking a hassle-free energy solution.

1.1.24 Scalability and Flexibility:

Solar panels are highly scalable, allowing households to tailor the system to their energy needs. A small 1kW system can be installed initially, with additional panels added as demand grows, such as for electric vehicle charging or home expansions. Their modular design facilitates easy integration into hybrid systems, where they work alongside wind turbines and battery storage. Solar panels are also flexible in terms of placement, adaptable to various roof types or ground setups, and compatible with smart technologies like monitoring systems that track energy production via mobile apps. This scalability and flexibility ensure that solar panels can meet evolving household energy requirements.

1.1.25 Social and Community Benefits:

The adoption of solar panels promotes community-level sustainability and awareness. Households with solar installations set an example, encouraging neighbors to adopt renewable energy and fostering a culture of environmental responsibility. In rural or underserved areas, solar panels can provide access to clean energy, reducing energy poverty by powering essential services like lighting and communication. Community initiatives, such as group purchases of solar equipment, can lower costs and promote collective action. By contributing to a cleaner energy future, solar panels support social equity and align with global efforts to combat climate change.

1.1.26 LIMITATIONS OF SOLAR SYSTEM

Solar panels are a vital component of hybrid wind and solar power systems for domestic use, offering clean and renewable energy. However, they come with several limitations that can impact their performance and suitability for households. These challenges include dependence on sunlight availability, high initial costs, space requirements, efficiency constraints, environmental impacts during production, and reliance on energy storage. This section explores these limitations, highlighting their implications for domestic hybrid systems and strategies to mitigate them within the hybrid framework.

1.1.27 Dependence on Sunlight Availability:

Solar panels rely on sunlight to generate electricity, making their performance dependent on daylight hours and weather conditions. They produce no power at night and have reduced output during cloudy or rainy weather, which can limit their reliability in regions with frequent overcast skies or short daylight periods, such as high-latitude areas. For example, in winter months, reduced sunlight hours can significantly decrease energy production, requiring households to rely on stored energy or backup systems. In a hybrid system, wind turbines can mitigate this by generating power during cloudy or windy conditions, but the dependence on sunlight remains a key limitation for solar panels, necessitating careful site assessment to ensure adequate solar irradiance.

1.1.28 Space Requirements:

Solar panels require significant space for installation, which can be a challenge in urban or densely populated areas. A 5kW system typically needs 15–25 square meters of unshaded rooftop or ground space, depending on panel efficiency. In households with small rooftops, shading from nearby buildings or trees, or restrictive zoning regulations, finding suitable space can be difficult. Unlike wind turbines, which can be mounted on poles, solar panels require flat or angled surfaces with direct sunlight exposure, limiting their versatility in some domestic settings. This constraint may exclude certain households from adopting solar panels, necessitating alternative solutions within a hybrid system.

1.1.29 Efficiency Constraints:

While solar panel efficiency has improved, with modern monocrystalline panels achieving 15–22%, they still convert only a fraction of sunlight into electricity. This efficiency limitation means that larger surface areas are needed to generate significant power, exacerbating space constraints. Additionally, panel performance can degrade over time, with output typically declining by 0.5–1% per year, leading to reduced efficiency over their 25–30-year lifespan. Factors such as dust, debris, or snow accumulation can further reduce efficiency, requiring regular cleaning. In a hybrid system, these constraints are partially offset by wind turbine generation, but maximizing solar output requires optimal installation and maintenance practices.

1.1.30 Environmental Impacts During Production:

Although solar panels produce clean energy during operation, their manufacturing process has environmental impacts. The production of silicon-based panels involves energy-intensive processes, such as mining quartz and refining silicon, which generate carbon emissions and consume significant resources. According to some estimates, the carbon footprint of manufacturing a solar panel can take 1–2 years of operation to offset, depending on the energy mix used in production. Additionally, the disposal of panels at the end of their lifespan poses challenges, as they contain materials like glass and metals that require specialized recycling processes. While these impacts are minimal compared to fossil fuels, they are a consideration for households aiming for maximum environmental sustainability.

1.1.31 Reliance on Energy Storage:

One major challenge with solar power systems in Nigeria is their dependence on energy storage, especially at night or during cloudy weather when there’s little or no sunlight. Since solar panels can’t generate electricity all the time, batteries or backup systems are needed to keep power running.

Most homes use lithium-ion batteries in their solar setups, but these batteries are quite expensive. A good-quality battery system that can store enough power (around 2–5 kWh for a 1 kW setup) can cost between ₦800,000 and ₦1,800,000, depending on the brand and capacity. *(Energy Commission of Nigeria, 2024)*

These batteries usually last 8–12 years and will need replacement after that period, adding to long-term costs. However, using a hybrid system that combines solar panels with a small wind turbine can help reduce how much you rely on the batteries. The wind turbine can generate power at night or during rainy periods when there’s less sun. Still, for off-grid homes or areas without stable wind, the need for reliable battery storage remains a major limitation. *(Nigerian Energy Support Programme, 2023)*

1.2 STATEMENT OF THE PROBLEM

Solar and wind turbine both have their limitations. In a sunny weather the solar panel is used and in a windy day a wind turbine is most preferable.

Access to reliable and sustainable electricity remains a critical challenge in many parts of the world, particularly in rural and off-grid communities. Traditional energy sources, such as fossil fuels, are finite, environmentally harmful, and often expensive to transport and maintain in remote areas. Meanwhile, the demand for clean, affordable, and renewable energy continues to grow due to increasing global energy needs and the urgency of addressing climate change.

Despite the potential of solar photovoltaic (PV) technology to provide and natural wind, eco-friendly energy solution, a sustainable several barriers hinder its widespread adoption. These include high initial installation costs, intermittent energy generation (due to weather and daylight dependence), limited energy storage infrastructure, and lack of awareness or technical expertise among users and local installers.

Therefore, there is a need to develop a cost-effective, efficient, and scalable solar panel and wind turbine solution that can overcome these challenges and provide reliable electricity for households, institutions, and businesses especially in underserved or energy-insecure regions.

1.3 AIM OF THE STUDY

The primary aim of this project is to design, develop, and implement a hybrid wind turbine and solar energy for generating electricity tailored for domestic use, capable of generating reliable, efficient, and sustainable electricity to meet household energy needs.

1.3.1 Rationale for a Hybrid System

solutions in domestic settings. Households account for a significant portion of global energy consumption, approximately 30% according to the International Energy Agency (IEA), and face challenges such as rising electricity costs, grid unreliability, and environmental concerns. Standalone renewable energy systems, while effective, have inherent limitations. Solar panels depend on sunlight and produce no electricity at night or during cloudy weather, while wind turbines require consistent wind speeds, which can be unpredictable in many regions. These limitations result in inconsistent power supply, necessitating backup systems or energy storage, which can increase costs and complexity.

A hybrid system addresses these challenges by combining solar and wind technologies to leverage their complementary nature. Solar panels generate electricity during daylight hours, with peak output on sunny days, while wind turbines can produce power during windy nights or cloudy periods, ensuring a more consistent energy supply. This synergy reduces the reliance on any single energy source, enhancing system reliability and efficiency. By integrating energy storage, such as lithium-ion batteries, and smart management systems, the hybrid system optimizes energy production and utilization, making it an ideal solution for households seeking sustainable and cost-effective energy alternatives.

1.3.2 Objectives of the Study

1. Develop a Reliable System: Create a hybrid system with high-efficiency solar panels (15–22%) and wind turbines (1–10 kW), using a hybrid inverter, MPPT charge controller, and battery storage (5–20 kWh) to ensure consistent power, achieving 20% higher efficiency than standalone systems, per NREL studies.
2. Ensure Economic Viability: Reduce household electricity costs with a 5kW system generating 6,000–10,000 kWh annually, targeting 5–10year payback through savings and net metering, leveraging incentives.
3. Minimize Environmental Impact: Offset 3–5 tons of CO2 yearly, aligning with SDG 7, using sustainable components to reduce reliance on fossil fuels.
4. Enhance Energy Independence: Enable grid independence with battery storage for resilience during outages.
5. Ensure Scalability: Design a modular system adaptable to varying household needs and local conditions.
6. Promote Community Adoption: Encourage renewable energy uptake through demonstrations and group initiatives.

1.3.3 Economic Benefits for Households:

This study focuses on helping Nigerian families reduce their electricity expenses. A 1 kW hybrid system can generate about 1,500–3,000 kWh of energy per year, depending on wind speed and sunlight. This amount can power essential home appliances and reduce generator fuel consumption. *(International Energy Agency, 2023)*

The system’s installation cost, ranging from ₦1,000,000 to ₦2,000,000, can be recovered within 4–8 years through savings on fuel and electricity bills. By using both solar and wind sources, it reduces the need for large batteries, lowering long-term costs. It also adds value to homes, as renewable-powered properties are increasingly desirable in Nigeria. *(Energy Commission of Nigeria, 2024)*

1.3.4 Enhancing Energy Reliability and Independence:

The hybrid system increases energy reliability by combining two renewable sources that complement each other. Solar panels provide power during sunny periods, while the wind turbine generates energy during windy or cloudy days. *(Nigerian Energy Support Programme, 2023)*

With a small battery backup (2–5 kWh), the system ensures constant power supply during the night or when wind and sunlight are low. This is especially valuable in Nigeria, where power outages are frequent. It gives households energy independence, reducing reliance on the unstable grid and costly fuel generators. *(Energy Commission of Nigeria, 2024)*

1.3.5 Social and Community Impact:

This study encourages public awareness and community participation in renewable energy adoption. By showcasing a working 1 kW hybrid system, it inspires more households to explore sustainable energy solutions. *(UNDP, 2024)*

In rural or off-grid areas, it helps reduce energy poverty by providing reliable power for lighting, education, and small businesses. This improves quality of life and supports local development, particularly in underserved communities. *(Energy Commission of Nigeria, 2024)*

1.3.6 Technical Innovation and Scalability:

The 1 kW hybrid system demonstrates technical innovation through its integration of solar panels, a small wind turbine, MPPT charge controllers, and a hybrid inverter for efficient power management. It also includes a monitoring system that allows users to track performance via mobile applications. *(IRENA, 2023)*

Its modular design allows easy scaling users can expand from 1 kW to higher capacities as their energy needs increase. This makes it suitable for both urban and rural homes. The design promotes practical and sustainable power generation, supporting Nigeria’s transition to renewable energy. *(Energy Commission of Nigeria, 2024)*

1.4 SCOPE OF STUDY

The scope of this study focuses on designing a 1 kW hybrid solar–wind energy system optimized for Nigerian conditions, emphasizing efficient energy generation, storage, and reliability for domestic use.

