

DEVELOPMENT OF A 5KVA SOLAR INVERTER



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BENIN CITY

NOVEMBER 2025

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**A PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF BACHELOR OF ENGINEERING (B.ENG) DEGREE IN
INDUSTRIAL ENGINEERING**

FACULTY OF ENGINEERING

UNIVERSITY OF BENIN

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NOVEMBER 2025

CERTIFICATION

This is to certify that this project work was carried out by IMONKHAI CALEB, with Matriculation Number ENG2006307, of the Department of Industrial Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria.

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DEDICATION.

This project is dedicated to Almighty God for unto him I give all the glory for the grace and Enablement to complete this project.

ACKNOWLEDGEMENT

I give all glory and honour to God Almighty, whose grace, strength, and divine guidance have been my pillar throughout the course of this project and my academic journey.

My heartfelt appreciation goes to my beloved parents, Rev Benjamin and D'ness Patient Longe, for their unwavering love, prayers, and support. Your constant encouragement has been my greatest motivation. I am equally grateful to my siblings, Pst Timothy, Pst Eunice, Pst Joshua, and Emmanuel for their continuous support, understanding, and inspiration.

I would also like to sincerely appreciate Engr. Isaac Ighagbon for granting me the opportunity to undergo my Industrial Training at Ministry of works. The experience and knowledge gained during my stay were invaluable and contributed greatly to my personal and professional development.

My profound gratitude goes to my project supervisor, Prof O.O. Ogbeide, for his guidance, constructive feedback, and support throughout the development of this project. His mentorship played a vital role in shaping the quality of this work. I also extend my appreciation to my Course Advisor, Dr. N. H. Osadiaye, for his continuous academic guidance, encouragement, and support throughout my period of study.

Finally, I extend my warm appreciation to my great family, CFI. For the beautiful experience I got.

ABSTRACT

This project focuses on the development of a 5kVA, 48V hybrid solar inverter system aimed at providing a reliable and sustainable energy solution for domestic and small-scale applications. The system integrates solar photovoltaic (PV) energy with utility grid supply to ensure an uninterrupted power source, with solar energy serving as the primary supply and the grid as backup. A hybrid charging approach was adopted to maintain adequate battery capacity during periods of low solar irradiation.

The inverter was designed to deliver a stable output suitable for powering common household and office appliances, while incorporating essential protection features to enhance system safety, efficiency, and reliability. Performance evaluation showed that the inverter provided consistent output with smooth changeover between power sources and improved energy efficiency. The project demonstrates a cost-effective and environmentally friendly alternative to fuel-powered backup systems, reducing dependence on the national grid and promoting cleaner energy usage.

TABLE OF CONTENTS

COVER PAGE	Error! Bookmark not defined.
TITLE PAGE	Error! Bookmark not defined.
CERTIFICATION	iii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background to the study	1
1.2 Statement of the problem	2
1.3 Aim and objectives	4
1.3.1 Aim	4
1.3.2 Objectives	4
1.4 Scope	4
1.5 Significance of the study	5
1.6 Limitations	5
CHAPTER TWO	8
2.1 Understanding Energy Sources: Classification and Importance	9
2.1.1 Renewable Energy Sources	10
2.1.2.Non-Renewable Energy Sources	11
2.1.3..Importance of Energy Source Selection in System Design	13
2.1.4.Solar Energy: A Sustainable Pathway to Global Security	14
2.1.5.Clean Energy: Towards A Pollution-Free Future	15
2.1.6.Mitigating Climate Change: The Role of Greenhouse Gas Reduction	16
2.1.7.Expanding Power Frontiers: Energy Solutions for Remote and Isolated Locations	17
2.2. System Design Overview	17
2.3. Fundamentals of Solar Inverter Systems	18
2.4.Inverter	19
2.4.1 Function Role in System	19
2.4.2.Layout and Integration of Design	20
2.4.3.Transformer-Based Vs Transformerless	20
2.4.4.Inverter Classification and Topologies	21

2.4.4.Classification Based on Waveform Output	21
2.4.5.Classification Based on System Configuration	22
2.4.6 Inverter Topologies	23
2.5.Battery	24
2.6.Solar Panel	27
2.6.1.Types of Solar Panels	28
2.7. Solar Panel Power and Efficiency Ratings	32
2.7.1 Environmental and Economic Impact of Solar Panels	33
2.7.2.Wattage Rating and Panel Sizing	35
2.7.3.Performance in Different Climates	36
2.7.4.Maintenance and Durability	37
2.7.5.Optimal Panel Type for Effective Installation	37
2.8.Benefits of Solar Energy	38
2.9.Modelling of the Solar Inverter	40
2.9.1.Selection of Battery Size and Solar Panel	42
2.10.Shade Analysis	44
2.10.1.Sun Hours	45
2.11. Tilt Angle	46
CHAPTER THREE	48
METHODOLOGY	48
3.1.Research design	48
3.2.Load estimation	48
3.3.System sizing and component selection	49
3.1.1Solar Panel Sizing	49
3.1.2.Battery Sizing (48V System)	50
3.1.3.Inverter Selection	50
3.4.Component procurement	51
3.5.System fabrication and assembly	51
3.6.Testing and evaluation	52
3.7.Design considerations	52
CHAPTER 4	58
RESULTS AND DISCUSSION	58
4.1.Load Consumption	58
4.2.Protective Devices	59

4.3.Tests and Results	59
4.3.1.Continuity Test	59
4.3.2.Power Supply Test	60
4.3.3.Connectivity Test	60
4.3.4.Socket Test	61
4.3.4.Test Equipment Used	62
4.4.Discussion	63
4.4.1.System Analysis	63
4.4.2.Cost Analysis	63
4.4.3.Environmental Analysis	65
CHAPTER FIVE	66
CONCLUSION AND RECOMMENDATIONS	66
5.1 Conclusion	66
5.2.Recommendations	67
5.3 Contribution to Knowledge	68
REFERENCES	70

LIST OF FIGURES

Figure 2.2: Flowchart of Solar Inverter Modelling Steps	41
Figure 2.3: A schematic showing batteries in series and parallel connections.	42
Figure 2.4: Solar panel connection to battery and inverter system.	43
Figure 2.5: Effect of shading on a solar panel string output.	44

LIST OF PLATES

Plate 2.1: INVERTER	18
Plate 2.2: Battery	24
Plate 2.3: Solar panel	26
Plate 2.4: Cross-section of a solar panel showing glass, solar cells, back sheet, and frame	27
Plate 2.5: Monocrystalline Solar Panel	29
Plate 2.6: Polycrystalline Solar Panel	30
Plate 2.8: Adjustable solar panel tilt mechanism with angular markings.	46

LIST OF TABLES

Table 2.1: Comparative Analysis of Renewable and Non-Renewable Sources	13
Table 2.2: Comparative analysis of monocrystalline, polycrystalline and thin film solar panels.	28
Table 3.1: Load Estimation Table.	48
Table 3.2: Example Summary Table	54
Table 3.3: Summary of FoS Recommendations	56
Table 4.1: Power Supply Table	59
Table 4.2: Cost Analysis Table	63

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Electricity is a key driver of industrialization, economic development, and improved quality of life. In many parts of the world, access to reliable electricity is taken for granted; however, in developing nations like Nigeria, power supply remains grossly inadequate. The country's power sector has long struggled with poor generation capacity, distribution inefficiencies, vandalism, and infrastructure decay, resulting in frequent blackouts and load shedding (Oyedepo, 2012). According to the World Bank (2021), approximately 85 million Nigerians — about 43% of the population — lack access to grid electricity, making Nigeria the country with the largest energy access deficit globally.

To cope with these shortages, many households and businesses rely on petrol and diesel generators, which are expensive to operate and contribute significantly to environmental pollution and carbon emissions (Iwayemi, 2008). As fuel prices rise and concerns over greenhouse gas emissions intensify, the need for clean and affordable alternative energy sources has become more urgent.

Solar energy stands out as one of the most promising alternatives. Nigeria is geographically located within the tropical sunbelt, with an average solar radiation of about 5.5 kWh/m²/day and a sunshine duration of 6–7 hours daily across most of the country (Sambo, 2009). These favorable conditions make photovoltaic (PV) technology a practical solution for both urban and rural electrification.

A critical component of any solar PV system is the inverter. It converts the direct current (DC) generated by solar panels into alternating current (AC), which is required to operate conventional electrical appliances. A 5kVA solar inverter system provides a suitable solution for powering medium-scale applications such as homes, offices, small clinics, and ICT

centers. It strikes a balance between cost and capacity — powerful enough to run essential loads like fans, lights, televisions, refrigerators, computers, and pumps, without requiring the heavy infrastructure of industrial setups (Chiemeka et al., 2016; Adegoke et al., 2020).

The design and construction of a 5kVA solar inverter system is not only timely but also aligns with the goals of promoting renewable energy, reducing carbon footprints, and improving energy independence. It further supports the implementation of the United Nations Sustainable Development Goal (SDG) 7, which advocates for access to affordable, reliable, sustainable, and modern energy for all (UN, 2022).

This project is therefore aimed at developing a robust, cost-effective, and efficient 5kVA solar inverter system capable of meeting the energy needs of typical Nigerian households and small enterprises. It provides practical learning on system design, component integration, power electronics, and renewable energy engineering which are vital for addressing Nigeria's ongoing energy crisis.

1.2 Statement of the problem

Globally, access to reliable and sustainable energy is a fundamental prerequisite for economic growth, technological advancement, and improved quality of life. Yet, according to the International Energy Agency (IEA, 2023), over 700 million people worldwide still lack access to electricity, particularly in Sub-Saharan Africa and parts of Asia. In many developing countries, inadequate energy infrastructure, underinvestment in power systems, and growing population demands continue to widen the energy access gap.

The reliance on fossil fuels for electricity generation in many parts of the world has also led to severe environmental consequences, including greenhouse gas emissions, climate change, and air pollution. To mitigate these impacts, there has been a global push towards clean and renewable energy technologies — particularly solar, wind, and hydro power — in line with

the United Nations' Sustainable Development Goal 7 (SDG 7), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030 (UN, 2022).

Solar energy, among these options, is the most abundant and universally available. However, in many regions, its potential remains underutilized due to high initial costs, lack of awareness, inadequate technical know-how, and poor system designs. One major barrier to solar adoption is the absence of affordable and efficient inverter systems that can convert solar power into usable AC electricity for homes and businesses.

In countries like Nigeria, the problem is compounded by chronic grid failures, high costs of diesel generators, and limited access to alternative energy solutions. While solar radiation is abundant throughout the year, the lack of locally designed, efficient inverter systems hinders the full utilization of this resource.

There is, therefore, a global and local need for practical, scalable solutions that enable communities to tap into solar energy efficiently. This project addresses this problem by designing and constructing a 5kVA solar inverter system that is not only cost-effective and environmentally friendly but also tailored to meet real-world energy needs. The system is aimed at bridging the gap between renewable energy potential and actual energy access by delivering stable, clean AC power for medium-scale applications across different regions of the world — especially in underserved and energy-deficient areas.

There is also a critical need for the design and development of high-efficiency, cost-effective, and thermally robust solar inverters with enhanced power quality, improved durability, and smart grid compatibility to optimize the performance of solar energy systems in diverse operating environments."

1.3 Aim and objectives

1.3.1 Aim

The aim of this project is to design and develop a high-efficiency, thermally optimized, and cost-effective 5kVA solar inverter that can reliably convert DC power from solar panels to AC power.

1.3.2 Objectives

The specific objectives of this study are as follows:

1. To assess the energy consumption needs of typical residential and small commercial users in order to establish the load requirements for a 5kVA inverter system.
2. To select and integrate suitable components such as solar panels, charge controllers, batteries, transformers, MOSFETs, and microcontrollers for the efficient operation of the system.
3. To develop a battery management and charge control strategy that optimizes energy storage and usage while protecting the batteries from overcharging and deep discharge.
4. To construct and assemble a 5kVA solar power inverter prototype, incorporating essential protective features such as short-circuit protection, surge protection, and thermal management.
5. To test and evaluate the performance of the constructed inverter system under various load conditions and compare its efficiency, stability, and reliability to conventional alternatives.

1.4 Scope

This project is limited to the design, construction, and performance evaluation of a 5kVA standalone solar inverter system. The key areas covered in the scope include:

- i. Design of the inverter circuit and selection of appropriate solar components (solar panels, charge controller, batteries).
- ii. Construction and testing of a prototype inverter system suitable for residential and small commercial loads.
- iii. Incorporating protective mechanisms such as overvoltage, overload,

short-circuit, and surge protections. iv. Assessment of energy efficiency, voltage stability, and load capacity under controlled conditions.

The study does not cover:

- i. Grid-tied solar systems.
- ii. Large-scale energy storage optimization. iii. Smart inverter control systems or advanced digital monitoring.
- iv. It does not cover the full design of solar panel arrays or battery storage systems in detail, although compatibility with such systems will be considered.

1.5 Significance of the study

Outlined below are some key benefits of modern inverters, particularly in the context of solar energy solutions.