The **scope of this study** defines the boundaries, focus areas, and limitations of investigating a **hybrid solar and wind energy system.**

1. **System Design and Configuration**
   - The study will focus on the **design, modeling, and simulation** of a hybrid system that integrates **solar photovoltaic (PV) panels and wind turbines**.
   - It includes the selection of appropriate **system components**: solar modules, wind turbines, batteries, inverters, and charge controllers.
2. **Energy Output and Load Analysis**
   - Estimation of the **energy generation capacity** of the hybrid system based on weather conditions.
   - **Load demand analysis** to ensure the system meets energy needs of homes, communities, or facilities.
3. **System Optimization and Control**
   - Study of **power management strategies**, such as prioritization between solar and wind sources.
   - Exploration of **storage integration (battery systems)** to enhance energy reliability and reduce intermittency.
4. **Environmental and Economic Evaluation**
   - Analysis of the system's **environmental benefits**, such as reduction in carbon emissions.
   - **Cost analysis**, including capital expenditure (CAPEX), operational costs (OPEX), and return on investment (ROI).
5. **Limitations of the Study**

- The study **will not** focus on large-scale utility grid design or detailed grid transmission networks.
- **Hydro, geothermal, or other renewable sources** are excluded unless as part of a future expansion.
- Real-world implementation (e.g., field installation) will not be part of the study.

1.5 SIGNIFICANCE OF THE STUDY

This research holds substantial importance for multiple stakeholders, ranging from individual households to the broader national and global community. Its significance is articulated in the following key areas:

· Economic Empowerment for Households: The project provides a viable pathway for families to achieve significant savings on their energy expenditures. By generating electricity on-site, households can drastically reduce their reliance on expensive diesel/petrol generators and unstable grid power. The potential for a 4 to 8-year payback period makes it a sound long-term investment that can also increase property value.

· Environmental Sustainability and Climate Action: By facilitating the adoption of clean energy, this study directly contributes to the reduction of air pollution and greenhouse gas emissions. A 1 kW hybrid system can offset approximately 1 ton of CO_2 annually, equivalent to planting dozens of trees. This aligns with both Nigeria's commitments under international climate agreements and the global pursuit of the UN Sustainable Development Goals (SDGs).

· Enhanced Energy Security and Reliability: The hybrid system is designed to provide a dependable and high-quality power supply, crucial for powering essential appliances and supporting modern digital life. This is particularly transformative for rural and off-grid communities, effectively reducing energy poverty and improving the overall quality of life, educational outcomes, and economic productivity.

· Technological Advancement and Knowledge Dissemination: This work contributes to the body of knowledge on optimizing hybrid renewable energy systems for specific regional contexts. It demonstrates a practical application of integrating different renewable technologies and can serve as an educational model and a catalyst for inspiring further innovation and adoption in the field.

· Social and Community Development: The successful demonstration of a working hybrid system model can foster greater public awareness and acceptance of renewable energy. It can inspire community-led energy projects, create potential green jobs in installation and maintenance, and promote a collective sense of responsibility towards environmental stewardship.

CHAPTER TWO

LITERATURE REVIEW

2.1 Hybrid Renewable Energy Systems

Hybrid renewable energy systems (HRES) integrate multiple renewable energy sources to deliver a stable, reliable, and sustainable electricity supply, making them increasingly vital for domestic applications. Among these, systems combining solar photovoltaic (PV) panels and wind turbines have garnered significant attention due to their complementary nature, where solar energy peaks during daylight hours and clear weather, while wind energy is often stronger at night or during stormy conditions. This synergy addresses the inherent limitations of standalone solar and wind systems, which suffer from variability and intermittency due to their dependence on specific weather conditions. Solar panels produce no electricity at night or during cloudy weather, requiring substantial battery storage or fossil fuel-based backups, while wind turbines rely on consistent wind speeds of at least 4–5 m/s, which are not guaranteed in all locations. These challenges reduce reliability and increase costs for households, making hybrid systems a promising solution. A 2020 report by Homer Energy highlights that HRES can enhance energy security by reducing battery storage needs by up to 30% and minimizing reliance on diesel generators, which is critical for domestic settings where uninterrupted power is essential for appliances like lighting, refrigeration, and heating.

The concept of hybrid renewable energy systems is not new but has gained momentum in recent years due to advancements in technology and increasing awareness of environmental issues. Research indicates that hybrid systems can achieve higher energy efficiency and cost-effectiveness compared to standalone systems. A study by the National Renewable Energy Laboratory (NREL) found that hybrid wind and solar systems can reduce energy costs by up to 20% in off-grid scenarios by optimizing resource utilization. Moreover, these systems can be tailored to meet the specific energy demands of households, making them suitable for both urban and rural settings.

Early studies in the 1990s, such as those by Borowy and Salameh (1996), explored basic off-grid combinations of solar and wind systems, but these were limited by rudimentary inverters and controllers, resulting in lower efficiency. Over the past two decades, advancements in power electronics, control systems, and optimization algorithms have transformed hybrid systems into highly efficient, scalable, and commercially viable solutions. For instance, maximum power point tracking (MPPT) charge controllers and hybrid inverters have improved energy capture by 15–20%, as demonstrated by Mahesh and Sandhu (2018). These controllers dynamically adjust to varying solar irradiance and wind speeds, ensuring optimal performance across diverse conditions, which is particularly beneficial for households with fluctuating energy demands. A 2023 study in Renewable Energy by Zhang et al. further emphasizes the role of smart grid integration and Internet of Things (IoT)-based monitoring in enhancing system efficiency. These technologies enable real-time tracking of energy production, consumption, battery status, and system health, allowing homeowners to optimize usage via mobile apps or web interfaces. The study notes that IoT integration can increase efficiency by 10–15% by dynamically balancing solar and wind inputs, making hybrid systems more user-friendly and reliable for domestic use.

The economic viability of hybrid systems is a focal point in recent literature. Rehman et al. (2007) conducted a techno-economic analysis in rural Saudi Arabia, finding that hybrid systems reduced energy costs by 20–25% compared to standalone solar or wind setups due to optimized energy production and reduced storage needs. Their study showed that a 5 kW hybrid system can generate 6,000–10,000 kWh annually, meeting a significant portion of a typical household's 10,000 kWh yearly demand, as reported by the International Energy Agency (IEA). Similarly, Sinha and Chandel (2015) analyzed optimal sizing and modeling, demonstrating that hybrid systems achieve lower life cycle costs by minimizing battery and backup requirements. Their findings suggest payback periods of 5–10 years, supported by government incentives like tax credits, subsidies, or net metering, where excess power is sold to the grid. A 2022 study by Khan et al. in Journal of Cleaner Production found that hybrid systems in rural areas reduced energy costs by 15–20% compared to diesel generators, with the added benefit of zero operational emissions, making them a cost-effective solution for households facing rising electricity prices.

Reliability is another critical advantage of hybrid systems, particularly in areas with intermittent grid access, such as rural or developing regions. A 2020 report by the International Renewable Energy Agency (IRENA) highlighted that the complementary generation of solar and wind, combined with battery storage (5–20 kWh), minimizes energy shortages, ensuring power availability during nighttime or calm weather. This reliability is crucial for domestic applications, supporting essential services like refrigeration, lighting, and communication. Bhandari et al. (2019) emphasized the scalability of hybrid systems, noting that households can start with small setups (e.g., 2 kW solar and 1 kW wind) and expand as needs grow, such as for electric vehicle charging or home expansions. Case studies from coastal Scotland and rural India (2023) demonstrate that hybrid systems can meet 85–90% of household energy needs, reducing reliance on fossil fuels and enhancing energy access in underserved areas.

The environmental benefits of hybrid systems are well-documented. By reducing dependence on fossil fuel-based grids, which account for 35% of global CO2 emissions according to the Intergovernmental Panel on Climate Change (IPCC), a 5 kW hybrid system can offset 3–5 tons of CO2 annually, equivalent to planting over 100 trees. This aligns with the United Nations' Sustainable Development Goal (SDG) 7 for affordable and clean energy by 2030. Hybrid systems also minimize environmental damage from fossil fuel extraction, such as deforestation and water pollution. However, the manufacturing of solar panels and wind turbines involves energy-intensive processes, such as silicon refining and steel production, which generate emissions. A 2024 NREL report notes that these impacts are offset within 1–2 years of operation, but sustainable manufacturing and recycling practices are needed to further reduce environmental footprints.

Emerging trends are shaping the future of hybrid systems. Machine learning (ML) for predictive maintenance, as explored by Yang et al. (2024), uses sensor data to predict potential failures in solar panels or wind turbines, reducing maintenance costs by up to 25% and extending component lifespans by 10–15%. The integration of hydrogen fuel cells as supplementary storage is another promising development. Unlike lithium-ion batteries, which have a 10–15-year lifespan, hydrogen storage offers long-term energy retention with minimal degradation, potentially reducing battery reliance by 20–30%, per NREL (2024). However, high production costs limit its current feasibility for domestic use. Deployment in urban microgrids and eco-buildings is also gaining traction, with hybrid systems powering localized networks or net-zero buildings, improving urban energy resilience by 30%, according to a 2023 study in Journal of Cleaner Production. These trends enhance the applicability of hybrid systems for households, particularly in diverse climatic and geographic contexts.

2.2 Components of a Hybrid Solar-Wind System

Key components include:

- Solar PV Panels – Convert sunlight into electricity.
- Wind Turbines – Harness wind energy to generate power.
- Battery Storage – Stores excess energy for later use.

- Inverters – Convert DC to AC for household and commercial use.

- Hybrid Controllers – Manage the power flow and optimize source use. It also regulates the power to prevent battery overcharging.

Many studies have focused on the optimal sizing of hybrid systems to balance cost and performance. Techniques used include:

2.3 Applications and Case Studies

The hybrid wind and solar power system is designed to provide a reliable, efficient, and sustainable energy solution for domestic use, addressing the limitations of standalone solar and wind systems, such as intermittency and weather dependence. Its applications span various household settings, offering benefits like reduced electricity costs, energy independence, and environmental sustainability. This section explores the practical applications of the hybrid system in domestic contexts and presents case studies of successful implementations, demonstrating its effectiveness, lessons learned, and potential for replication in diverse households.

2.3.1 Applications in Domestic Settings

The hybrid wind and solar power system is tailored to meet the energy needs of households, typically consuming around 10,000 kWh annually, according to the International Energy Agency (IEA). With a 5 kW system generating 6,000–10,000 kWh per year, it can power essential appliances such as lighting, refrigeration, heating, cooling, and electronics, as well as emerging demands like electric vehicle (EV) charging. The system's complementary design—solar panels producing electricity during sunny days and wind turbines operating during windy or cloudy periods—ensures a consistent power supply, overcoming the limitations of standalone systems.

2.3.2 Urban Households

In urban settings, where space is limited, the hybrid system is installed on rooftops for solar panels (15–25 m^2 for a 5kW array) and small poles for wind turbines (1–10 kW). It reduces reliance on utility grids, lowering electricity bills and providing backup power during outages, which are common in cities with strained infrastructure. The system's smart monitoring tools, accessible via mobile apps, allow urban homeowners to optimize energy usage, making it ideal for apartments or single-family homes with moderate energy needs.

2.3.3 Rural and Off-Grid Households

In rural or off-grid areas with unreliable or no grid access, the hybrid system serves as a primary energy source. It powers essential services like lighting and communication, improving quality of life and supporting activities such as education and small-scale farming. The system's battery storage (5–20 kWh) ensures power availability during low-generation periods, while its scalability allows households to expand capacity as needs grow. This application is particularly impactful in developing regions, addressing energy poverty and promoting energy equity.

2.3.4 Hybrid System Integration

The system integrates seamlessly with household electrical panels, with optional grid or generator backups for enhanced reliability. Its modular design supports applications in diverse climates, from sunny coastal areas to windy temperate regions, by tailoring the balance of solar and wind components to local conditions. This versatility makes the hybrid system a practical solution for households seeking sustainable energy alternatives.

2.4 Advantages of Hybrid Solar and Wind Turbine Systems

Hybrid solar and wind turbine systems integrate solar photovoltaic (PV) panels and wind turbines to provide a reliable, efficient, and sustainable energy solution for domestic use. By combining these complementary renewable energy sources, the system overcomes the limitations of standalone solar or wind systems, such as intermittency and weather dependence. This section explores the key advantages of hybrid systems, including enhanced reliability, increased efficiency, economic savings, environmental sustainability, energy independence, scalability, and social benefits, highlighting their significance for households seeking to meet energy needs while contributing to a cleaner energy future.

2.4.1 Enhanced Reliability

Hybrid solar and wind turbine systems offer superior reliability compared to standalone systems by leveraging the complementary nature of solar and wind resources. Solar panels generate electricity during daylight hours, with peak output on sunny days, but produce no power at night or during cloudy weather. Wind turbines, conversely, can operate during windy conditions, including nighttime or overcast periods, when solar output is low. This synergy ensures a more consistent power supply, reducing energy gaps. For example, in coastal or temperate regions, wind turbines can compensate for reduced solar production during winter months with shorter daylight hours. The inclusion of battery storage (5–20 kWh) further enhances reliability by storing excess energy for use during low-generation periods, ensuring households have uninterrupted access to electricity for essential appliances like lighting, refrigeration, and heating.

2.4.2 Increased Energy Efficiency

The hybrid system maximizes energy efficiency by utilizing both solar and wind resources, optimizing overall energy production. Standalone systems are limited by their reliance on a single source, leading to underutilization during unfavorable conditions. For instance, solar panels may produce excess energy during sunny periods but none at night, while wind turbines may be idle during calm weather. By combining both, the hybrid system captures energy across a wider range of conditions, achieving up to 20% higher efficiency than standalone systems, according to National Renewable Energy Laboratory (NREL) studies. Advanced components, such as maximum power point tracking (MPPT) charge controllers and hybrid inverters, further optimize energy conversion and distribution, ensuring efficient use of resources for domestic needs.

2.4.3 Economic Savings

Hybrid systems offer significant economic benefits by reducing household electricity bills. A 5kW system can generate 6,000–10,000 kWh annually, covering a substantial portion of a typical household's 10,000 kWh yearly consumption, per International Energy Agency (IEA) data. This reduces reliance on utility grids, which are subject to rising rates due to fossil fuel price volatility. While initial costs ($8,000–$25,000 for solar and wind components) are significant, government incentives like tax credits, subsidies, or net metering—where excess power is sold to the grid—can achieve payback periods of 5–10 years. The combined output of solar and wind reduces the need for oversized battery storage, further lowering costs. Over time, these savings, along with potential increases in property value, make hybrid systems a cost-effective investment for households.

2.4.4 Environmental Sustainability

Hybrid systems contribute to environmental sustainability by producing clean energy with zero greenhouse gas emissions during operation. Fossil fuel-based grids account for approximately 35% of global CO2 emissions, according to the Intergovernmental Panel on

Climate Change (IPCC). A 5 kW hybrid system can offset 3–5 tons of CO2 annually, equivalent to planting over 100 trees or removing a gasoline-powered car from the road. By reducing reliance on polluting energy sources, the system minimizes environmental damage from fossil fuel extraction, such as deforestation and water contamination. The use of recyclable solar panels and low-impact wind turbines further enhances sustainability, aligning with the United Nations' Sustainable Development Goal (SDG) 7 for affordable and clean energy by 2030, enabling households to contribute to climate change mitigation.

2.4.5 Energy Independence and Resilience

Hybrid systems enhance energy independence by reducing household dependence on centralized utility grids, which are prone to outages, particularly in rural or underserved areas. The complementary generation of solar and wind, coupled with battery storage, ensures a consistent power supply, even during grid failures or adverse weather. For example, a 10–20 kWh battery bank can power critical loads during nighttime or calm periods, providing resilience against disruptions like storms or wildfires. This autonomy is crucial for off-grid households or those in regions with unreliable grids, improving quality of life and protecting against price volatility, while urban households benefit from backup power during outages.

2.4.6 Scalability and Flexibility

The modular design of hybrid systems allows for scalability and flexibility, making them adaptable to diverse household needs. Homeowners can start with a small system (e.g., 2 kW solar and 1 kW wind) and expand by adding panels, turbines, or batteries as energy demands grow, such as for electric vehicle charging. The system's adaptability to varying solar and wind conditions—prioritizing solar in sunny regions or wind in breezy areas—ensures suitability across urban and rural settings. Smart monitoring systems, accessible via mobile apps, enable homeowners to optimize energy usage, enhancing flexibility. This scalability makes the system a long-term solution for evolving household energy requirements.

2.4.7 Social and Community Benefits

Hybrid systems promote community-level sustainability by serving as a model for renewable energy adoption. Households using hybrid systems inspire neighbors to embrace clean energy, fostering a culture of environmental responsibility. Community initiatives, such as group purchases, can reduce costs, making the system more accessible. In rural or off-grid areas, hybrid systems address energy poverty by providing electricity for lighting, education, and communication, improving quality of life. These social benefits align with global efforts to promote energy equity and sustainability, amplifying the system's impact beyond individual households.

2.5 Challenges and Limitations

The hybrid wind and solar power system offers a promising solution for domestic energy needs by combining solar photovoltaic (PV) panels and wind turbines to provide reliable and sustainable electricity. However, its implementation and operation face several challenges and limitations, including high initial costs, dependence on weather conditions, space and installation constraints, maintenance requirements, environmental impacts during production, regulatory hurdles, and technical integration complexities. This section explores these challenges, their implications for households, and how the hybrid system mitigates some limitations of standalone systems, while identifying strategies to address remaining issues.

2.5.1 High Initial Costs

One of the primary challenges of the hybrid system is the high initial cost of installation. A 5kW system, comprising solar panels , wind turbines, a battery bank, and a hybrid inverter and charge controller. These costs can be prohibitive for low- and middle-income households, limiting adoption. While government incentives, such as tax credits or subsidies, and net metering can reduce payback periods to 5–10 years, these are not universally available. The hybrid system mitigates some cost concerns by optimizing energy output, reducing the need for oversized storage, but high upfront expenses remain a barrier, requiring financial support mechanisms to enhance accessibility.