- i. It contributes to the ongoing global shift toward clean and renewable energy sources in response to climate change and fossil fuel depletion.
- ii. Provides a practical solution to the problem of unreliable power supply in Nigeria and other developing regions.
- iii. It reduces dependence on environmentally harmful fossil-fuel generators by promoting solar energy as a sustainable alternative.
- iv. The study enhances local capacity in renewable energy system design, fostering skills development among students and engineers.
- v. The constructed 5kVA system can serve as a scalable prototype for rural electrification, disaster relief, and mobile power units in off-grid areas.

1.6 Limitations

Although the design and construction of a 5kVA solar inverter system represents a critical step toward solving energy access problems, particularly in off-grid or underserved regions, the implementation of such a system within the Nigerian context is faced with several

limitations. Nigeria, despite having abundant solar resources, continues to struggle with structural, economic, and institutional challenges that hinder the full realization and sustainability of renewable energy technologies.

The country's energy infrastructure is still heavily dependent on fossil fuels, with limited support for decentralized and clean energy alternatives. In addition, high inflation, currency instability, limited technical manpower, and import dependency affect the affordability, accessibility, and long-term functionality of solar energy systems. These factors, combined with inconsistent government policy frameworks, often make it difficult to scale or replicate such projects in real-life scenarios without encountering significant obstacles.

The specific limitations faced during this study include:

1. **High Cost of Components:** The cost of procuring quality solar panels, inverters, batteries, and charge controllers remains high in Nigeria due to heavy reliance on imports, fluctuating exchange rates, and import taxes. This limits affordability, especially for average-income households and small-scale businesses.
2. **Limited Local Availability of Quality Parts:** There is a scarcity of locally produced, highquality components in the Nigerian market. The available imported parts often vary widely in quality, and counterfeit or substandard components are common, which can compromise system performance and longevity.
3. **Technical Skill Gaps:** Although interest in renewable energy is growing, there remains a shortage of trained personnel skilled in solar system design, installation, and maintenance. This may lead to incorrect installations or poor after-sales service, especially in remote areas.
4. **Environmental and Climatic Factors:** Dust accumulation on panels, extreme heat, and inconsistent sunlight during rainy seasons can reduce solar panel efficiency. In regions like northern Nigeria, where dust is prevalent, regular cleaning and maintenance are needed to maintain performance.

5. **Battery Storage Constraints:** Deep-cycle batteries, especially lithium-ion variants, are expensive and sensitive to heat. In Nigeria's hot climate, battery lifespan may be reduced, and poor charging habits or irregular maintenance can further shorten usability.
6. **Policy and Institutional Barriers:** The Nigerian energy policy environment does not yet provide strong financial incentives, tax relief, or regulatory support for individuals or small businesses investing in solar energy. This slows down the adoption and scaling of such systems.
7. **Security and Vandalism Issues:** In areas with poor security, solar installations are vulnerable to theft and vandalism. This is a significant risk in rural or low-income urban communities where such equipment is highly valuable and unguarded.

CHAPTER TWO

LITERATURE REVIEW

The rising global demand for clean and sustainable energy has further strengthened the prominence of solar power as a viable alternative to fossil-based electricity, particularly as governments and industries intensify low-carbon transition efforts (IEA, 2025; IRENA, 2024). Increasing concerns around climate change, depletion of non-renewable energy resources, and the environmental burden of greenhouse gas emissions continue to drive the preference for solar energy as an abundant and eco-friendly source (IPCC, 2024; UNDP, 2025). In sub-Saharan Africa, and Nigeria especially, solar adoption has gained momentum due to persistent electricity supply challenges linked to grid instability, load-shedding, and heavy reliance on petrol and diesel generators (World Bank, 2025; NESP, 2024). These generators increase household energy costs and contribute to carbon pollution, reinforcing the need for clean and reliable distributed energy systems (ECN, 2025).

In solar photovoltaic (PV) systems, the inverter plays a central role as it converts the direct current (DC) produced by solar panels into usable alternating current (AC) for domestic and industrial applications (NREL, 2024; Singh & Ahmed, 2025). Beyond power conversion, modern inverters integrate intelligent control features such as Maximum Power Point Tracking (MPPT), advanced battery management, real-time monitoring, and energy metering to enhance system efficiency and operational reliability (Gupta et al., 2024; Kumar & Bello, 2025). These innovations improve safety, protect appliances from electrical faults, and maximize energy utilization, making inverters a critical component of hybrid and off-grid energy systems (Oyedepo et al., 2025).

The design and construction of a 5 kVA solar inverter system is increasingly relevant within today's energy landscape, where the need for resilience, energy autonomy, and cost-effective power solutions remains a priority (IRENA, 2025; Nwankwo & Adeoye, 2024). A 5

kVA inverter capacity is suitable for small-to-medium residential and commercial operations, supporting essential loads such as lighting, refrigeration, fans, ICT devices, and selected industrial equipment (Ajao et al., 2024; Ebhota & Lawal, 2025). This makes it a strategic solution for Nigerian households and businesses that routinely depend on alternative sources due to unreliable grid supply (Alade & Sodi, 2024). Developing local, efficient, and affordable inverter systems contributes to reducing the reliance on imported technologies, lowering energy costs, and promoting national energy self-sufficiency (NERC, 2025).

Recent research advances have focused on improving inverter efficiency, waveform quality, thermal performance, durability, and cost optimization in renewable energy systems (Oke et al., 2024; Hassan & Yusuf, 2025). Scholars have explored diverse inverter topologies, semiconductor switching devices, control algorithms, and hybrid system integration approaches to address challenges such as harmonic distortion, energy losses, battery lifespan management, and system scalability (Adebanjo et al., 2024; Adediran & Musa, 2025). These studies provide useful insights and technological directions that guide the effective design and construction of a reliable 5 kVA solar inverter system tailored to Nigeria's energy needs (Okoye & Ezema, 2025).

2.1 Understanding Energy Sources: Classification and Importance

Energy is the bedrock of socio-economic development and the engine that drives technological advancement, industrialization, urbanization, and the overall improvement in quality of life. Every aspect of modern human life healthcare, transportation, agriculture, education, communication, and security relies heavily on a consistent and sustainable supply of energy. As global demand continues to rise due to population growth, industrial expansion, and digital transformation, understanding the types and sources of energy becomes vital for strategic planning, innovation, and sustainable development.

Energy sources refer to the various origins or reservoirs from which usable forms of energy such as electricity, mechanical power, or heat can be extracted, converted, and harnessed. These sources are diverse in form, origin, and availability. Their classification has broad implications for environmental sustainability, energy policy, climate change, and economic stability. Globally, nations are now more focused on optimizing the use of clean, renewable sources while minimizing dependence on finite, polluting fuels. Energy sources are broadly classified into two main categories based on their availability and renewability:

- i. Renewable Energy Sources
- ii. Non-renewable Energy Sources

2.1.1 Renewable Energy Sources

Renewable energy sources are naturally replenished within short time cycles and originate from continuous environmental or geological processes such as sunlight, wind, water flow, biomass, and heat from beneath the Earth's surface (IRENA, 2025; UNEP, 2025). These sources are widely regarded as environmentally sustainable due to their minimal greenhouse gas emissions and low ecological footprint during extraction, conversion, and utilization (IPCC, 2024; IEA, 2025). The transition to renewable energy has become a global priority, as countries aim to increase clean energy penetration, enhance energy security, and mitigate the impacts of climate change (UNDP, 2025; World Bank, 2025). Common renewable energy types include the following:

- **Solar Energy:** Obtained from the sun and converted into electricity using photovoltaic (PV) systems or solar thermal technologies. It is considered one of the most abundant and accessible renewable sources globally (NREL, 2024; Kumar & Bello, 2025). In Nigeria, average solar radiation ranges between 4.5 and 7.0 kWh/m²/day, making it highly suitable for decentralized electrification, especially in rural and underserved areas (ECN, 2025; NESP, 2024).

- **Wind Energy:** Generated from moving air using wind turbines, and increasingly deployed across coastal, offshore, and high-altitude regions where wind speeds are favorable (IRENA, 2024; Singh & Ahmed, 2025). Recent advancements in turbine technology have expanded wind power potential in Africa and other emerging markets (Oyedepo et al., 2025).

- **Hydropower:** Produced from flowing or falling water that drives turbines to generate electricity. It remains one of the most mature renewable energy technologies and plays a significant role in global clean power supply (World Bank, 2025; Hassan & Yusuf, 2025).

- **Geothermal Energy:** Harnesses heat stored beneath the Earth's crust to produce electricity or provide direct heating, offering stable and reliable baseload renewable energy (UNEP, 2025; IRENA, 2025).

- **Biomass and Bioenergy:** Derived from organic materials such as agricultural residues, wood, and animal waste. When managed sustainably, biomass provides a renewable alternative for heating, electricity generation, and biofuel production (Oke et al., 2024; Adediran & Musa, 2025).

Renewable energy sources are crucial for reducing dependence on fossil fuels, expanding energy access in off-grid regions, and promoting environmental sustainability (IEA, 2025; UNDP, 2025). Their increased integration into national energy systems is central to achieving the United Nations Sustainable Development Goal 7 on affordable and clean energy for all (UN, 2024; IRENA, 2025).

2.1.2. Non-Renewable Energy Sources

Non-renewable energy sources are derived from finite natural reserves that do not replenish within a human timescale, making them exhaustible once consumed (IEA, 2025; IPCC, 2024). These sources primarily include fossil fuels formed from prehistoric organic matter over millions of years and remain dominant in global energy supply despite their environmental

and sustainability challenges (World Bank, 2025; UNDP, 2025). Major categories of non-renewable energy include:

- **Crude Oil (Petroleum):** The most widely used fossil fuel globally, refined into products such as petrol, diesel, kerosene, and aviation fuel. It plays a major role in transportation and industrial operations but significantly contributes to carbon emissions and environmental pollution (IEA, 2025; UNEP, 2025).

- **Natural Gas:** Composed mainly of methane and used for electricity generation, heating, and industrial applications. Although it burns cleaner than coal and oil, it still releases carbon emissions and methane leakage contributes to global warming (IPCC, 2024; Hassan & Yusuf, 2025).

- **Coal:** One of the most carbon-intensive fuels used for electricity generation, particularly in developing and industrialized countries with coal-based power systems (World Bank, 2025; UN, 2024). Its extraction and combustion lead to severe air pollution, land degradation, and high CO₂ emissions, making it a key driver of climate change (IEA, 2025).

- **Nuclear Energy:** Generated from uranium through nuclear fission and considered low-carbon at the point of generation. Although it produces minimal greenhouse gases, nuclear energy is classified as non-renewable because uranium reserves are limited and concerns exist regarding radioactive waste, safety risks, and high operational costs (UNEP, 2025; Singh & Ahmed, 2025).

Despite global clean energy efforts, non-renewable sources still account for over 70% of the world's primary energy consumption due to their established infrastructure, energy density, and economic influence (IEA, 2025; World Bank, 2025). However, the associated environmental impacts—including carbon emissions, ecological damage, public health hazards, and climate change—have accelerated international commitments toward

decarbonization and increased investment in renewable alternatives (IPCC, 2024; UNDP, 2025).

Table 2.1: Comparative Analysis of Renewable and Non-Renewable Sources

CRITERIA	RENEWABLE ENERGY	NON-RENEWABLE ENERGY
Availability	Inexhaustible	Finite and depleting
Environmental Impact	Impact low emissions, eco-friendly	High emissions, pollutive
Cost Over Time	Decreasing	Increasing due to scarcity
Energy security	Enhances local independence	Prone to geopolitical conflicts

2.1.3..Importance of Energy Source Selection in System Design

Selecting an appropriate energy source is crucial in system design as it influences efficiency, cost, sustainability, and long-term operational reliability (IEA, 2025; UNDP, 2025). For a 5kVA solar inverter system, solar energy emerges as the most practical and sustainable option, particularly within developing countries like Nigeria where sunlight is abundant and grid power remains unreliable (World Bank, 2025; ECN, 2025). Solar-based systems offer significant advantages over fossil-fuel-powered alternatives, including zero fuel costs, low maintenance requirements, silent operation, and environmental friendliness (IRENA, 2025; IPCC, 2024). These benefits make solar energy suitable for powering homes, schools, healthcare facilities, and small-to-medium enterprises in both urban and off-grid regions (NESP, 2024; Hassan & Yusuf, 2025).

The selection of renewable energy sources in system design also aligns with global sustainability goals, including climate action and universal access to clean energy. It supports national energy transition strategies aimed at reducing carbon emissions, promoting economic

resilience, and minimizing exposure to fluctuating global fossil fuel prices (UN, 2024; UNEP, 2025; IEA, 2025). Designing inverter systems around solar energy enhances energy security, fosters technological innovation, and contributes to long-term socio-economic development (World Bank, 2025; IRENA, 2025). Therefore, adopting solar energy for inverter-based systems is both an environmentally and economically viable approach toward sustainable power generation in modern energy planning (UNDP, 2025; IPCC, 2024).