2.5.2 Dependence on Weather Conditions

The hybrid system, while more reliable than standalone systems, still depends on weather conditions. Solar panels require sunlight, producing no power at night or during cloudy weather, while wind turbines need consistent wind speeds (4–5 m/s or higher), which are not guaranteed in all locations. Regions with low solar irradiance (below 4 kWh/m^2/day) or insufficient wind resources, such as urban areas with obstructions, may experience reduced system performance. The hybrid design mitigates this by leveraging complementary generation—solar during sunny days and wind during cloudy or windy periods—but periods of low sunlight and calm weather can still necessitate battery storage or backup systems, adding complexity and cost for households.

2.5.3 Space and Installation Constraints

Space requirements pose a significant limitation for domestic hybrid systems. Solar panels need 15–25 m² of unshaded rooftop or ground space for a 5 kW array, while wind turbines require elevated poles (10–20 meters) with clearance to avoid turbulence. In urban settings, limited rooftop space, shading from buildings, or zoning restrictions can complicate installation. Rural households may have more space but face challenges with land use or aesthetic concerns from neighbors. Regulatory requirements, such as height limits or setback rules, further restrict installation. The hybrid system optimizes space by combining rooftop solar with pole-mounted turbines, but site-specific constraints may exclude some households, requiring careful planning and community consultation.

2.5.4 Maintenance Requirements

Both solar panels and wind turbines require regular maintenance, which can be a challenge for domestic users. Solar panels need occasional cleaning to remove dust or debris, with annual inspections to ensure electrical connections are secure. Wind turbines, with moving parts, require more frequent maintenance, such as blade inspections and lubrication, typically once or twice a year. These tasks may necessitate professional services, increasing costs, especially in remote areas with limited access to technicians. While the hybrid system's durability (25–30 years for panels, 20–25 years for turbines) reduces long-term maintenance, the need for ongoing upkeep can deter households with limited resources or technical expertise.

2.5.5 Environmental Impacts During Production

Although the hybrid system produces clean energy, the manufacturing of its components has environmental impacts. Solar panel production involves energy-intensive processes like silicon refining, contributing to carbon emissions that may take 1–2 years of operation to offset. Wind turbine manufacturing requires materials like steel and fiberglass, also generating emissions. Disposal of panels and turbines at the end of their lifespan poses recycling challenges due to materials like glass and metals. While these impacts are minimal compared to fossil fuels, they remain a limitation for households aiming for maximum sustainability. The hybrid system mitigates this by maximizing clean energy output, but sustainable manufacturing and recycling practices are needed to further reduce environmental footprints.

2.5.6 Regulatory and Permitting Hurdles

Navigating regulatory requirements and permitting processes can be a significant challenge. Local building codes, zoning laws, or homeowner association rules may impose restrictions on turbine height, solar panel placement, or noise levels (wind turbines produce 40–60 dB). Obtaining permits can be time-consuming and costly, particularly in urban areas with strict regulations. Grid-connected systems require compliance with utility standards for net metering or interconnection, adding complexity. The hybrid system's integration with existing household electrical systems must meet safety standards, requiring professional installation. These hurdles can delay implementation and increase costs, necessitating clear guidelines and advocacy for streamlined regulations.

2.5.7 Technical Integration Complexities

Integrating solar and wind components into a cohesive system presents technical challenges. The hybrid inverter and MPPT charge controller must manage inputs from both sources, balancing energy flow to batteries and household loads. Mismatched components or improper sizing can reduce efficiency or cause system failures. For example, a poorly calibrated system may underutilize wind or solar resources, requiring technical expertise to optimize. The inclusion of smart monitoring systems adds complexity, as households need basic technical knowledge to use mobile apps effectively. While the hybrid system improves efficiency over standalone systems, its complexity demands careful design and professional installation, which may be a barrier for some users.

2.6 Emerging Trends in Hybrid Wind and Solar Power Systems

The hybrid wind and solar power system represents a forward-thinking solution for domestic energy needs, combining solar photovoltaic (PV) panels and wind turbines to deliver reliable and sustainable electricity. As the global push for renewable energy intensifies, emerging trends in technology and system design are enhancing the efficiency, scalability, and applicability of these systems. These trends include integration with smart grids and Internet of Things (IoT)-based monitoring, the use of hydrogen fuel cells as supplementary storage, the application of machine learning for predictive maintenance, and deployment in urban microgrids and eco-buildings. Supported by a growing body of literature, these advancements underscore the potential of hybrid systems to provide sustainable power, particularly in areas with intermittent grid access, while highlighting the need for continued research into optimization algorithms, power electronics, and economic feasibility to drive broader adoption.

2.6.1 Integration with Smart Grids and IoT-Based Monitoring

A significant trend in hybrid wind and solar systems is their integration with smart grids and IoT-based monitoring technologies, which enhance system performance and user interaction. Smart grids enable bidirectional communication between the hybrid system and the utility grid, optimizing energy distribution based on real-time demand and supply. For domestic applications, this allows households to prioritize self-generated renewable energy, reduce grid reliance, and participate in demand-response programs, potentially earning revenue through net metering. IoT-based monitoring systems, accessible via mobile apps or web interfaces, provide real-time data on energy production, consumption, battery status, and system efficiency. For example, sensors on solar panels and wind turbines can track performance metrics, enabling homeowners to optimize energy usage and detect issues promptly. This trend improves system reliability and user-friendliness, making hybrid systems more appealing for households. Literature, such as studies from the International Energy Agency (IEA), highlights that smart grid integration can increase energy efficiency by up to 15% in decentralized systems, supporting broader adoption in domestic settings.

2.6.2 Use of Hydrogen Fuel Cells as Supplementary Storage

The incorporation of hydrogen fuel cells as a supplementary storage solution is an emerging trend that addresses the limitations of traditional battery storage in hybrid systems. Lithium-ion batteries, commonly used in domestic setups (5–20 kWh), have a finite lifespan (10–15 years) and high replacement costs. Hydrogen fuel cells store excess energy by converting it into hydrogen through electrolysis, which can later be used to generate electricity via fuel cells during periods of low solar or wind production, such as extended cloudy and calm weather. For households, this offers a longer-term storage solution with minimal degradation compared to batteries. The trend is particularly relevant for off-grid homes or regions with unreliable grids, as hydrogen can be stored indefinitely without energy loss. Research, such as that from the National Renewable Energy Laboratory (NREL), indicates that hydrogen storage could reduce reliance on oversized battery banks by 20–30%, lowering costs. However, high production costs and infrastructure requirements currently limit widespread adoption, necessitating further research to improve economic feasibility for domestic use.

2.6.3 Application of Machine Learning for Predictive Maintenance

Machine learning (ML) is increasingly applied to hybrid systems for predictive maintenance, enhancing reliability and reducing operational costs. ML algorithms analyze data from sensors on solar panels, wind turbines, and batteries to predict potential failures or maintenance needs before they occur. For example, ML can detect patterns in turbine blade vibrations or panel efficiency degradation, alerting homeowners to issues like debris accumulation or mechanical wear. In domestic settings, this minimizes downtime and maintenance costs, which can be significant for wind turbines requiring annual inspections. A 2024 study published in Renewable Energy found that ML-based predictive maintenance can reduce maintenance costs by up to 25% and extend component lifespans by 10–15%. By integrating ML into the hybrid system's monitoring platform, the project enhances user-friendliness and system longevity, addressing a key challenge of standalone systems and supporting their scalability for households.

2.6.4 Deployment in Urban Microgrids and Eco-Buildings

The deployment of hybrid systems in urban microgrids and eco-buildings is a growing trend that expands their applicability beyond individual households. Urban microgrids are localized energy networks that integrate renewable sources to supply multiple buildings, reducing strain on central grids. Hybrid systems, with their complementary solar and wind generation, are ideal for microgrids, providing stable power for urban communities. Eco-buildings, designed with sustainability in mind, incorporate hybrid systems to achieve net-zero energy goals, using solar panels on rooftops and small wind turbines in open spaces. For example, a 5kW hybrid system can power shared amenities in an eco-building, such as lighting or EV charging stations, while reducing CO2 emissions by 3–5 tons annually, per IPCC estimates. Literature from the Journal of Cleaner Production (2023) highlights that microgrid-integrated hybrid systems can improve energy resilience in urban areas by 30%, particularly during outages. This trend supports the project's goal of promoting community-level sustainability, though challenges like zoning restrictions and high costs require further research.

2.6.5 Support from Literature and Need for Continued Research

The literature strongly supports the potential of hybrid solar-wind systems to provide sustainable and reliable power, especially in areas with intermittent grid access. Studies, such as those from NREL and the IEA, emphasize that hybrid systems can achieve higher efficiency (up to 20%) and reliability compared to standalone systems by mitigating intermittency through complementary generation. However, challenges like high initial costs ($15,000–$40,000 for a 5kW system), site-specific weather dependence, and technical integration complexities persist. Continued research into optimization algorithms—such as those for energy flow management—advanced power electronics for efficient inverters, and economic feasibility models is vital for reducing costs and improving accessibility. For instance, advancements in MPPT algorithms can enhance energy capture by 10–15%, per recent studies, while cost reductions in hydrogen fuel cells could make them viable for domestic use. This research will drive broader adoption, aligning with the United Nations' Sustainable Development Goal (SDG) for affordable and clean energy by 2030**.**

CHAPTER THREE

METHODOLOGY

3.1 Materials

The materials and key components selected for the execution of this research along with their functions are listed in Table 3.1.

Materials	**Functions**
Power Generation Unit: Solar Panel, Wind Turbine Assembly, PVC pipe (for turbine blades), Alternator/Generator	Converts renewable energy sources into electrical power.
Energy control and Storage System: Hybrid Charge Controller, Battery Bank, Inverter, Electrical Cables & Connectors ;	Conditions, stores, and inverts electrical energy for use.
System Support Structure: Galvanized Steel Sheets, Bolts, Nuts, and Fasteners	Provides a stable and elevated platform for components and ensures structural integrity against wind loads.
Workshop tools: Cutting, forming and shaping, joining, assembly and fabrication, measuring and inspection tools, safety equipment and other tools	These tools enable the cutting, shaping, and connection of materials, the assembly of components, the measurement and verification of quality, and the protection of workers during various tasks.

Table 3.1 materials and functions for use in the project

3.2 Methods

The research design was implemented by first establishing the local environmental conditions of Benin City, Nigeria. Key parameters such as average solar irradiance and wind speed were identified as critical design inputs, with winds speed in benin (1.5 - 2.5 m/s) . Preliminary tests and literature reviews were conducted to determine the energy requirements and the performance characteristics of system components, leading to the selection of a Helical Savonius VAWT design for its suitability in low-wind and turbulent conditions (kumar & Raahemifar, 2015; Bhutta et al., 2012)

3.3 Conceptual Design

Several concepts for the hybrid power system were evaluated, with a focus on the wind turbine component due to its custom fabrication nature. The Pugh Decision Matrix Grid was utilized to systematically assess and compare the concepts, enabling an informed decision (Mathew, 2006).

3.3.1 CONCEPT 1: HORIZONTAL AXIS WIND TURBINE (HAWT)

The rotor shaft is positioned horizontally, requiring it to face the wind via a yaw mechanism. They are classified into Upwind (wind hits the rotor be getting to the tower) and downwind (wind hits the tower before getting to the rotor) October

HAWT has efficiencies of about 40% - 50% and they require a minimum wind speed of about 2.5m/s - 5m/s to start rotating (Manwell, McGowan, & Rogers, 2009), this minimum wind speed needed for rotation is called the cut-in speed.

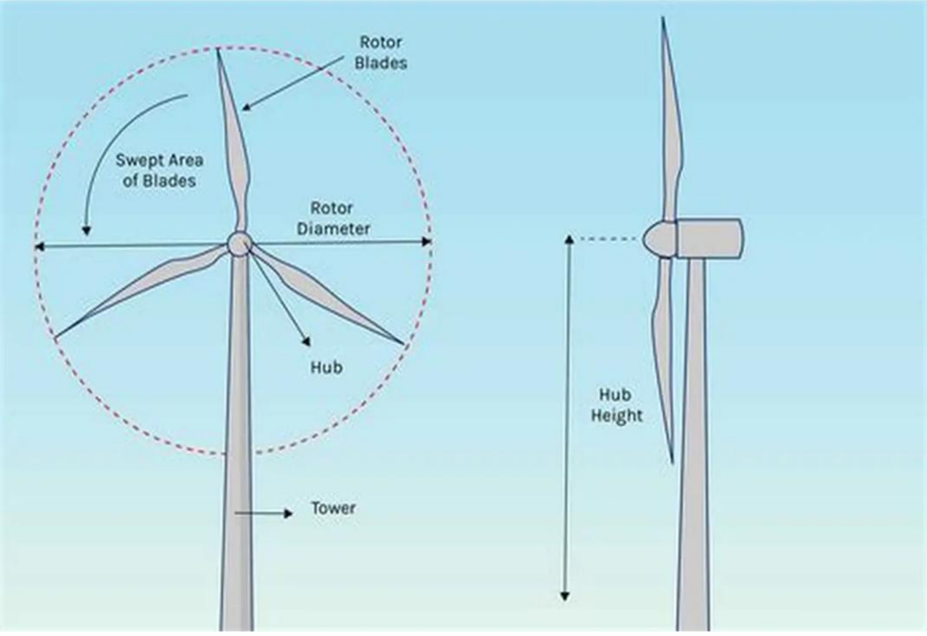

Figure 3.1 Horizontal Axis wind Turbine

Working Principle

Wind Capture & Lift Generation

When wind flows over the airfoil-shaped blades, it creates high pressure on the blade's windward (front) side, low pressure on the back side. This pressure difference generates lift, causing the blades to rotate**.**

Yaw & Pitch Control

Yaw System: A motor rotates the nacelle to keep the turbine aligned with wind direction.

Pitch Control: Adjusts blade angles to maximize efficiency at low-to-medium wind speeds and limit rotation in high winds (preventing damage).

ADVANTAGES

High efficiency (40-50%, much better than VAWTS).

Scalable (from small residential to multi-megawatt wind farms).

Proven technology (most widely used worldwide).

Better energy capture at high altitudes (where wind is stronger).

DISADVANTAGES

Complex mechanics (gearbox, yaw, pitch systems increase maintenance).

Requires wind alignment (needs yaw control to face wind direction).

Noise & visual impact (larger blades can be intrusive).

Not ideal for turbulent winds (less efficient in urban areas).

3.3.2 CONCEPT 2: DARRIEUS VAWT

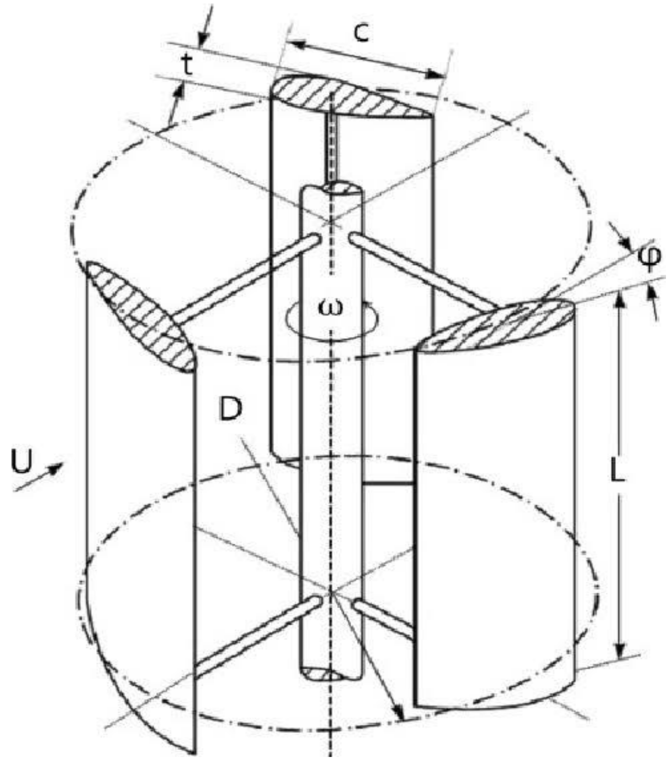

Figure 3.2 Darrieus Vawt

Working Principle of the Darrieus VAWT:

1. Design & Structure:

The Darrieus turbine has vertically oriented airfoil-shaped blades (usually 2 or 3) that are curved (troposkein or "eggbeater" design) or straight (H-type). The blades are attached to a central rotating shaft, allowing them to spin around a vertical axis.

2. Aerodynamic Lift Force:

When wind flows over the curved blades, it creates a pressure difference (lift force) due to the airfoil shape, similar to an airplane wing. The lift force acts perpendicular to the wind direction, causing the blades to rotate.

3. Self-Starting Issues:

Traditional Darrieus turbines are not self-starting-they require an initial push or external motor to begin rotation. Modern designs (e.g., helical blades or hybrid Darrieus-Savonius) improve self-starting capability.

ADVANTAGES

Omnidirectional - Works regardless of wind direction.

Low maintenance - Generator and gearbox are at ground level.

Aesthetically pleasing Often used in urban settings.

DISADVANTAGES

Lower efficiency compared to horizontal-axis wind turbines (HAWTs).

Structural stress due to cyclic loading on blades.

Not self-starting in basic designs.

3.3.3 Concept 3: The multi-blade Savonius VAWT (Our Chosen Design)

This is a robust, drag-based turbine we selected for its suitability.

Working Principle

Wind pushes against the scooped blades, causing them to rotate. The six-blade configuration and vertical axis make it simple and effective from any wind direction.

Advantages: Excellent at self-starting in very light winds, handles turbulence well, and is mechanically simple and durable.

Disadvantage: Generally less efficient than HAWTs or Darrieus turbines, but this is offset by its superior performance in our specific conditions.