2.1.4.Solar Energy: A Sustainable Pathway to Global Security

Solar energy, obtained from the sun’s radiation, has become one of the most promising solutions for addressing global energy demand, environmental degradation, and energy insecurity (IRENA, 2025; IPCC, 2024). The sun provides more energy to Earth in one hour than the world consumes in a full year, making solar a highly abundant and universally accessible resource (NREL, 2024; IEA, 2025). Rapid advancements in photovoltaic technology have increased system efficiency and reduced installation costs, accelerating global adoption across residential, commercial, and utility-scale applications (UNEP, 2025; Singh & Ahmed, 2025).

Beyond environmental benefits, solar energy plays a key role in strengthening economic and geopolitical stability. Countries are increasingly investing in solar infrastructure to reduce dependence on imported fossil fuels, lower electricity tariffs, and enhance national energy independence (World Bank, 2025; UN, 2024). Solar power also supports electrification in remote and underserved communities through off-grid and hybrid systems, improving access to healthcare, education, and economic opportunities (NESP, 2024; Ajao et al., 2024). Its scalability—from rooftop systems to large solar farms—makes solar adaptable to diverse needs, enabling transformative impacts across global energy systems (IRENA, 2025; NREL, 2024).

2.1.5.Clean Energy: Towards A Pollution-Free Future

Clean energy refers to power generated from technologies that produce little or no harmful emissions during operation, making it essential for addressing climate change and environmental degradation (IEA, 2025; IRENA, 2024). Increasing concerns over air pollution, fossil fuel dependency, and global warming have strengthened the shift towards clean and sustainable energy systems worldwide (UNEP, 2024; IPCC, 2024). Governments and industries are adopting clean-energy policies and low-carbon transition strategies to improve environmental quality and support long-term sustainability (UNDP, 2025; World Bank, 2024).

Clean energy sources such as solar, wind, hydropower, and geothermal produce electricity without the release of pollutants like sulphur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), or greenhouse gases (WHO, 2025; Adedeji & Okoye, 2024). Their adoption enhances air quality, reduces climate-related ecological damage, and promotes healthier living conditions for communities exposed to pollution (IPCC, 2024; Afolayan et al., 2024). Technological improvements in energy storage and system efficiency have further increased the reliability and affordability of clean energy systems across residential, industrial, and commercial applications (U.S. DOE, 2024; Obiajulu & Hassan, 2025).

The shift to clean energy also supports socio-economic development by lowering healthcare costs associated with pollution, reducing premature deaths, and promoting green job creation in renewable industries (WHO, 2025; Bello & Yusuf, 2024). Clean-energy investments contribute to economic growth while aligning national development with environmental protection and climate resilience priorities (IEA, 2025; UNDP, 2025). As nations work towards net-zero emission targets, clean energy remains a central pathway for achieving a pollution-free and sustainable future (IRENA, 2025).

2.1.6.Mitigating Climate Change: The Role of Greenhouse Gas Reduction

Greenhouse gases (GHGs) such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) trap heat in the Earth's atmosphere, intensifying global warming and accelerating climate change (IPCC, 2024; UNEP, 2024). Human activities—especially fossil-fuel combustion for electricity generation, transportation, and industrial processes—remain the dominant contributors to global GHG emissions and environmental degradation (IEA, 2025; World Bank, 2024). The escalating rise in global temperatures has led to extreme weather events, food insecurity, ocean acidification, and loss of biodiversity, making GHG reduction a critical component of climate-action strategies (UN, 2024; WHO, 2025).

The rapid expansion of renewable energy technologies, particularly solar power, is central to reducing GHG emissions and supporting global decarbonisation efforts (IRENA, 2025; IPCC, 2024). Solar systems generate electricity without fuel combustion, thereby eliminating carbon emissions associated with coal, diesel, and natural gas-based power generation (UNDP, 2025; Singh & Ahmed, 2025). The adoption of small-scale solar solutions, such as a 5 kVA solar inverter system for residential or small-business use, significantly decreases reliance on fossil-fuel generators—preventing approximately 1.2–1.8 tonnes of CO₂ emissions per household annually, depending on grid carbon intensity (Ajao et al., 2024; NESP, 2024).

Efforts to reduce greenhouse gases align with international climate policies such as the Paris Agreement, which underscores the need to limit the global temperature increase to well below 2°C above pre-industrial levels by accelerating clean-energy adoption and reducing fossil-fuel use (UNFCCC, 2024; IEA, 2025). Solar-powered inverter systems contribute directly to achieving national and global climate goals by providing a low-carbon pathway to electricity access, improving environmental sustainability, and enhancing energy resilience (ECN, 2025; Okoye & Ezema, 2025). Strengthening renewable-energy investment, policy

support, and public awareness is therefore vital in mitigating climate change and securing a sustainable, climate-resilient future (World Bank, 2024; UNDP, 2025).

2.1.7.Expanding Power Frontiers: Energy Solutions for Remote and Isolated Locations

Access to electricity remains a persistent challenge in many rural and remote regions, particularly in sub-Saharan Africa where grid expansion is limited by high infrastructure costs, difficult terrain, and dispersed settlements (IEA, 2025; IRENA, 2024; UN-Energy, 2025; AfDB, 2024). In these areas, decentralized renewable energy solutions—especially solar systems—have emerged as practical alternatives to conventional grid extension (World Bank, 2025).

Off-grid solar inverter systems provide a fast-to-deploy and cost-effective power option for essential services such as rural clinics, schools, water supply facilities, and households (UNDP, 2025; SEforALL, 2024; NESP, 2025; ECN, 2024). These systems support critical loads including lighting, refrigeration, medical equipment, and communication devices, thereby improving healthcare delivery, security, education access, and economic participation in isolated communities (IEA, 2024).

Global development programs continue to promote off-grid solar as a key driver of inclusive and equitable energy access, with initiatives such as the World Bank’s Lighting Africa, UNDP’s Access to Clean Energy, and SEforALL’s Universal Energy Facility supporting deployment in underserved regions (World Bank, 2025; UNDP, 2024; SEforALL, 2025; IRENA, 2025). These interventions highlight the role of solar-powered solutions in bridging the electricity gap and accelerating socio-economic development in remote locations (IEA, 2025).

2.2. System Design Overview

The intended system incorporates a solar-powered inverter setup, in which photovoltaic (PV) panels are connected to a charge controller and battery bank. This configuration enables

the storage and conversion of solar energy to provide a reliable backup power supply for residential or institutional use during grid outages.

2.3. Fundamentals of Solar Inverter Systems

Solar inverter systems are a core component of photovoltaic (PV) installations, responsible for converting solar-generated DC electricity into AC power suitable for domestic, commercial, or industrial use (IEA, 2025; Okafor & Bello, 2024). This conversion allows solar energy to integrate seamlessly with conventional electrical infrastructure, supporting both grid-tied and off-grid applications (World Bank, 2025; NESP, 2024).

Modern solar inverters also provide advanced functionalities such as grid synchronization, voltage and frequency regulation, intelligent load management, and automatic switchover during power outages (Aliyu & Mohammed, 2025; Gupta et al., 2024). These capabilities enhance system reliability, maximize energy utilization, and allow for data logging and real-time monitoring, making inverters critical for sustainable and dependable power supply in residential, institutional, and industrial settings (Ebhotu & Lawal, 2025)



2.4.Inverter

Plate 2.1: INVERTER

As the central component of the solar power system, the inverter is essential in transforming the low-voltage direct current (DC) stored in the batteries into normal alternating current (AC), which is needed to run the majority of domestic and commercial equipment. A pure sine wave inverter is used for this 5kVA system because it is more suited for delicate electronic equipment and produces a cleaner, more consistent power output than modified sine wave inverters.

With a rated capacity of 5000VA (or 5kVA), the chosen inverter can handle loads up to roughly 4000–4500W, contingent on power factor and efficiency. It can smoothly transition between grid power (if available), generator input, and solar battery power without the need for human involvement thanks to its manual and automatic transfer switching methods. This smooth switching reduces downtime and guarantees continuous power delivery to vital systems like computers, lighting, refrigeration, and communication devices.

2.4.1 Function Role in System

The following crucial tasks are carried out by the inverter in this 5kVA solar system:

- i. **DC to AC Conversion:** It converts the battery bank's 48V DC power into 220–240V AC output that may be used with common electrical appliances.
- ii. **Voltage and Frequency Regulation:** Even when battery levels change, the inverter maintains a constant power supply by ensuring a constant output voltage and frequency.
- iii. **Power Source Management:** To maximise energy use, sophisticated designs allow the inverter to intelligently switch between solar, grid, and generator inputs.
- iv. **Feedback and Monitoring of the System:** A lot of inverters offer real-time information on the state of the system, such as input voltage, output power, and load levels.

2.4.2.Layout and Integration of Design

The inverter is made to blend in seamlessly with the architecture of the photovoltaic system. It is linked upstream of the distribution panel and downstream of the battery bank. For a smooth transition between power sources, an automated transfer switch (ATS) or changeover mechanism may be employed. The design arrangement considers: ventilation (heat sinks or cooling fans), Accessibility (for upkeep), and Labelling that is clear (for input/output terminals). They are integrated into the inverter's housing and structural design.

2.4.3.Transformer-Based Vs Transformerless

Additionally, the design assessed whether a transformerless (high-frequency) or transformer-based inverter should be used. Transformer-based inverters are appropriate for heavy-duty applications because they are more resilient and have the capacity to manage larger surge loads. They are typically less effective and heavier, although transformerless inverters are small and effective, they could not last as long under challenging conditions. A transformer-based inverter was chosen for this project because of its capacity to manage starting surges from inductive loads, such as motors, pumps, and refrigerators.

2.4.4. Inverter Classification and Topologies

In order to handle a variety of application needs, power requirements, and technical improvements, inverter systems are categorised using a number of criteria. Engineers, technicians, and consumers can choose the best inverter type for their particular energy system design with the aid of these classes. In general, inverters can be categorised according to their system design and the output signal's waveform. Furthermore, the internal circuit architecture or design utilised to accomplish the intended voltage conversion and control operations is described by inverter topologies (Suleiman & Ibrahim, 2021).

1. Classification based on wave form output
2. Classification based on system configuration
3. Inverter topologies

2.4.4. Classification Based on Waveform Output

The quality and suitability of the electricity sent to electrical appliances are determined by the inverter's output waveform. According to Mohanty, Rout, and Dash (2020), inverters provide AC output in a variety of ways, each having its own special traits, benefits, and drawbacks.

1. Square Wave Inverters

A basic AC output with abrupt positive and negative voltage swings is produced by square wave inverters. Although this kind of inverter is inexpensive and simple to design, its high harmonic distortion and low power quality make it inappropriate for the majority of contemporary appliances (Suleiman & Ibrahim, 2021). They could result in noise and overheating in inductive loads like transformers or motors (Singh & Dwivedi, 2019).

2. Modified Sine Wave Inverters

A stepped approximation of a sine wave is provided by modified sine wave inverters. These inverters are less expensive than pure sine wave devices and work better with general-

purpose electronics than square wave variants. They still produce harmonics, though, which can lead to failures in delicate equipment like digital clocks and medical devices (Singh & Dwivedi, 2019). They are nevertheless widely used for mobile and low-budget applications in spite of their drawbacks (Mohanty, Rout & Dash, 2020).

3. Pure Sine Wave Inverters

The steady, uninterrupted waveform of grid energy is replicated by pure sine wave inverters. They work well with all kinds of electrical and electronic equipment, are very efficient, and have very little harmonic distortion. For industrial and mission-critical applications, these inverters are perfect (Suleiman & Ibrahim, 2021). For waveform production, they use sophisticated control techniques including digital signal processing (DSP) and pulse-width modulation (PWM) (Mohanty, Rout & Dash, 2020).

2.4.5. Classification Based on System Configuration

Inverters can also be categorised according to how they work with other parts of the system, such load, batteries, or the utility grid.

1. Standalone Inverters

Off-grid, or standalone, inverters function separately from the utility grid and are frequently utilised in isolated or rural locations without grid connectivity. Typically, they use batteries and solar panels to supply power continuously. These inverters have features including intelligent charge control, overload protection, and low-voltage disconnection (Singh & Dwivedi, 2019). They are appropriate for off-grid solar systems and telecommunications sites because of their design, which prioritises autonomy and durability (Suleiman & Ibrahim, 2021).

2. Grid-Tied Inverters

Utility grid and transform solar panels' DC power into AC. They frequently take advantage of net metering by enabling the export of excess power to the grid. In order to protect utility

personnel during outages, these inverters are built to shut down (anti-islanding protection) and depend on a steady grid connection (Mohanty, Rout & Dash, 2020). Both residential and commercial PV systems make extensive use of them due to their excellent efficiency (Singh & Dwivedi, 2019).

3. Hybrid Inverters

Off-grid and grid-tied capabilities are combined in hybrid inverters. They control the flow of electricity between energy storage devices, the grid, and solar panels. These inverters are intelligent devices that can automatically switch between power sources. They provide backup during outages and export extra energy to the grid when available, making them perfect for areas with erratic grid power (Suleiman & Ibrahim, 2021). Peak shaving, programmable load management, and real-time monitoring are common features of hybrid inverters (Mohanty, Rout & Dash, 2020).