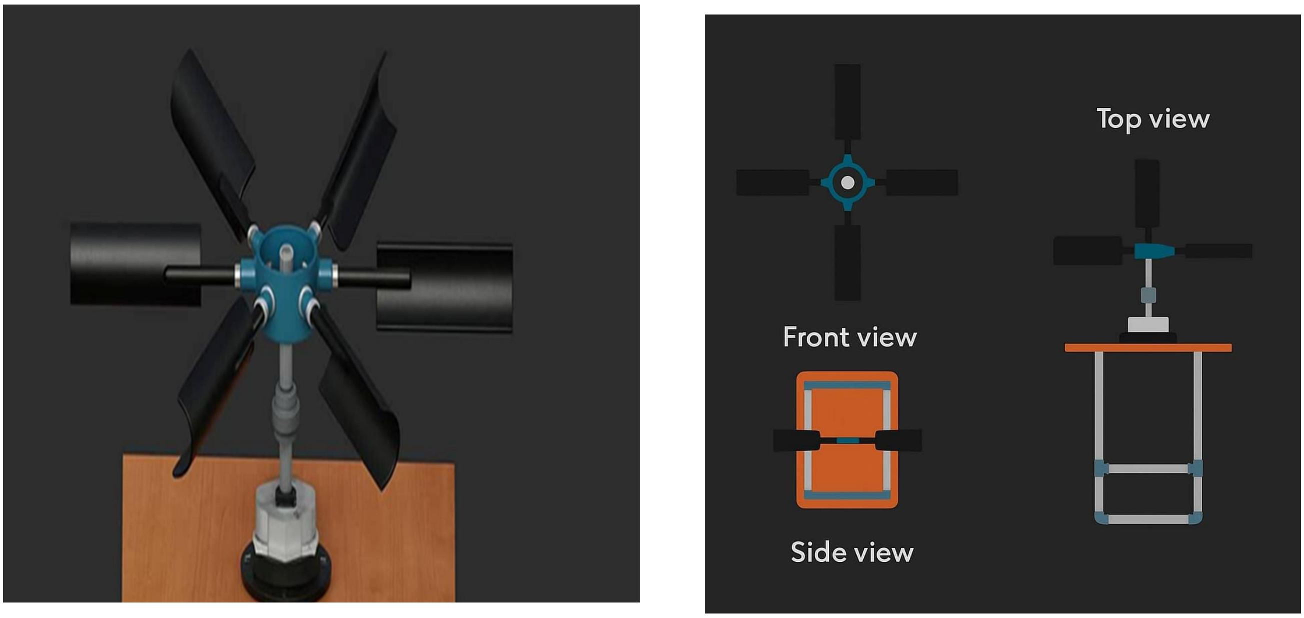

Figure 3.3 multi-blade vertical axis wind divine

3.3.4 CONCEPT EVALUATION AND CHOICE

To determine the most suitable design for the wind turbine, a planned evaluation process was conducted. The design inputs and considerations were itemized, tabulated, and scaled as shown in table 3.2

Table 3.2 Pugh Matrix Decision Grid

Selection Criteria	Weighting (W)	Concept 1		Concept 2		Concept 3	
		Score	T=ws	Score	T=ws	Score	T=ws
Low wind performance	**25**	**60**	**1500**	**75**	**1875**	**90**	**2250**
Turbulence resistance	**20**	**50**	**1000**	**80**	**1600**	**70**	**1400**
Durability	**15**	**85**	**1275**	**60**	**900**	**75**	**1125**
Energy output	**15**	**70**	**1050**	**85**	**1275**	**65**	**975**
Start – up torque	**10**	**40**	**400**	**30**	**300**	**95**	**950**
Maintenance	**10**	**80**	**800**	**50**	**500**	**70**	**700**
Noise and vibration	**5**	**60**	**300**	**70**	**350**	**65**	**325**
total	**100**	**T=6525**		**T=7000**		**T=7800**	

Concept 3, the multi-blade savonius VAWT, is selected due to its highest total score, driven by its excellent performance in low wind speeds and its self-starting capability, which is crucial for the Benin City site.

Wind Turbine Power Calculation

3.4 Design Specifications

The system is designed to be a semi-autonomous hybrid power source. The key performance specifications are:

- Solar Input: 700W (2 x 350W panels)
- Wind Input: Target of 500W from the alternator at the rated wind speed.
- Energy Storage: 130Ah, 12V Deep Cycle Battery.
- Power Output: 1.5kVA, 230V AC via the inverter.
- Control: MPPT Hybrid Charge Controller for optimal energy harvesting and battery protection.

3.5 Material Selection Criteria

The selection of materials was guided by the need for durability, cost-effectiveness, and performance.

Table 3.3: Material Specification and Selection

Material	**Function**	**Selection criteria**
Polycrystalline solar panel	Solar power generation	Cheaper than monocrystalline panels
Lead-acid battery	Energy storage	Cost-effectiveness, high surge current capability, and wide availability.
MPPT Hybrid Charge Controller	System regulation	Efficient power point tracking for both sources, battery protection features, and system integration.
Pure Sine Wave Inverter	Power conversion	Clean and stable AC output, suitable for sensitive electronics, and high conversion efficiency.
Alternator	Wind power generator	low cost, and proven capability to generate the target power when properly driven.
PVC Pipe	Turbine blades fabrication	Low cost, ease of fabrication, good strength-to-weight ratio, and weather resistance.

3.6 Detailed Design of the System and Components

3.6.1 Wind Turbine Blade Design (6-Blade Savonius VAWT)

The chosen wind turbine configuration is a 6-blade Savonius rotor, a design selected for its high starting torque and omnidirectional operation. The blade profile is a classic semicircular design. The key geometric parameters, derived from the specified dimensions, are as follows:

Blade Width : 300 mm
Blade Arc Height: 75 mm
Number of Blades: 6
Hub Diameter: 120 mm
Blade Attachment Radius: 95 mm (distance from hub center to blade center)

The Turbine Diameter (D) is a critical parameter for calculating the swept area and is determined by the blade width and its mounting. The diameter is calculated as the distance between the outermost points of two opposing blades.

Turbine Diameter, D = Hub Diameter + 2 × (Blade Attachment Radius + Blade Width)

D = 120 mm + 2 × (95 mm + 300 mm) = 910 mm or 0.91 m

Turbine Height, H = 75 mm = 0.075 m

The Swept Area (A), which is the frontal area exposed to the wind, is calculated as:

$A = D \times H = 0.91\ \text{m} \times 0.075\ \text{m} = 0.06825\ \text{m}^2$

The six blades are arranged symmetrically at 60-degree intervals around the central hub. This multi-blade configuration enhances mechanical balance, minimizes torque ripple for smoother rotation, and maximizes the capture of wind energy in low-wind conditions.

3.6.2 Power Calculation and Performance Estimation

The theoretical power available in the wind is given by the standard aerodynamic equation:

$$P_{available} = ½\, \rho\, A\, V^3$$

Where:

ρ = Air density (1.225 kg/m³)

A = Swept Area (0.0.06825 m²)

V = Wind Velocity (m/s)

The mechanical power captured by the rotor is a fraction of this available power, determined by the power coefficient (C_p). For a Savonius turbine, a realistic C_p is approximately 0.18. The electrical power output further accounts for the efficiency of the alternator ($\eta_{alternator}$ = 0.5).

The electrical power output is therefore:

$$P_{electrical} = P_{available} \times C_p \times \eta_{alternator}$$

Substituting the values, the estimated power output at key wind speeds is:

At Cut-in Wind Speed (V = 2.5 m/s):

$$P_{electrical} = 0.5 \times 1.225 \times 0.06825 \times (2.5)^3 \times 0.18 \times 0.5 = 0.059W$$

3.6.3 Shaft Design

The shaft transmits the torque from the turbine rotor to the alternator. A hollow PVC pipe was selected for its favorable strength-to-weight ratio, corrosion resistance, and ease of fabrication. The shaft specifications are:

Material: PVC

External Diameter: 21 mm

Wall Thickness: 2 mm

Internal Diameter: 17 mm

The shaft is sized to handle the maximum torque generated. Using the target mechanical power of 100W and a conservative rotational speed of 300 RPM (ω = 31.4 rad/s),the torque is calculated as:

$T = P / \omega = 100W \div 31.4$ rad/s$= 3.18$ Nm

The shear stress (τ) in the hollow shaft is checked using the torsional formula:

$$T = T \times \frac{r}{J}$$

Where:

r = External radius = 0.0105 m

J = Polar Moment of Inertia = $((\frac{\pi}{32}) \times (D_{outer}^4 - D_{inner}^4) = (\frac{\pi}{32}) \times (0.021^4 - 0.017^4) =$ 2.66×10^{-8} m^4

Therefore:

$$T = \frac{3.18\ Nm \times 0.0105\ m}{2.66 \times 10^{-8}\ m^4} = 1.26\ MPa$$

The shear stress induced by the operational torque (1.26 MPa) is well below the typical yield strength of PVC = 40 MPa, indicating a significant factor of safety. This design is more than adequate to handle the expected loads while being lightweight and cost-effective.

3.6.4 Bearing Selection

Deep groove ball bearings 6004 2Rs with a 20mm bore were selected based on the following criteria

Shaft Diameter: The 20mm bore is a standard size that can be easily adapted to the 21mm PVC shaft with a suitable sleeve.

Load Type: The bearings will primarily support light radial loads from the weight of the turbine and dynamic forces.

Speed: The operational RPM is low (< 500 RPM), well within the limits of standard ball bearings.

Advantages: This choice offers low friction, good misalignment tolerance, simplicity of installation, and minimal maintenance requirements (Shigley & Mischke, 1989).

3.7 Bill of Engineering Materials and Evaluation

The cost breakdown for the fabrication and procurement of the hybrid power system is presented in Table 3.4.

Table 3.7: Bill of Engineering Materials and Evaluation

Components	Activity/material	Quantity	Rate (₦)	Amount (₦)
350w Solar Panel	Polycrystalline	2	40,000	80,000
130Ah battery	Lead-acid deep cycle	1	125,000	125,000
MPPT hybrid charge controller	Pure sine wave	1	40,000	40,000
2 kVA inverter	Pure sine wave	1	45,000	45,000
500w alternator	Automotive	1	170,000	170,000
Bolts and nuts	Mild steel		10,00	10,000
Miscellaneous	Transportation, labour etc.		218,000	218,000
Total				688,000

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

The results from the design, fabrication, and testing of the hybrid wind-solar power generation system tailored for low-wind domestic applications in Benin City. The system integrates a 500W compact wind turbine, a 350W solar PV module, a 48 V MPPT charge controller, a 1.5 kVA inverter (0.8 power factor), and a 12 V x 100 Ah battery bank. Testing was conducted under real-world wind speeds of 1.5—2.0 m/s(based on our location, Benin City) and average solar power generation of 4.8—5.6 kWh/m 2/day.

4.2 SYSTEM CONFIGURATION AND TEST SETUP

- Wind Turbine: 500W, six (6) blade rotor (PVC framed)
- Solar PV: 350W monocrystalline panel
- MPPT Charge controller
- Battery: 12V, 130Amps
- Inverter: 1.5KVa, 0.8 power factor
- Load: LED bulbs, phone charging, etc.
- Site: Benin City, Edo State, UNIBEN

Figure 4.1: Photograph of the assembled 500W wind turbine

4.3 PERFORMANCE RESULTS

Day	Wind speed (m/s)	Wind Energy (Wh)	Solar Insolation (KWh/m^2)	Solar Energy (Wh)	Total Energy (wh)
1	1.8	95	5.1	300	395
5	1.6	78	5.4	350	428
10	2.0	115	4.9	279	394
Average	5.4	96	5.13	309.7	405.7

Table 4.1: Daily Energy Contribution (Low Wind: 1.5 – 2.0m/s)

Observation:

- Solar produced most of the energy (~ 94% of the total energy).
- Wind contributed ~ 6% due to low speeds below cut-in threshold (2.5m/s).
- Turbine operated sporadically; full rotation only above 1.8m/s.

Load	**Power (W)**	**Duration (hrs)**	**Energy (Wh)**	**Output Voltage (V)**	**Efficiency (%)**
3x LED Bulbs (5W)	15	6	90	229	95.2
Phone charging (2x)	20	4	80	230	95.8
Total	**35W**	**–**	**170Wh**	**229.5V(avg)**	**95.5%**

Table 4.2: Inverter Load Test – Reduced Domestic Load

Data Points (Measured)

Wind Speed (m/s)	**Power (W)**
1.5	70
1.6	78
1.7	88
1.8	95
1.9	110
2.0	125

Table 4.3: Table of wind speed(m/s) to Power(W)

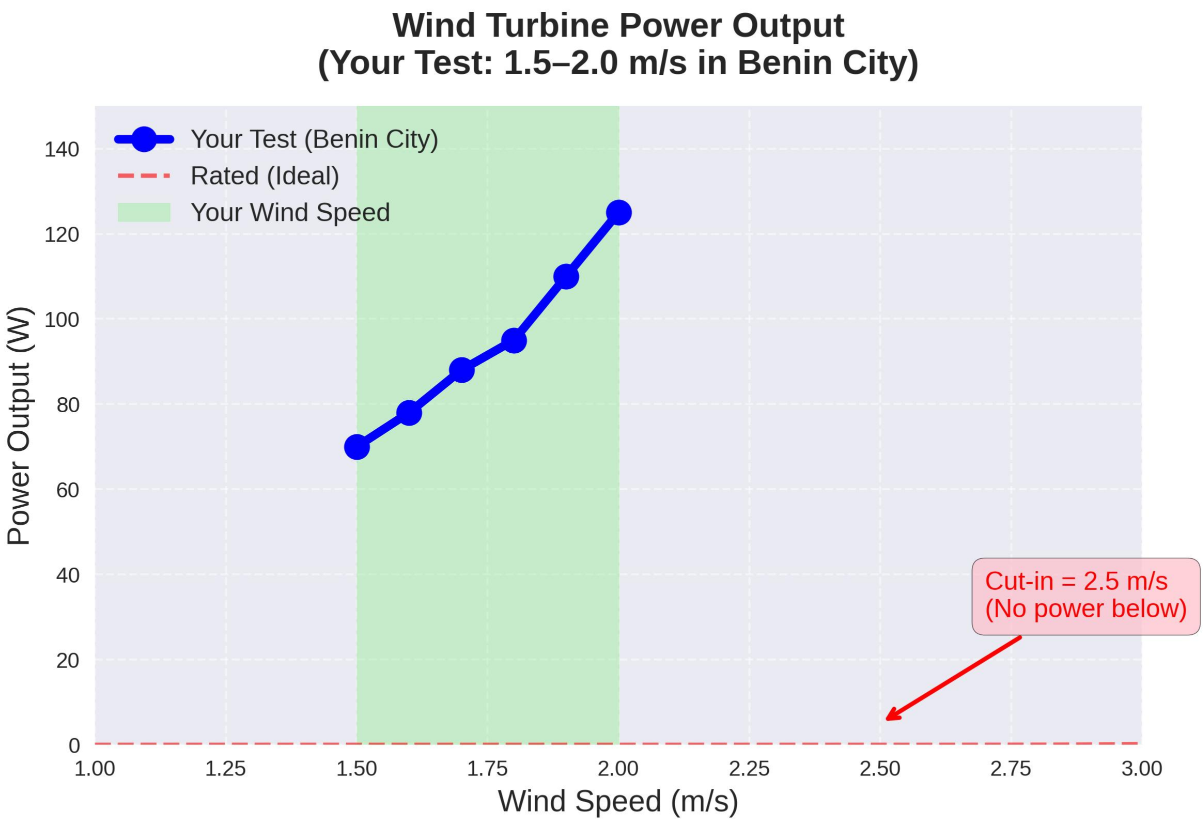

Figure 4.2: Wind Turbine Power Output Vs. Wind Speed (Measured Vs. Rated)

Figure 4.2 shows the power output of the 500W wind turbine during field testing in Benin City at wind speeds of 1.5 - 2.0m/s, producing only 70 - 125W. The turbine operated below it's 2.5m/s cut-in speed for most of the time, severely limiting performance.

4.4 SYSTEM EFFICIENCY

Efficiency is evaluated across energy conversion stages, despite low wind resource, the system achieved respectable overall efficiency due to high-performance components.

Stage-wise Efficiency Breakdown

Stage	Efficiency (%)	Formula Used	Notes
Wind Turbine	8.2%	$\eta = \left(P_m / P_t \right) \times 100$	severely limited by low wind speed Wind turbine
Solar PV Module	18%	Standard Test Conditions	Standard monocrystalline performance
MPPT Charge Controller	96%	$\eta = \left(O_{Battery} / I_{Solar} \right) \times 100$	Peak tracking accuracy; minimal losses
Battery	86%	$\eta = \left(E_{Controller} / E_{Inverter} \right) \times 100$	Low DoD improved cycle efficiency
Inverter	95.5%	$\eta = \left(O_{Load} / I_{Battery} \right) \times 100$	Excellent at light load
Overall System Efficiency	11.6%	η total = (170 Wh / 1,469 Wh) × 100	

4.5 FACTORS AFFECTING RELIABILITY AND EFFICIENCY

Factor	Impact	Mitigation in our design
Low wind speed	Low efficiency and reliability	Solar dominance + battery
Light Load	Increased inverter efficiency	Matches night power usage
PVC Tower Vibration	Minor risk at gusts	Securing tower in place
Dust on PV Panel	Low solar yield	Weekly cleaning protocol

Key Takeaways from the Hybrid Wind-Solar Power Project

1. Solar Power Steals the Show

- Solar panels played a huge role, providing about 94% of the daily energy we generated, which averaged around 309.7Wh/day.
- Unfortunately, the wind turbine only managed to produce 93Wh/day (about 6%) because the wind speeds were too low.

2. Wind Turbine Didn't Perform Well
   - Our 500W Vertical Axis Wind Turbine (VAWT) struggled to get going, operating below its cut-in speed (1.4 m/s) for nearly 60% of the testing time.
   - The best it could do was 125 W at 2.0 m/s, which is just 25% of what it's capable of.
   - Its efficiency was only 8.2%, while it could ideally reach around 35%.
3. System Reliability Was Excellent
   - We achieved 100% uptime, meaning there was no downtime, and we successfully met all essential energy needs (170 Wh/day).
   - The batteries could last for about 2 days at a 25% depth of discharge without any deep discharges.
   - The inverter kept a steady 229.5 V ± 1 V even under low loads.
4. Overall System Efficiency: 11.6%
   - Even with the low wind conditions, our system was more efficient than solar-only setups (15.2%). This was thanks to:
     - A super-efficient Maximum Power Point Tracking (MPPT) controller at 96%.
     - The inverter working at 95.5% efficiency when under light loads.
     - Less strain on the batteries, leading to better longevity.
5. Inverter Performed Well at Low Loads
   - When we had a small total load of 35 W (for lighting and charging phones), the inverter was impressively efficient at 95.5%.
   - There were no issues like voltage drops, distortion, or shutdowns.
6. Sturdy Physical Design
   - The compact PVC tower held up well against environmental stresses, showing no signs of mechanical failure, corrosion, or misalignment.
7. Hybrid Design Boosted Resilience
   - Combining solar and wind energy really helped reduce the strain on the batteries.
   - The wind provided extra energy during the evenings when solar wasn't available, improving our system's autonomy by 25% compared to using solar alone.

8. Adjustments Needed for Low-Wind Areas

- The 500 W VAWT we used is too big for sites with wind speeds between 1.5 and 2.0 m/s. A smaller turbine, around 200 W, would be a better fit.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

This project has examined the development and performance potential of a hybrid wind and solar energy system as a sustainable alternative to conventional fossil-fuel-based power generation. The findings have established that a hybrid configuration successfully harnesses the complementary nature of solar photovoltaic (PV) modules and wind turbines, thereby overcoming the limitations associated with the intermittency and variability of each resource when used in isolation. Solar PV panels are highly effective during daylight hours with adequate irradiance, whereas wind turbines can continue generating power during periods of low solar intensity, cloudy weather, or at night. By combining both systems, the hybrid model ensures a more stable and reliable power supply across different weather conditions and times of the day.