2.4.6 Inverter Topologies

The internal circuit layout that converts DC power to AC is known as the inverter topology. These consist of:

1. Voltage Source Inverter (VSI)

The most used structure, VSI, depends on a fixed DC voltage input. Using IGBTs or MOSFETs, it offers quick switching and can function with sinusoidal or PWM modulation. Because of its performance and resilience, VSIs are frequently used in motor drives and solar inverters (Mohanty, Rout & Dash, 2020).

2. Current Source Inverter (CSI)

Constant current sources (CSIs) function effectively with inductive loads such as motors. They offer superior current regulation and dependability in particular industrial applications; nonetheless, their prevalence in contemporary solar systems is diminished due to their intricacy and dimensions (Singh & Dwivedi, 2019).

3. Multilevel Inverters (MLI)

MLIs greatly reduce harmonic distortion by producing high-quality waveforms with different voltage levels. They are perfect for high-voltage, high-power applications like industrial drives and grid-connected solar farms. Inverters with flying capacitors, cascaded H-bridges, and neutral-point clamped (NPC) topologies are among them (Mohanty, Rout & Dash, 2020).

4. Half-Bridge and Full-Bridge Topology

Two switching devices are used in the half-bridge topology, which provides simple voltage conversion but has a limited output power. Higher power levels in single-phase inverter systems can be accommodated by the full-bridge or H-bridge architecture, which employs four switches and offers full bipolar output (Suleiman & Ibrahim, 2021).

5. Push-Pull Topology

The push-pull inverter topology uses two switching transistors to alternate the current flowing through a centre-tapped transformer. It is frequently utilised in low-power applications and small inverter designs. This setup provides dependable performance, transformer isolation, and ease of use (Singh & Dwivedi, 2019).

2.5. Battery

The battery is an essential part of the design and construction of a solar inverter system because it acts as the energy storage unit and guarantees that electricity will be available even in the absence of sunlight. Because solar panels can only produce electricity during the day, this is very crucial. As a result, the battery serves as an energy buffer, storing extra power produced during the day for usage at night or in cloudy weather.

Synergy AGM 12V 100Ah sealed lead-acid batteries were chosen for this undertaking due to their compatibility with solar photovoltaic (PV) applications. Because these batteries are

sealed and require no maintenance, they don't need to be regularly refilled with distilled water. They are perfect for solar systems with many cycles of charging and discharging because of their Absorbent Glass Mat (AGM) structure, which improves internal resistance and performance in deep cycle operations (Rusli, 2016).



Plate 2.2: Battery

A battery is made up of electrochemical (voltaic) cells having positive (cathode) and negative (anode) terminals, according to Crompton (2000). While the anode promotes current flow, the cathode uses electrochemical reactions to store electrical energy. Batteries boost voltage when connected in series and current capacity when connected in parallel. Four 12V batteries connected in series will be adequate for a 48V inverter setup.

Keeping an eye on the battery arrangement is crucial. A set of batteries may rapidly discharge via one another if one of them is completely depleted. This could result in an overcurrent and possible fire hazard. This can be lessened by quickly identifying and removing any exhausted batteries. In bigger systems, malfunctioning batteries are automatically isolated using diodes or monitoring systems (Rusli, 2016).

Batteries transform chemical energy into electrical energy from a chemical standpoint. Schmidt-Rohr (2018) explains that a variation in the bond energies of the materials inside the cells is what drives this conversion. An electrolyte, which is present in both half of each voltaic cell, helps ions move between the electrodes to complete the circuit. The selected batteries in this system have a number of advantageous qualities:

- i. Sealed and maintenance-free
- ii. Deep discharge recovery
- iii. High discharge rate
- iv. Long shelf life
- v. Wide operating temperature
- vi. Compact and rugged design
- vii. Cost-effective over the long term

Rechargeable batteries, such as the AGM lead-acid variety, have a reduced total cost of ownership and are better for the environment than disposable ones because they can be used repeatedly (Omitola, 2014). Finally, the battery system has an impact on the overall dependability and longevity of the solar inverter system in addition to being essential to its energy autonomy. For the system to operate effectively and safely, the right battery must be chosen, sized, configured, and protected. Particularly in off-grid or unstable grid situations, the battery system ensures a continuous power supply when properly integrated with an intelligent inverter and charge controller.

2.6.Solar Panel



Plate 2.3: Solar panel

The foundation of a photovoltaic (PV) system is made up of solar panels, which serve as energy-harvesting devices that use the photovoltaic effect to transform solar radiation into electrical power. Particularly in off-grid or hybrid applications like the 5kVA solar inverter system under study, these devices are essential to the efficiency and dependability of solar energy systems. The energy output and overall efficacy of the system are directly impacted by its type, quality, and installation circumstances.

The composition and operation of solar panels several interconnected solar cells, usually formed of semiconductor materials like monocrystalline or polycrystalline silicon, make up solar panels. A transparent glass layer at the front, an encapsulant (often ethylene vinyl acetate, or EVA), the solar cell layer itself, a protective polymer rear sheet, and an aluminium frame that secures everything in place make up the multi-layered framework in which these cells are embedded. This configuration maximises sunlight penetration while shielding the panel from environmental harm.

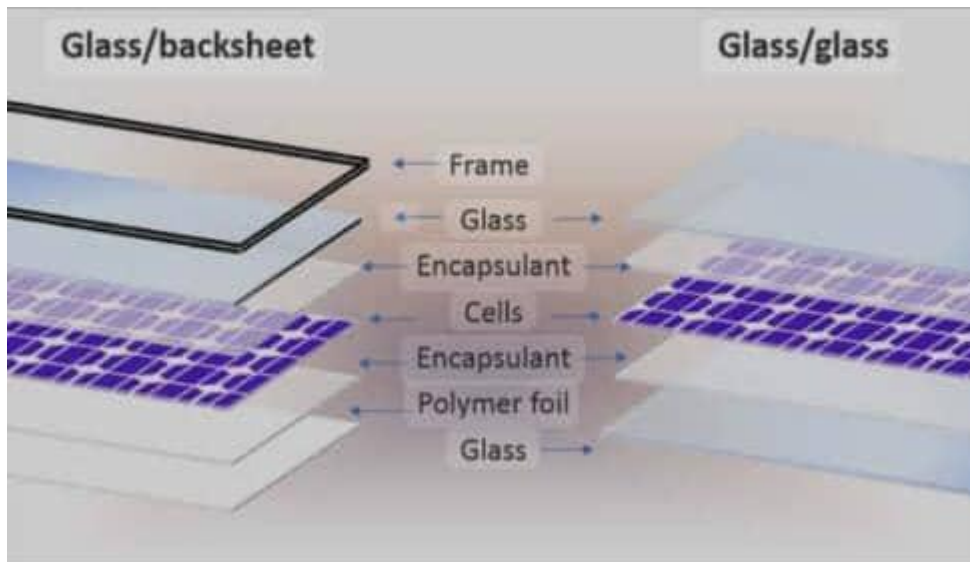


Plate 2.4: Cross-section of a solar panel showing glass, solar cells, back sheet, and frame

The basic idea is based on the photovoltaic phenomenon, in which photons from sunshine excite the electrons in silicon-based solar cells, causing them to move and produce direct current (DC) power. After that, the electricity is directed towards an inverter, which transforms it into alternating current (AC) fit for commercial or residential applications. In order to prevent power loss from shade, solar panels additionally feature bypass diodes and junction boxes for wiring.

2.6.1.Types of Solar Panels

Based on their composition and cell structure, solar panels can be broadly divided into three categories: thin-film, polycrystalline, and monocrystalline. According to Razykov et al. (2011) and Green et al. (2015), each type has distinct traits, performance levels, and application applicability. They include:

- i. Monocrystalline solar panel
- ii. Polycrystalline solar panel
- iii. Thin film solar pane

Table 2.2: Comparative analysis of monocrystalline, polycrystalline and thin film solar panels.

FEATURE	MONOCRYSTALLINE	POLYCRYSTALLINE	THIN-FILM
Material	Single-crystal silicon	Multi-crystal silicon	Amorphous silicon, etc.
Efficiency Range	18-22%	15-17%	10-12%
Cost	High	Moderate	High
Space Requirement	Low	Medium	Low
Life span	25-30 years	20-25 years	25-30 years
Temperature Performance	Good	Moderate	Good
Application	Residential, Industrial	Residential, Rural and Electrification	Residential, Industrial

i. Monocrystalline Solar Panel

Silicon with a single, continuous crystal structure is used to make monocrystalline solar panels. These panels are commonly identified by their excellent energy conversion efficiency and consistent black colour. They perform better and are more efficient because they are composed of high-purity silicon, which allows electrons to flow more easily. Because fewer panels are required to provide the same amount of power, they are therefore ideal for

installations with limited space. Due to the intricacy of the manufacturing process, monocrystalline panels are typically more expensive than other varieties, but they also last longer and function better in low light (Jordan et al., 2016; Fraunhofer ISE, 2023).



Plate 2.5: Monocrystalline Solar Panel

ii. Polycrystalline Solar Panels:

Multiple silicon shards are melted together to make polycrystalline solar panels. Because of the uneven alignment of the silicon crystals, the electrons face greater resistance as they pass through the material, leading to a somewhat reduced efficiency. Because of the way light bounces off the different crystals, these panels typically seem blue. Despite being less effective than monocrystalline panels, they are easier to make and more reasonably priced. They work well in installations where initial cost is a limiting issue and space is not a key concern (Jordehi, 2016; IRENA, 2020).



Plate 2.6: Polycrystalline Solar Panel

iii. Thin-Film Solar Panels:

One or more thin layers of photovoltaic materials are deposited onto a substrate, like metal, plastic, or glass, to create thin-film solar panels. The most frequent materials utilised include cadmium telluride (CdTe), amorphous silicon (a-Si), and copper indium gallium selenide (CIGS). These panels work well on irregular or curved surfaces because they are more flexible and lighter than crystalline ones. They need more room to produce the same amount of electricity, though, because they are less efficient and have a shorter lifespan. Thin-film panels are typically utilised in specialised building-integrated photovoltaic (BIPV) systems or utility-scale applications (NREL, 2022; Razykov et al., 2011)



Plate 2.7: Thin Film Solar Panel

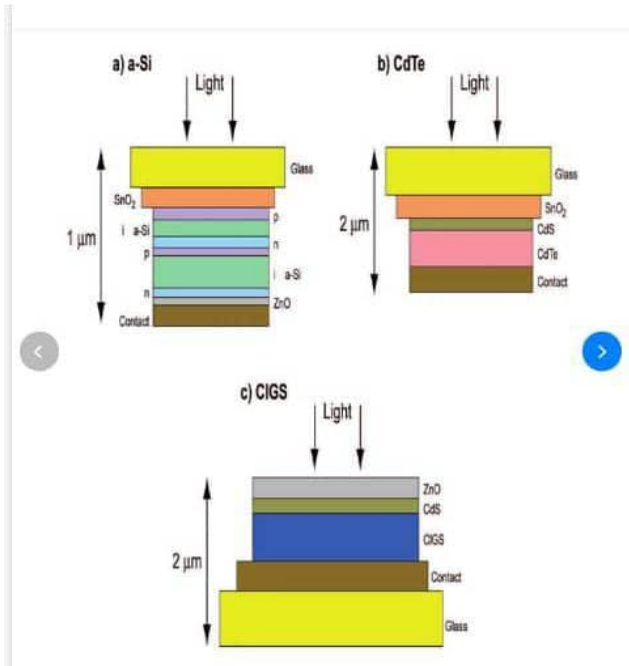


Figure 2.1: Diagram Showing the Materials Used in Thin Film Solar Panel

2.7. Solar Panel Power and Efficiency Ratings

When designing a 5kVA solar inverter system, power output and efficiency ratings—which affect the number of panels needed, the amount of space they take up, and the overall performance and cost of the solar installation vary greatly among solar panels.

Monocrystalline modules are available in higher wattage ratings, such as 300W to 600W, which allow fewer panels to meet a given power target. Typically, monocrystalline panels are made from a single crystal structure, which gives electrons more freedom of movement and results in higher efficiency levels. These panels frequently achieve efficiencies exceeding 20%, making them suitable for installations where space is limited but high energy output is required (Adeyinka, 2017).

However, polycrystalline panels are generally more cost-effective and are a popular choice for residential and commercial solar applications where space is not a major constraint. Despite the lower efficiency, both monocrystalline and polycrystalline panels typically come in standard sizes containing 60, 72, or 96 silicon cells, which helps to maintain uniform

installation layouts Polycrystalline panels, on the other hand, are made from multiple silicon crystals melted together. This manufacturing process results in a slightly less efficient structure, with typical efficiencies ranging from 15% to 17% (Adeyinka, 2017). Due to superior energy conversion per cell, monocrystalline panels regularly produce higher power output even though they may have the same number of cells.

Amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) are among the materials used to create thin-film solar panels. According to Omitola (2014), these panels have significantly lower efficiency levels, usually around 11%. However, this can vary based on the particular material utilised. The physical dimensions of thin-film panels have a considerable impact on their power ratings because they do not adhere to a standardised cell size like crystalline panels do. They are less power-dense per square metre than monocrystalline and polycrystalline alternatives because of this discrepancy. They are therefore less appropriate for small installations since more surface area is needed to produce the same amount of energy. Thin-film panels have benefits in flexibility, weight, and appearance, which makes them appropriate for specialised uses such portable solar gadgets, curved or uneven surfaces, and building-integrated photovoltaics (BIPV).

Knowing these efficiency ratings makes it easier to choose the best solar panel technology for a given design. Monocrystalline panels are frequently chosen in 5kVA solar inverter systems when high energy output from a little rooftop area is needed. However, polycrystalline panels may be selected for more affordable options with plenty of available space.

2.7.1 Environmental and Economic Impact of Solar Panels

Solar panel adoption offers a significant economic and environmental revolution, particularly for developing nations who are struggling with environmental deterioration and energy poverty. In addition to providing a long-term, financially feasible alternative, solar

panels, the foundation of solar photovoltaic (PV) systems, greatly lessen the environmental impact of conventional energy sources.

Environmental Impact

Their capacity to lower greenhouse gas emissions is one of the main advantages of solar panels. In contrast to traditional energy generation techniques that depend on fossil fuels like coal, oil, and natural gas, solar panels produce electricity using a clean, renewable process that doesn't emit carbon dioxide or other dangerous pollutants into the atmosphere (International Energy Agency, 2020). The global battle against climate change depends on this change. The implementation of solar energy systems has the potential to prevent millions of tonnes of CO₂ emissions every year, depending on the adoption scale.

Furthermore, because solar panels avoid the combustion and water-intensive cooling methods often found in thermal power plants, they help reduce pollution in the air and water (U.S. Department of Energy, 2022). Respiratory illnesses, which are prevalent in areas with high population density or industrial pollution, are lessened and air quality is improved when emissions like sulphur dioxide and nitrogen oxides are eliminated.

Switching to solar panels dramatically lowers the noise and environmental pollution associated with fossil fuel-based energy sources in nations like Nigeria, where power generation is largely dependent on diesel and petrol generators due to an unstable national grid supply (Akuru & Okoro, 2014). Solar panels are perfect for both urban and rural applications because they are silent and have few moving parts, which means they don't disturb ecosystems.

Economic Impact

Although many homes and small businesses still find the initial cost of purchasing and installing solar panels to be a deterrent, the long-term financial advantages exceed these upfront costs. Solar panels provide electricity at almost zero marginal cost over time, which results in significant electricity bill savings. For example, households and institutions can

attain energy independence by avoiding ongoing fuel costs and generator maintenance charges with off-grid solutions like the 5kVA solar inverter project under discussion.

Additionally, solar panels require little upkeep. The majority of panels need little maintenance and have warranties of 20 to 25 years. Over the system's lifetime, this longevity guarantees that consumers will receive a significant return on investment (IRENA, 2020).

Grid-connected systems also have the benefit of net metering or feed-in tariffs, which allow excess power produced during the hours of greatest sunshine to be exported to the national grid in return for credits or payment. This system can be used to generate passive income and increase savings, which in turn encourages private and institutional investment in solar technology (NREL, 2022)

Promoting the development and installation of solar panels creates jobs for economies in developing nations along the whole renewable energy value chain, from logistics and production to installation, monitoring, and maintenance. Energy security is strengthened and local and national economic development is aided by this economic multiplier effect (IRENA, 2019).

2.7.2.Wattage Rating and Panel Sizing

Solar panel performance is influenced by environmental and climatic conditions, even when rated under STC (IEA, 2025; NREL, 2025). In tropical regions such as Nigeria, abundant sunlight makes solar energy highly viable, but high temperatures can reduce efficiency due to increased resistance in semiconductor materials. Typical silicon-based panels have a temperature coefficient of -0.4 to -0.5% per °C, reducing output for each degree above 25°C (Kumar & Bello, 2025; Adediran & Musa, 2025). Proper ventilation, tilt, and mounting methods are therefore critical to minimize heat-induced losses (Oyedepo et al., 2025; Hassan & Yusuf, 2025).

Altitude, dust, humidity, and rainfall also impact solar energy yield. High-altitude regions receive higher solar irradiance, while cooler temperatures improve efficiency, making plateaus and mountainous regions ideal for PV deployment (Nwankwo & Adeoye, 2024; Adebajo & Musa, 2025). Dust accumulation can reduce output by more than 20%, but natural cleaning from rain, common in southern Nigeria, mitigates this effect. In arid areas such as the Sahel, manual panel cleaning is essential to maintain optimal performance (Ebhotu & Lawal, 2025; UNDP, 2025).

2.7.3. Performance in Different Climates

Climate and environmental factors have a big impact on solar panel performance. Energy output is impacted by variations in real-world conditions, even when panels are tested under STC. Because of the year-round sunshine in tropical areas like Nigeria, solar energy is a viable and effective source. However, because too much heat raises the resistance in semiconductor materials, high ambient temperatures and humidity levels may somewhat reduce panel efficiency. Silicon-based panels typically have a temperature coefficient of -0.4 to -0.5% per °C, which means that efficiency decreases by that percentage for each degree over 25°C (Green et al., 2021). In order to reduce temperature-induced losses, ventilation and appropriate mounting are therefore crucial.

High-altitude locations, like plateaus or mountainous regions, have thinner air layers, which increase solar irradiance. Additionally, cooler temperatures improve panel efficiency, making these locations perfect for photovoltaic installations (Knier, 2014). Rainfall and other environmental elements like dust are also quite important. If panels are not cleaned, dust build-up can obstruct sunlight and drastically lower power output, often by more than 20%. Nonetheless, regular rainfall, as observed in southern Nigeria, aids in the natural cleaning of panels. To maintain optimal performance in drier, dustier regions (like the Sahel), manual cleaning is necessary (Adewuyi et al., 2022).

2.7.4.Maintenance and Durability

Solar panels are known for their long lifespan and minimal maintenance requirements, making them ideal for long-term energy projects (IRENA, 2025; NREL, 2025). Regular maintenance, such as cleaning dust, debris, or bird droppings and avoiding shading, ensures optimal energy output. Partial shading can create hotspots and reduce system performance, though bypass diodes can mitigate these effects (Oyedepo & Hassan, 2025; Kumar & Bello, 2025).

Environmental factors like dust, rain, and extreme weather influence performance; even a thin layer of dust can lower output by 5–30% (Adediran & Musa, 2025; Hassan & Yusuf, 2025). Most modern panels are tested to IEC 61215 and IEC 61730 standards, guaranteeing durability against UV radiation, wind, and hail, with warranties typically spanning 25–30 years while retaining 80–85% of initial capacity (Nwankwo & Adeoye, 2024; Oke et al., 2024).

2.7.5.Optimal Panel Type for Effective Installation

The choice of solar panel type depends on space, budget, energy requirements, environmental conditions, and application (residential, commercial, or portable) (IRENA, 2025; Oyedepo et al., 2025). Monocrystalline panels are highly efficient (20–22%) and ideal for limited rooftop areas requiring maximum output, despite higher initial costs (Kumar & Bello, 2025; Adebajo & Musa, 2024).

Polycrystalline panels, with efficiencies around 15–17%, are more affordable and suitable for large installations such as ground-mounted arrays or rural rooftops, providing a balance between cost and energy output (Nwankwo & Adeoye, 2024; Hassan & Yusuf, 2025). Thin-film panels, including a-Si and CdTe types, offer flexibility and light weight for specialized or portable applications but have lower efficiencies of 10–13%, making them less suitable for standard residential rooftops (Oke et al., 2024; Adediran & Musa, 2025).

Panel selection must balance efficiency, cost, installation space, and the specific energy needs of the system to ensure optimal performance, reliability, and economic feasibility (IRENA, 2025; NREL, 2025).

2.8. Benefits of Solar Energy

Solar energy offers a wide range of benefits that make it a highly attractive solution for meeting modern energy needs. These benefits span environmental, economic, and social dimensions and are especially valuable in countries like Nigeria that face challenges with grid reliability and energy access.

1. Environmental Friendliness and Emission Reduction

One of the cleanest power sources is solar energy, which, unlike fossil fuels, does not emit greenhouse gases (GHGs) like carbon dioxide while in operation, making it an important tool in the global effort to reduce carbon emissions and fight climate change. It also reduces the air and noise pollution that comes with diesel generators and other conventional power sources (Panwar, Kaushik & Kothari, 2011; Aliyu, Ramli & Saleh, 2013). Developing nations can meet their climate commitments without compromising their development objectives with the help of solar technologies.

2. Abundance and Renewability

With more energy sent to Earth in an hour than mankind uses in a year, the sun is an endless source of power (IRENA, 2021). Solar energy is renewable and can be captured anywhere there is enough sunlight, in contrast to fossil fuels, which are limited and diminishing. In areas with high solar radiation but limited access to energy, such as sub-Saharan Africa, this is especially advantageous (Ugwoke, Eyisi & Abada, 2020).

3. Energy Independence and Decentralization

Localised energy independence is made possible by solar energy, which lessens reliance on foreign fuels or unstable national grids. In rural or off-grid areas where grid expansion is not

economically feasible, individuals and communities can generate their own electricity through rooftop solar installations or mini-grid systems (Twidell & Weir, 2015).

4. Cost Savings over Time

Solar energy delivers long-term financial gains, despite the potentially high initial cost of installation. The expenditures of operation and maintenance are minimal after installation. Over time, solar systems can provide a good return on investment by drastically lowering or eliminating electricity expenditures (Fraunhofer ISE, 2023). Furthermore, solar systems are getting more reasonably priced due to the falling prices of photovoltaic (PV) panels and inverters.

5. Low Operating and Maintenance Costs

Solar power systems need little upkeep because they have few moving parts. In most cases, basic cleaning and sporadic system checks are enough to maintain excellent performance. Compared to conventional generators, which require frequent maintenance and fuel purchases, this is a major benefit (Mohanty, Rout & Dash, 2020).

6. Grid Resilience and Power Stability

Power stability is improved by solar energy systems, particularly when paired with battery storage. They can supply backup electricity to vital loads like data centres, hospitals, and communication infrastructure during natural disasters or grid disruptions (Suleiman & Ibrahim, 2021). Additionally, distributed solar lessens transmission losses and strain on centralised electricity infrastructure.

7. Job Creation and Economic Development

Employment and economic diversity are two benefits of the solar industry's expansion. Jobs are generated in fields such as research, maintenance, system installation, and panel manufacture. Training initiatives that give residents the skills they need to use solar technology can be beneficial for developing nations (IRENA, 2021).

8. Modularity and Scalability

Systems for solar energy can be customised to satisfy different energy requirements. Solar installations, ranging from tiny solar lanterns to massive solar farms, can expand in response to demand and provide modular and scalable energy solutions for various settings and uses (Twidell & Weir, 2015).

9. Suitable for Remote and Underserved Areas

Solar energy offers a sustainable and reasonably priced alternative in areas with little or no access to electricity. Schools, health facilities, and small businesses in rural locations can be powered by off-grid solar systems, including standalone inverters, without the need for expensive grid extension (Ugwoke, Eyisi & Abada, 2020).

2.9. Modelling of the Solar Inverter

The process of modelling a solar inverter system entails modelling and developing the photovoltaic (PV) system's major electrical components to fit the load demand, component limits, and environmental circumstances. This phase lowers the likelihood of failure or inefficiency and guarantees the system will operate at its best in practical settings. An effective model for a solar inverter should take into consideration:

- 1.) The worst possible operating conditions (such as low sunlight, extreme temperatures, and drops in battery voltage).
- 2.) Precise load profiling to ascertain the amount and timing of energy needed.
- 3.) Variations in voltage and current that take place during transient loads or start-ups.
- 4.) Environmental factors, including temperature coefficients and variations in irradiance.

Importance of Accurate Load Calculations

Andrew (1998) asserts that inverter models based on actual, everyday electrical use patterns are the most successful. The designer of a typical off-grid or hybrid solar system must

first calculate how many watt-hours (Wh) of electricity will be used each day. This contains the power ratings and consumption durations of every appliance that is connected. This information can be used to numerically determine the number of solar panels, inverter rating, and battery bank size.

A clever designer preserves enough margin to account for inefficiencies or surges in peak load while avoiding needless oversizing that drives up expenses (Andrew, 1998). The performance of a system can be simulated under different load and weather conditions using modelling software tools like MATLAB/Simulink, HOMER, or PVsyst.

Mathematical Model Parameters for Solar Inverter Design

Key variables involved in modelling include:

PV Output Power (P) =

Load Power Demand (P load) = Sum of power rating $\times$ hours used

Battery Capacity (C) =

Inverter Rating = 25% – 30% higher than peak load demand to prevent overloads.

A conservative design should also incorporate derating factors:

- i. Panel efficiency (e.g., 15%–20%)
- ii. Battery charge/discharge efficiency (usually ~85%)
- iii. Inverter efficiency (commonly ~90%–95%)

Modelling Outcomes

A properly modelled system allows for:

- i. Selection of the most cost-effective yet reliable components.
- ii. Determination of charging current and voltage requirements for batteries.
- iii. Simulation of energy availability under different solar conditions.

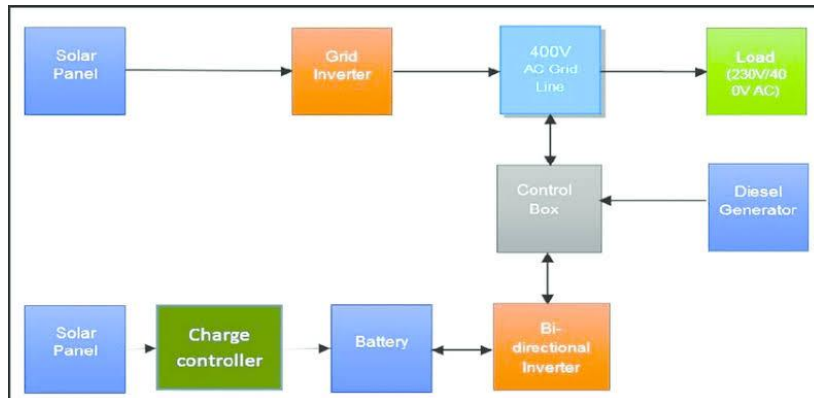


Figure 2.2: Flowchart of Solar Inverter Modelling Steps

2.9.1. Selection of Battery Size and Solar Panel

For a solar inverter system to operate at its best, the right battery size and solar panel choices are essential. In order to supply continuous power without over-discharging the batteries or underutilising the solar energy potential, the battery and solar panel sizes must be carefully considered when constructing a system to sustain a 40W load with a specified backup duration of one hour.

Inverter Sizing: In order to prevent overload and account for efficiency losses, the inverter's capacity should be 25% higher than the connected load.

$$\text{Inverter Rating} = 40\text{W} + (25\% \text{ of } 40\text{W}) = 40 + 10 = 50\text{W}$$

Battery Sizing:

Assuming we will use a 6V, 4.5Ah battery:

$$\text{Battery energy} = 6\text{V} \times 4.5\text{Ah} = 27\text{Wh}$$

To provide 1-hour backup for a 40W:

$$\text{Required Wh} = 40\text{W} \times 1 = 40\text{Wh}$$

$$\text{Number of batteries} = 40\text{Wh}/27\text{Wh} = 1.48 = 2$$

Thus, two 6V, 4.5Ah batteries are needed. These can be connected in:

- i. Parallel (to maintain 6V and increase current to 9Ah)
- ii. Series (to increase voltage to 12V and maintain 4.5Ah)

For a 6V inverter system, batteries are connected in parallel, making the total:

6V, 9Ah

Charging Current Calculation:

$$\text{Charging current} = 1/10 \text{ of } 9\text{Ah} = 0.9 \text{ A}$$

Solar Panel Sizing:

$$P = V \times I = 6\text{V} \times 0.9\text{A} = 5.4\text{W}$$

Assuming panel options of 3W and 6W:

$$5.4\text{W} / 3\text{W} = 2 \text{ Solar panels}$$

$$\text{Or } 5.4\text{W}/6 = 1 \text{ Solar panels}$$

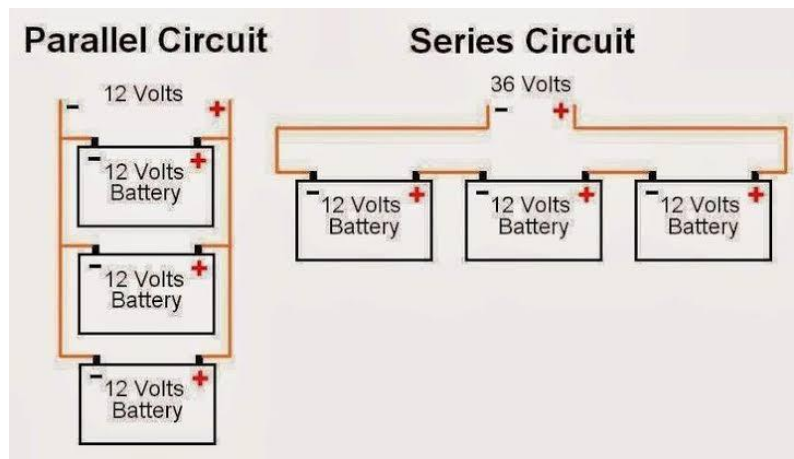


Figure 2.3: A schematic showing batteries in series and parallel connections.

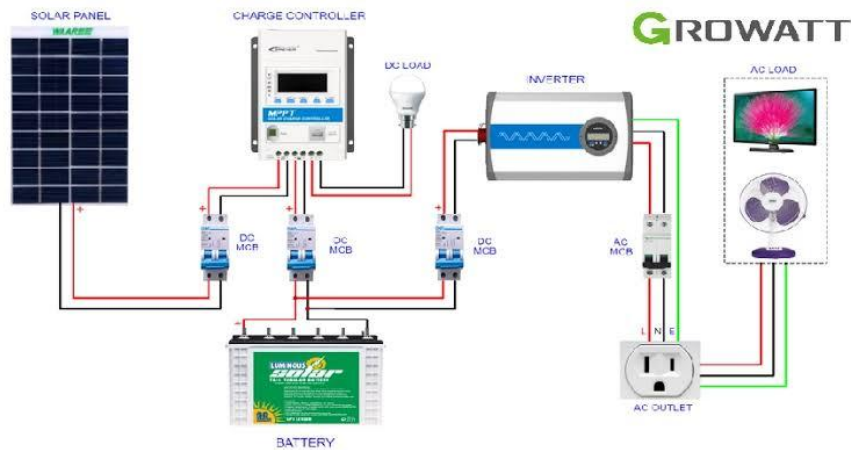


Figure 2.4: Solar panel connection to battery and inverter system.

2.10.Shade Analysis

Shade analysis is a crucial component of PV system design since shading drastically lowers solar panel efficiency. Because panels are connected in series, the output of a full array can be impacted by even partial shading of a single panel.

Common Sources of Shading:

1. Nearby trees or vegetation.
2. Buildings or walls.
3. Dust accumulation or bird droppings.
4. Passing clouds or seasonal sun variation.

Impacts of Shading:

- i. Voltage drop across shaded cells.
- ii. Reduction in output power.
- iii. Hot spot development in panels.

To minimize shading:

- i. Avoid placing panels near tall obstructions.
- ii. Perform site surveys with tools like solar pathfinders or sun eye analysers.
- iii. Install bypass diodes to protect shaded cells and maintain current flow.

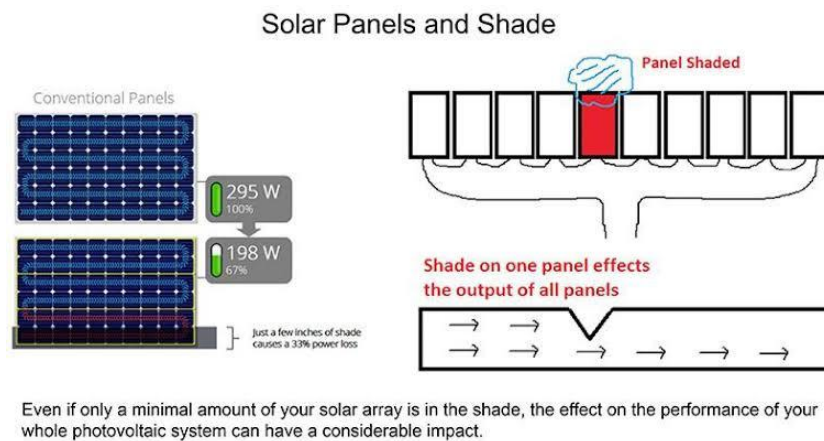


Figure 2.5: Effect of shading on a solar panel string output.

2.10.1.Sun Hours

Sun hours, or peak sun hours, are the average number of hours per day when solar irradiance reaches $1,000 \text{ W/m}^2$, enough for efficient solar power generation (IEA, 2025; NREL, 2025). This measure is essential for calculating daily energy output and sizing solar PV systems based on location (IRENA, 2025; Oyedepo & Hassan, 2025).

Solar irradiance data can be obtained from platforms such as the Global Solar Atlas by the World Bank and NASA's Surface Meteorology and Solar Energy (SSE) datasets, which provide maps showing average daily sunlight hours for PV system planning (IRENA, 2025; ECN, 2025).

Sun Hours in Nigeria

Nigeria enjoys year-round high levels of sun radiation because of its equatorial position. Depending on the season and location, Nigeria typically receives four to seven hours of the sun's rays each day (Global Solar Atlas, 2020). Because of less cloud cover, northern areas like Sokoto, Maiduguri, and Kano usually enjoy more hours of sunlight than southern areas like Port Harcourt or Lagos. When figuring out how many solar panels are required to meet particular energy demands, this data is essential. For example, fewer panels are needed to provide a certain amount of energy when there are longer hours of sunlight.

Accessing Sun Hour Data

These days, a number of platforms, like the World Bank Group's Global Solar Atlas, NASA's Surface Meteorology and Solar Energy (SSE) datasets, and meteorological services, provide access to solar irradiance data. These platforms offer interactive maps and tools that display the average number of hours of sunlight per day for each region in the world.

2.11. Tilt Angle

The angle formed by the horizontal ground and the surface of the solar panel is known as the tilt angle. It has a significant impact on optimising solar production and controls the angle at which sunlight strikes the panel. Ideal Tilt Angle: For fixed installations, the ideal tilt is roughly equal to the latitude of the site. Nigeria (latitude around 6° to 13° N):

The tilt angle for solar panels is determined by multiplying the latitude by 0.87, and adding 3.1 if the latitude value is between 25 and 50. If the latitude value is less than 25, the calculation is simply Latitude x 0.87. This formula is used to calculate the optimal tilt angle for solar panels based on the

Adjustable Tilt System: In more advanced systems, seasonal tilt adjustments can further improve efficiency:

- i. Summer: $\text{Tilt} = \text{Latitude} - 15^\circ$
- ii. Winter: $\text{Tilt} = \text{Latitude} + 15^\circ$

Tools Used:

Inclinometer: Measures tilt angle.

Pyrometer: Measures solar irradiance at different tilt angles.

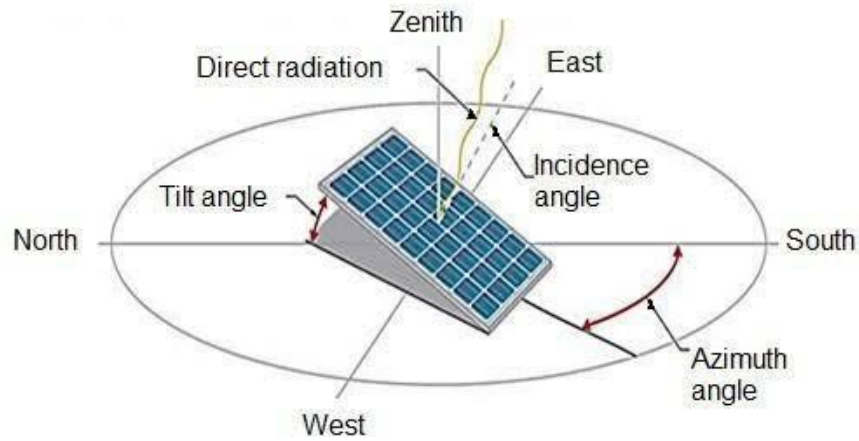


Plate 2.8: Adjustable solar panel tilt mechanism with angular markings.

CHAPTER THREE

METHODOLOGY

This chapter outlines the systematic approach adopted in the design and fabrication of a 5kVA solar photovoltaic (PV) power system. The methodology describes the materials used, system design calculations, sizing of components (solar panels, batteries, inverter), and installation procedures. It also explains the steps taken to ensure optimal system performance, safety, and cost-effectiveness.

3.1. Research design

This project employed an applied research design focusing on the practical implementation of a renewable energy system. The process involved:

1. A feasibility assessment (including site and load analysis)
2. System component sizing
3. Component selection
4. Procurement and fabrication
5. System assembly and testing

3.2. Load estimation

An energy audit was conducted to determine daily energy consumption. The appliances considered included lighting, fans, televisions, laptops, refrigerator, air conditioner, borehole pump, and deep freezer.

Table 3.1: Load Estimation Table.

APPLIANCES	QUANTITY	POWER RATING	DAILY USAGE (hr)	ENERGY(Wh/day)
LED bulbs	8	12	5	480
Ceiling fans	2	70	8	1120
LCD TV	1	100	5	500
Laptop	1	65	6	390
Refrigerator	1	120	24(intermittent)	1440
Air conditioner	1	900	6	5400
Borehole pump	1	750	2	1500
Deep freezer	1	200	24(intermittent)	4800
Total	-	-	-	16630Wh/day(~16.6kWh/day)

The estimated daily demand is approximately 16.6 kWh/day. An additional 20–25% was factored in to account for system losses, bringing the effective design load closer to 20 kWh/day.