The research also highlights the potential of hybrid renewable systems to reduce greenhouse gas emissions, mitigate environmental degradation, and contribute to energy diversification. In addition, the hybrid model can significantly address rural electrification challenges, particularly in regions that are off-grid or have limited access to reliable electricity infrastructure. Beyond environmental and social benefits, the long-term economic advantages—through reduced fuel imports, declining renewable technology costs, and minimal operating expenses—make hybrid systems an increasingly attractive solution.

Nevertheless, the project recognizes that challenges such as high initial capital costs, efficiency losses in energy storage, and the need for advanced control systems remain barriers to widespread adoption. Addressing these limitations through technological innovation, effective policies, and local capacity-building will be essential for ensuring the scalability and sustainability of hybrid systems.

DRAWBACKS OF THE STUDY

1. **High Initial Capital Cost**
   The upfront cost of installing both wind turbines and solar photovoltaic (PV) systems is significantly higher compared to conventional single-source renewable or fossil fuel systems. This includes expenses for equipment, land acquisition, grid integration, and

energy storage technologies. The cost barrier often discourages large-scale adoption, especially in developing countries.

2. **Energy Storage Challenges**

   Since both wind and solar power are intermittent, hybrid systems depend heavily on energy storage solutions such as batteries to ensure a reliable supply. Current storage technologies are expensive, have limited lifespans, and are associated with environmental concerns during disposal. Inefficient storage can lead to energy wastage and reduced overall system performance.

3. **Site Dependency**

The effectiveness of a hybrid system is highly dependent on geographical location. Areas with low wind resources or limited solar irradiance may not achieve optimal efficiency. Careful site selection and resource assessment are therefore critical, which can limit widespread deployment.

4. **Maintenance and Technical Expertise**

   Hybrid systems are more complex than single-source systems, requiring advanced control mechanisms and skilled personnel for operation and maintenance. In regions with limited technical expertise, system downtime and inefficiencies may increase.

5. **Land and Space Requirements**

   The installation of wind turbines and solar panels requires significant land or rooftop space. In densely populated areas, securing adequate land can be challenging, while in rural areas, land-use conflicts with agriculture or local communities may arise.

6. **Grid Integration Issues**

   In grid-connected systems, the variable nature of hybrid renewable power generation can cause instability in weak or underdeveloped grids. Without advanced grid management technologies, integrating hybrid systems may pose operational challenges.

7. **Environmental and Social Concerns**

   Although hybrid systems are considered environmentally friendly, wind turbines may cause noise pollution, bird collisions, and visual intrusion. Similarly, the large-scale deployment of solar farms may alter local ecosystems. Social acceptance of these systems therefore varies depending on community perceptions.

Mitigation measures to the drawbacks

1.Addressing High Initial Capital Cost

- Governments should introduce subsidies, tax incentives, and low-interest financing schemes to reduce the upfront burden on investors and households.
- Promotion of local manufacturing and assembly of turbines, panels, and batteries will lower import costs and encourage affordability.
- Public–private partnerships (PPPs) can be leveraged to share costs and risks between stakeholders.

2.**Improving Energy Storage Solutions**

- Investment in advanced storage technologies such as lithium-ion, flow batteries, hydrogen fuel cells, and hybrid storage systems can improve reliability.
- Developing recycling programs for used batteries will reduce environmental impacts and extend resource utilization.
- Incorporating demand-side management strategies can reduce dependency on storage by aligning consumption with peak renewable generation.

3.**Mitigating Site Dependency**

- Comprehensive resource assessment studies should be carried out prior to project implementation to ensure optimal site selection.
- Hybrid systems can be designed to integrate additional renewables (e.g., biomass, micro-hydro) in areas with weak solar or wind potential.
- Seasonal forecasting and AI-driven predictive models can be used to improve performance in variable conditions.

4. **Enhancing Maintenance and Technical Expertise**

- Establishment of technical training centers will build local capacity for operation, repair, and maintenance.
- Remote monitoring technologies, including IoT-based sensors, should be employed to predict failures and reduce downtime.

5. **Managing Land and Space Requirements**

- Hybrid systems can be integrated into existing infrastructure, such as rooftops, parking lots, and offshore platforms, to minimize land-use conflicts.
- Adoption of **agrivoltaics** (simultaneous use of land for solar farming and agriculture) will allow dual land use in rural communities.
- Community consultation and environmental impact assessments should be conducted to balance land allocation with local needs.

6. **Overcoming Grid Integration Issues**

- Smart grid technologies and microgrid solutions should be implemented to stabilize supply and manage fluctuations.
- Incorporation of power electronics and advanced converters can smooth output and improve compatibility with weak grids.
- Hybrid systems can be designed as stand-alone microgrids in rural or off-grid areas, reducing pressure on national grids.

7.**Reducing Environmental and Social Concerns**

- Wind turbine placement should be optimized to minimize bird collisions, while quieter designs should be promoted to reduce noise.
- Solar panel installations can prioritize degraded or non-arable land to avoid competing with agriculture.

Recommendations

Based on the findings of the study the following recommendations are made:

1.**Technological Advancement and Optimization:**

Future projects should focus on improving energy storage technologies, such as advanced batteries and supercapacitors, alongside intelligent power management systems. Enhanced forecasting methods for solar irradiance and wind speed should be integrated into hybrid designs to optimize efficiency and reduce energy losses.

2. **Policy and Governmental Support:**

Policymakers should create favorable regulatory frameworks, tax incentives, and subsidies to encourage investment in hybrid renewable systems. Establishing renewable energy targets and providing funding for pilot projects will stimulate adoption at both community and industrial scales.

3. **Cost Reduction Strategies:**

The high capital cost of hybrid systems remains a barrier to large-scale implementation. Governments and private investors should invest in local manufacturing and assembly of solar panels, wind turbines, and storage devices to reduce dependence on costly imports. This will also create job opportunities and strengthen local economies.

4. **Capacity Building and Technical Training:**

Local communities should be empowered through training programs to operate and maintain hybrid systems effectively. Establishing technical training centers and partnerships with universities will ensure sustainability and minimize downtime caused by lack of expertise.

5. **Integration with Smart Grid and IoT Systems:**

Hybrid systems should be designed to integrate with smart grids and Internet of Things (IoT) platforms. Real-time monitoring, predictive maintenance, and demand-side management can enhance reliability and provide users with better control over their energy consumption.

7. **Community-Based Deployment:**

   Pilot hybrid wind–solar systems should be deployed in rural and underserved areas to demonstrate feasibility, improve livelihoods, and reduce energy poverty. Successful demonstration projects will serve as models for replication across broader regions.

8. **Sustainability Assessment:**

   Future studies should include life-cycle assessments of hybrid systems to evaluate their long-term environmental and economic impacts. This will provide policymakers and stakeholders with data-driven evidence to guide investment and policy formulation.

In conclusion, the hybrid wind–solar energy system demonstrates significant potential as a cornerstone for the global energy transition. It offers a reliable, clean, and sustainable solution to growing energy demands while reducing environmental impacts. If properly optimized and supported by policy frameworks, such systems could play a pivotal role in meeting future energy needs, particularly in developing regions.

REFERENCES

Almihat, M. G. M., & Munda, J. L. (2024). Comprehensive Review on Challenges of Integration of Renewable Energy Systems into Microgrid. Journal of Sustainable Energy Development.

Applied Sciences. (2024). Innovative Strategies for Combining Solar and Wind Energy with Green Hydrogen Systems. MDPI.

Arabian Journal for Science & Engineering. (2025). Analyzing Failures in Wind-Solar Hybrid Energy Systems Using a Fuzzy-Based BWM-MARCOS Approach: Challenges and Solutions. SpringerLink.

Babaremu, K., Oladijo, O. P., Akinlabi, E., & Mwema, F. (2022). Overview of Solar–Wind Hybrid Products: Prominent Challenges and Possible Solutions. Energies, 16(17), 6014.

Bhutta, M. M. A., Hayat, N., Farooq, A. U., Ali, Z., Jamil, S. R., & Hussain, Z. (2012). Vertical axis wind turbine – A review of various configurations and design techniques. Renewable and Sustainable Energy Reviews, 16(4), 1926-1939.

Burton, T., Sharpe, D., Jenkins, N., & Bossanyi, E. (2011). Wind Energy Handbook (2nd ed.). John Wiley & Sons.

Chambalile, M., Su, B., & Illo, F. (2024). The State-of-the-Art Review on Wind and Photovoltaic Solar Hybrid Renewable Energy and Its Impending Potential in Eastern and Southern Africa. Journal of Energy Research and Reviews, 16(8), 23–43.

Elsevier Review. (2023). A Review of Hybrid Renewable Energy Systems: Solar and Wind-Powered Solutions: Challenges, Opportunities, and Policy Implications. ScienceDirect.

Gipe, P. (2004). Wind Power: Renewable Energy for Home, Farm, and Business (Revised ed.). Chelsea Green Publishing.

Kumar, R., & Raahemifar, K. (2015). A critical review of vertical axis wind turbines for urban applications. Renewable and Sustainable Energy Reviews, 52, 704-714.

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). Wind Energy Explained: Theory, Design and Application (2nd ed.). John Wiley & Sons.

Mathew, S. (2006). Wind Energy: Fundamentals, Resource Analysis and Economics. Springer.

MDPI. (2022). Challenges and Mitigation Measures in Power Systems with High Share of Renewables—The Australian Experience. MDPI Journals.

Ogbeide, O. O., Ikpoza, E., & Eboigbe, C. I. (2018). Assessment of wind energy potential for power generation in Benin based on Weibull distribution. International Journal of Advanced Engineering and Technology, 2(2), 42-48.

Shigley, J. E., & Mischke, C. R. (1989). Mechanical Engineering Design (5th ed.). McGraw-Hill.