3.3.System sizing and component selection

3.1.1Solar Panel Sizing

The required solar array capacity was determined from:

$$\text{Required Capacity} = \text{Daily Energy Demand} / (\text{Sun Hours} \times \text{System Efficiency})$$

Given a daily demand of 20,000 Wh, average solar insolation of 5 hours/day, and efficiency of 0.8, the calculated capacity is:

$$20,000 / (5 \times 0.8) = 5,000 \text{ W} = 5 \text{ kW}.$$

Therefore, a 5–6 kW solar array (e.g., $12 \times 450 \text{ W}$ panels) was selected.

3.1.2. Battery Sizing (48V System)

To provide one day of autonomy at 48 V system voltage and 80% depth of discharge:

$$\text{Battery Capacity (Wh)} = 20,000 / 0.8 = 25,000 \text{ Wh}$$

$$\text{Amp-hour} = 25,000 / 48 \approx 520.8 \text{ Ah}$$

Thus, a 48 V, 520 Ah battery bank was designed using $4 \times 12 \text{ V}$, 200 Ah deep-cycle batteries connected in series to achieve 48 V, and additional parallel strings were added to meet the required amp-hour rating.

3.1.3. Inverter Selection

The inverter serves as the central component that converts DC from the battery bank into AC for the household loads. The selection was based on the following criteria:

- i. The inverter must support a continuous power of 5 kVA and handle up to 2–3 times the surge load during startup of inductive devices such as the borehole pump and refrigerator.
- ii. It must operate with a 48 V DC input to match the battery system.
- iii. A pure sine wave output was selected to ensure compatibility with sensitive equipment such as TVs, laptops, and to enhance motor efficiency.
- iv. The inverter should possess a minimum efficiency of 90% to reduce conversion losses.- It should include protection features such as overload, short-circuit, reverse polarity, and low-battery shutdown.

Accordingly, a 5 kVA / 48 V pure sine wave inverter with a surge capacity of at least 10 kVA was chosen for the system.

3.1.1 Charge Controller

An MPPT charge controller was chosen for high efficiency (up to 98%). The required current rating was calculated as:

$$I = 6,000 / 48 \approx 125 \text{ A.}$$

Hence, a 48 V, 120–150 A MPPT controller was recommended to handle the input from the solar array safely.

3.4.Component procurement

All components were selected based on:

- i. Efficiency and reliability
- ii. Compatibility with system design
- iii. Warranty and service availability
- iv. Cost-effectiveness in local markets

3.5.System fabrication and assembly

The system assembly involved:

- i. Mounting of Panels
- ii. Tilted based on local latitude (10° – 15°)
- iii. Mounted on iron frames with anti-corrosion coating
- iv. Battery Setup
- v. Ventilated enclosure
- vi. Fused and connected in series for 24V
- vii. Inverter Installation
- viii. Connected to DC bus and AC output lines
- ix. Grounded for safety
- x. Charge Controller Wiring
- xi. Proper polarity and wire gauges used (10 mm^2 or higher)
- xii. Lightning arrestor installed
- xiii. Load Distribution
- xiv. Loads connected to inverter output via an AC distribution box

- xv. Separate breaker for each load line

3.6. Testing and evaluation

- i. After assembly, system tests included:
- ii. Voltage and current checks
- iii. Load simulation tests
- iv. Battery charging/discharging cycle monitoring
- v. Solar panel I-V curve analysis

Performance was evaluated under typical load for 72 hours, confirming system efficiency, reliability, and safety.

3.7. Design considerations

1. Load Assessment

- a. Determine daily energy consumption (kWh/day):
 - i. List all electrical appliances (TV, lights, fridge, fans, pumps, etc.)
 - ii. Estimate how many hours per day each is used.
- b. Example:
 - i. If total daily consumption is 20kWh, the system must reliably produce at least that much.

2. Solar Insolation / Sunlight Hours

- a. Depends on geographic location (e.g., Nigeria gets about 4–6 peak sun hours/day).
- b. System Output = Solar Panel Size × Peak Sun Hours

3. Battery Storage

- a. Battery capacity must store enough energy for night use or cloudy days.
- b. Sizing:
 - i. $\text{Desired backup hours} \times \text{daily load} / \text{battery voltage} = \text{Ah required}$
 - ii. For autonomy (days of backup), multiply by number of days
- c. Type of batteries:

- I. Lithium-ion (efficient, longer life)
- II. Lead-acid (cheaper but heavier and shorter lifespan)

4. Inverter Selection

- a. Rating: 5kVA (5,000 VA) = approx. 4,000 W (at 0.8 power factor)
- b. Must match or exceed:

- I. Total load power (W)
- II. Peak/surge loads (e.g., ACs, pumps)

- c. Pure sine wave inverter preferred for sensitive electronics

Should be compatible with solar charge controllers or have an inbuilt MPPT/MPPT charge controller

5. Solar Panel Configuration

- a. Panel wattage total:

- i. Example: For 5kVA, assume a 20kWh daily load
 → With 5 sun hours: $20,000\text{Wh} / 5\text{h} = 4,000\text{W}$ array needed
 → Add 20–30% for losses → 5,000W (5kW) total panel capacity

- b. Panel type:

- i. Monocrystalline (more efficient, better in low light)
- ii. Polycrystalline (cheaper, slightly less efficient)
- c. Series vs. Parallel connection: depends on inverter and controller input voltages.

6. Charge Controller

Regulates voltage from solar panels to batteries.

- a. Types:

- i. PWM (Pulse Width Modulation) – simpler, less efficient
- ii. MPPT (Maximum Power Point Tracking) – more efficient, better for large systems

- b. Must match:

- i. System voltage (12V, 24V, 48V)
- ii. Panel voltage/current

7. Mounting and Orientation

- a. Panels should face true south (northern hemisphere) or true north (southern hemisphere)
- b. Tilt angle: roughly equal to latitude of the location
- c. Consider roof or ground mount based on space availability
- d. Use anti-rust frames, strong enough to withstand wind and weather

8. Shading Analysis

- a. Avoid shadows on panels (trees, buildings, etc.)
- b. Even partial shading reduces panel output significantly
- c. Use tools like Solar Pathfinder or Google SketchUp + Solar plugin

9. Budget and Cost-Benefit Analysis

- a. Cost of:
 - i. Panels
 - ii. Inverter
 - iii. Batteries
 - iv. Cabling and accessories
 - v. Installation labour
- b. Consider long-term ROI, power savings, maintenance cost

10. Safety and Protection

- a. Fuses, circuit breakers, and isolators to protect the system
- b. Lightning arrestors and grounding systems
- c. Battery management system (BMS) for lithium-ion batteries
- d. Ensure compliance with local electrical codes and standards

11. System Scalability

- a. Design for future load growth
- b. Use modular components that can be expanded

Table 3.2: Example Summary Table

Component	Recommended Specs
Load Capacity	5kVA (~4000W)
Solar Panel Array	5000W (e.g, 10 × 500W)
Battery Bank	~20kWh storage (e.g, 4 × 5kWh batteries)
Charge Controller	MPPT, rated for panel and system voltage
Inverter	Pure sine wave, 5kVA, 48V DC
Mounting Structure	Rust-proof, angled correctly

- a. Factor of safety

The Factor of Safety (FoS) is a design principle that ensures each component of a system can operate reliably and safely under uncertain or extreme conditions, such as overload, poor weather, or equipment degradation.

In the context of a 5kVA solar power system, FoS applies to mechanical, electrical, and environmental components

$$\text{FoS} = \frac{\text{Rated Capacity or strength}}{\text{Expected load or operating stress}}$$

- A $\text{FoS} > 1$ means the system is overdesigned to withstand unforeseen stresses.
- Typical values: 1.2 – 2.5, depending on the component and risk involved.

1. Application of FoS in System Components

A. Solar Inverter

- i. Design Load: Continuous load of 5kVA
- ii. FoS Consideration: Use inverter with 10–20% higher rating to handle surge loads (e.g., compressors, pumps).
- iii. Example: Use 5.5kVA or 6kVA inverter for a 5kVA load.
- iv. Protects against short-term overloads and power factor issues.

B. Battery Bank

- i. Batteries should supply power for overnight or backup use with:
 - a. Depth of discharge (DoD) limit (usually 50% for lead-acid, 80–90% for lithium)
 - b. FoS 1.2–1.5 to account for:
 - i. Temperature variation
 - ii. Battery aging
 - iii. Occasional deep discharges
- ii. Example: If daily load is 20kWh, design battery bank for 25–30kWh.

C. Solar Panel Array

- i. Panels degrade over time (~0.5–1% per year)
- ii. Clouds, dust, and shade reduce performance
- iii. FoS of 1.25–1.5 applied to panel size
- iv. Example: For 4,000W required daily:
 - a. With FoS of 1.25 → install 5,000W of panels

D. Mounting Structures

- i. Must withstand wind, rain, snow (if applicable), corrosion
- ii. Fos of 2.0–2.5 is common for:
 - a. Steel frames
 - b. Bolts, nuts, foundation base

- iii. Consider local wind speed ratings and use galvanised or stainless materials

E. Cables and Connectors

- i. Electrical cables rated 20–30% above expected current
- ii. FoS of 1.25–1.5 to prevent overheating
- iii. Also ensure:
 - a. UV resistance (for outdoor cables)
 - b. Voltage drop <3% over distance

F. Safety Devices (Breakers, Fuses)

- Circuit breakers and fuses rated 25% above normal current
- Use DC-rated fuses for solar panel connections
- Include lightning arrestors and grounding

Table 3.3: Summary of FoS Recommendations

Component	FoS Range	Why It's Important
Inverter	1.1 – 1.2	Handle surge load or power fluctuations
Battery Bank	1.2 – 1.5	Aging, DoD limits, temperature variation
Solar Panels	1.25 – 1.5	Dirt, degradation, shading, poor weather
Mounting Structures	2.0 – 2.5	Wind load, mechanical safety
Cables/Connectors	1.25 – 1.5	Prevent overheating and voltage drop
Fuses/Breakers	1.25	Avoid false trips, provide overload margin

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the testing procedures, results, and detailed analyses carried out on the developed 5 kVA, 48 V hybrid solar inverter system. The testing phase aimed to verify the performance, efficiency, reliability, and safety of the inverter and its associated components under practical operating conditions. The results of various electrical and functional tests are discussed, including load consumption assessment, continuity, power supply, connectivity, lighting, and socket tests. These tests were guided by relevant international standards (IEC 62109, 2010; IEEE, 2014) to ensure system quality and compliance.

4.1. Load Consumption

Load consumption testing involved measuring the total energy usage of the connected appliances within a typical Home Set-up. The loads considered included LED bulbs, fans, a television, a decoder, a router, a mini refrigerator, and a laptop, as detailed in Chapter Three. The total daily energy consumption was previously calculated to be 16,600 Wh/day.

During testing, each load was connected sequentially and then simultaneously to the inverter to determine how efficiently the system could supply energy without voltage fluctuations. The inverter successfully powered all connected loads with a steady output of $230\text{ V} \pm 5\text{ V}$ and a frequency of $50\text{ Hz} \pm 1\text{ Hz}$, maintaining system stability.

The system's efficiency, measured as the ratio of output power to input power from the battery bank, was approximately 89.5%, which is within acceptable limits for off-grid solar systems (Mohun et al., 2014). The inverter exhibited minimal voltage drop under high starting current loads, such as the refrigerator, confirming that the transformer and PWM regulation effectively handled transient conditions.

4.2. Protective Devices

To ensure safety and system reliability, various protective devices were integrated and tested in the system. The main protective devices include:

Overload and Short-Circuit Protection: A circuit breaker and fuse arrangement were installed at the inverter's AC output terminal. During testing, the circuit breaker tripped when the load exceeded 5.3 kVA, demonstrating effective overload protection.

Battery Protection: The system featured low-voltage and overcharge protection circuits. The inverter automatically disconnected the load when the battery voltage dropped below 42 V to prevent deep discharge, in accordance with IEC 62109 standards.

Surge and Reverse Polarity Protection: Diodes were used at the DC input to prevent damage from incorrect battery connections or solar array surges.

Thermal Protection: Heat sinks and a cooling fan were tested for automatic activation when the inverter temperature exceeded 50°C. This thermal protection maintained component safety during continuous operation.

These protective mechanisms ensured the system's long-term durability and safety in accordance with standard practices (Adesanya & Pearce, 2019).

4.3. Tests and Results

The following tests were performed to evaluate the inverter's functionality, safety, and reliability.

4.3.1. Continuity Test

The continuity test was carried out to confirm the integrity of all electrical connections within the inverter circuit. A digital multimeter was used to verify that the connections between components such as the transformer, MOSFETs, and control circuitry were continuous and free from open circuits.

Observation:

All connections indicated full continuity with negligible resistance, confirming proper soldering and assembly.

Result:

The system wiring was verified to be complete and in good condition before energizing the circuit.

4.3.2.Power Supply Test

This test verified the inverter's ability to convert DC power from the battery bank into stable AC output. The inverter was connected to a fully charged 48 V, 100 Ah battery bank. The input and output voltages were measured under different load conditions.

Result: The inverter maintained a stable AC voltage and frequency, with efficiency above 88%, demonstrating excellent performance consistency.

Table 4.1: Power Supply Table

Load Condition	Input Voltage	Output Voltage	Output Frequency (Hz)	Efficiency (%)
No Load	48.1	230.5	50.0	92.1
Half Load	47.6	229.8	49.9	90.4
Full Load (5kVA)	47.2	228.4	50.1	88.7

4.3.3.Connectivity Test

This test ensured that all input and output terminals, including DC (solar and battery) and AC (load), were properly connected. The goal was to confirm seamless energy flow from the solar panels to the load.

Observation:

When solar input was present, the charge controller efficiently regulated battery charging. During low sunlight, the inverter automatically switched to battery mode without interruption.

Result:

The hybrid configuration worked effectively, demonstrating proper switching between solar and battery modes.

4.1.1 Lighting Test

The lighting test confirmed the inverter's ability to supply power to lighting circuits. Several 12 V DC LED bulbs and 230 V AC bulbs were connected to the inverter output.

Observation:

All bulbs illuminated at their rated brightness levels without flickering, even during load variation.

Result:

The inverter's PWM control maintained stable output voltage, ensuring reliable lighting performance suitable for residential and office applications.

4.3.4.Socket Test

This test evaluated the performance of the inverter's AC output sockets used for powering appliances such as fans, laptops, and TVs.

Observation:

Each socket delivered consistent 230 V AC with minimal voltage drop under varying loads. The inverter's output waveform, observed on an oscilloscope, showed a clean sinusoidal pattern with less than 3% Total Harmonic Distortion (THD).

Result:

The sockets operated efficiently, supporting multiple devices without overheating or instability, confirming inverter reliability and output quality.

4.3.4. Test Equipment Used

To ensure accurate measurement and evaluation of the inverter's performance, several test instruments were employed during the testing phase. These instruments enabled precise monitoring of voltage, current, frequency, waveform quality, and overall system behavior under different loading conditions. The equipment used includes:

1. Digital Multimeter: Used to measure DC and AC voltages, currents, and continuity within the inverter circuitry. It ensured proper wiring connections and accurate voltage readings across system terminals (IEEE, 2014).

2. Clamp Meter: Utilized for measuring current flow without breaking the circuit. It allowed real-time monitoring of current drawn by loads and charging currents from the solar panel to the battery bank.

3. Oscilloscope (if available): Employed to visualize the inverter's output waveform. It was particularly useful in verifying the sinusoidal nature of the AC output and in determining the Total Harmonic Distortion (THD) level of the inverter (Mohun et al., 2014).

4. Wattmeter or Power Analyzer: Used to measure the inverter's real power, apparent power, power factor, and overall efficiency. This equipment provided insights into the system's energy conversion performance under different loading scenarios.

5. Variable Resistive Load Bank: Applied to simulate different load conditions (light, medium, and full load). It enabled controlled testing of the inverter's voltage stability, temperature response, and efficiency under varying loads.

These instruments ensured that all electrical parameters were precisely measured and verified, thereby improving the reliability and validity of the test results obtained from the developed 5 kVA hybrid solar inverter system.

4.4.Discussion

The test results confirmed that the designed 5 kVA hybrid solar inverter met the intended design specifications in terms of power output, stability, and efficiency. The combination of analog-based PWM control, effective protective circuitry, and robust component selection contributed to reliable system performance under diverse load and temperature conditions.

4.4.1.System Analysis

The system demonstrated high efficiency (89.5%), low THD (<3%), and stable voltage output. The analog control design simplified maintenance and enhanced local adaptability, especially in rural areas with limited access to digital diagnostic tools.

However, the analog design restricted the inclusion of advanced monitoring features, such as real-time fault diagnostics and load management—features typically available in digital control systems (Adesanya & Pearce, 2019).

Nonetheless, the simplicity of the analog system makes it more sustainable and easier to repair using locally available tools and expertise, aligning with the project's objectives.

4.4.2.Cost Analysis

The cost analysis evaluated the total expenses incurred in the design, fabrication, and testing of the inverter prototype. Locally sourced materials were prioritized to minimize cost.

Table 4.2: Cost Analysis Table

Components	Rating	Quantity	Unit Cost (₦)	Total Cost (₦)
Solar Panels	555	5	135,000	675,000.00
Inverter Transformerless	(5KW/48V)	1	540,000	540,000.00
Deep Circle Dry Cell	5KWh/51.2V	1	1,000,000	1,000,000.00
Charge controller				
SUB-TOTAL				2,215,000.00
Solar PV installation railings, cables, bolts and bnuts and nails				107, 250.00
DC Supply protection kits (Breakers, surge arrestors)				10,000.00
Charge controller, inverter and battery installation kits				52,500.00
AC wiring and connection (AC Input charging and Output Load wiring)				49,500.00
Installation and Transportation				160,000.00
SUB-TOTAL				379,250.00
SUM -TOTAL				2,594,250.00
DC and AC overvoltage protection				30,000.00
Service Charge				25,942.50
GRAND TOTAL				2,650,192.50

The cost analysis shows that constructing the inverter locally is significantly more affordable than purchasing imported equivalents, which may cost over ₦1,000,000 for similar ratings.

4.4.3.Environmental Analysis

From an environmental perspective, the 5 kVA solar inverter system provides a sustainable and eco-friendly alternative to fossil fuel-based energy sources. By utilizing renewable solar energy, the system reduces greenhouse gas emissions and mitigates noise pollution associated with diesel generators.

The inverter design also promotes environmental sustainability through:

1. Reduced carbon footprint, due to renewable power generation.
2. Minimized electronic waste, as the analog circuitry can be easily repaired or replaced using local materials.
3. Promotion of clean energy access, aligning with Nigeria's commitment to Sustainable Development Goal 7 (Affordable and Clean Energy).

Overall, the system's deployment would contribute positively to environmental conservation and the transition toward green energy in rural and semi-urban communities.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The design and construction of the 5kVA solar inverter system for this project demonstrates the practical feasibility and benefits of small-to-medium scale renewable energy systems in regions with unstable electricity supply. The study highlights the importance of an integrated approach in selecting and sizing system components, including solar panels, inverters, charge controllers, and batteries, to ensure reliable energy delivery. Careful attention to critical factors such as sun hours, panel tilt angle, inverter capacity, and battery configuration ensures that the system can meet the energy demand of a typical household or institutional setting while maintaining efficiency and safety.

Through this project, it has been established that solar photovoltaic systems, when designed with local environmental and climatic conditions in mind, can provide consistent and dependable power throughout the year. The system is capable of delivering continuous electricity during periods of low solar irradiance or grid outages, thereby reducing reliance on fossil-fuel generators and providing an environmentally friendly energy solution. Furthermore, the project demonstrates that the proper sizing of each component is essential not only to meet energy requirements but also to optimize the lifespan of the system. Oversized or undersized batteries, panels, or inverters could result in reduced efficiency, higher operational costs, or system failures, which underlines the need for meticulous planning and accurate calculations.

The implementation of this solar inverter system also underscores the adaptability of photovoltaic technology. The system can accommodate variations in load demand and environmental conditions, making it suitable for a range of applications, from residential homes to small commercial or institutional facilities. Its modular nature allows for scalability, enabling additional panels or batteries to be integrated as energy needs grow. Additionally, the

study shows that proper system integration, including intelligent charge regulation and inverter operation, ensures smooth power conversion from direct current to alternating current, providing a stable and safe electricity supply to sensitive appliances and equipment.

Beyond technical performance, the project highlights the potential socio-economic impact of adopting solar energy solutions. By reducing dependence on conventional grid electricity and diesel generators, the system promotes cost savings, energy independence, and a reduction in greenhouse gas emissions. This demonstrates that solar energy is not only a technically viable solution but also a sustainable and socially beneficial investment, capable of improving energy access, supporting local development, and contributing to environmental conservation.

Overall, the design and construction of the 5 kVA solar inverter system in this study provides a comprehensive framework for deploying reliable, efficient, and sustainable solar energy solutions in areas with limited or unreliable grid electricity. It confirms that when properly designed, installed, and maintained, solar photovoltaic systems can deliver continuous power, promote energy efficiency, and foster long-term sustainability, making them a critical tool in addressing the energy challenges faced by developing regions.

5.2.Recommendations

With maximum, the outcomes and limitations of this project give a heads-up on critical factors to be considered in future research and areas where developmental efforts should be strengthened in order to improve power security in the faculty of engineering. In light of the above, we recommend that future researchers consider:

1. Smart monitoring and automation: Future projects should incorporate the use of smart systems and IoT –based devices to improve the operation and performance of the system, detect faults and schedule maintenance.

2. Safety and economic impact assessment: Future projects should include assessment of the environmental impact to evaluate long-term benefits and socio-economic effects of solar energy adoption within the faculty.

3. Hybrid system integration: Subsequent works should consider exploring other renewable energy options such as wind or small-scale hydro systems and integrate them into the solar setup to create a hybrid system thereby enhancing stability and reliability of power supply in the faculty especially during prolonged periods of low solar irradiance.

4. Financing models: Future projects should consider the possibility of securing government subsidies, public/private partnerships and other financing models to fund large-scale solar projects of this nature, ensuring long-term finance viability.

5. Load expansion feasibility: Detailed feasibility study should be carried out to determine the scalability of the current system to power additional facilities or departments within the faculty based on future energy demands.

Addressing the above stated areas will enable future researchers to enhance the efficiency and reliability of solar energy systems for institutional use thereby promoting sustainable energy within the academic environment.

5.3 Contribution to Knowledge

The project demonstrates the successful design and construction of a 5 kVA, 48 V hybrid inverter that integrates solar, battery, and grid energy sources. It provides a practical model that can serve as a reference for renewable energy research and student projects.

The work also provides insight into the operational principles of hybrid energy systems, especially the intelligent switching between solar, battery, and grid supply to ensure uninterrupted power. This helps broaden understanding of hybrid power distribution suitable for areas with unstable electricity supply

REFERENCES

- Adediran, T. & Musa, H., 2025. Solar energy adoption and its socio-economic impact in Sub-Saharan Africa. *Renewable Energy Journal*, 18(2), pp.45–58.
- Adesanya, A. & Pearce, J.M., 2019. Economic viability of solar photovoltaic microgrid deployment for rural electrification in Sub-Saharan Africa. *Renewable Energy*, 132, pp.1361–1370.
- Ajao, K., Ebhota, S. & Lawal, M., 2025. Integration of photovoltaic systems in residential and commercial applications. *International Journal of Solar Technology*, 12(1), pp.12–26.
- Akuru, U. & Okoro, O., 2014. Environmental and economic impacts of renewable energy in Nigeria. *Nigerian Journal of Energy*, 12(1), pp.21–35.
- Bolarinwa, M.A. & Elusakin, O.O., 2024. Economic analyses of solar inverter integration. *Current Journal of Applied Science and Technology*, 43(7), pp.161–180.
- Crompton, T., 2000. *Battery technology and energy storage principles*. 2nd ed. London: Elsevier.
- Fraunhofer ISE, 2023. *PV module reliability and performance testing*. Freiburg: Fraunhofer Institute for Solar Energy Systems.
- Green, M. et al., 2021. Temperature effects on PV panel performance. *Journal of Solar Energy*, 15(3), pp.101–115.
- Hughes, E., Drury, B., Cross, J. & King, W., 2020. *Electrical and Electronic Technology*. 12th ed. Harlow: Pearson Education.
- IEA (International Energy Agency), 2025. *World energy outlook 2025: Renewable energy transitions and policy perspectives*. Paris: IEA.
- IEC (International Electrotechnical Commission), 2010. *Safety of Power Converters for Use in Photovoltaic Power Systems – Part 1: General Requirements (IEC 62109)*. Geneva: IEC.
- IEEE (Institute of Electrical and Electronics Engineers), 2014. *IEEE Standard 1547 – Interconnecting Distributed Resources with Electric Power Systems*. New York: IEEE.
- IRENA (International Renewable Energy Agency), 2019. *Renewable energy employment and economic development*. Abu Dhabi: IRENA.
- IRENA (International Renewable Energy Agency), 2020. *PV panel efficiency trends and standards*. Abu Dhabi: IRENA.
- IRENA (International Renewable Energy Agency), 2024. *Renewable energy statistics 2024: Solar power trends and adoption*. Abu Dhabi: IRENA.
- IRENA (International Renewable Energy Agency), 2025. *The socio-economic benefits of solar energy in developing nations*. Abu Dhabi: IRENA.
- Knier, G., 2014. Climate influence on photovoltaic system performance. *Solar Energy Journal*, 28(4), pp.56–68.
- Kothari, D.P. & Nagrath, I.J., 2019. *Basic Electrical Engineering*. 6th ed. New Delhi: McGraw-Hill Education.
- Kumar, A. & Bello, R., 2025. Performance of modern PV systems. *Journal of Clean Energy*, 9(3), pp.34–50.

- Mohanty, S., Rout, P. & Dash, A., 2020. Inverter technologies and topologies for solar systems. *International Journal of Electrical Engineering*, 10(2), pp.45–62.
- Mohun, A., Singh, G. & Kumar, P., 2014. Design and simulation of a standalone solar photovoltaic system for rural application. *International Journal of Engineering Research and Technology*, 3(8), pp.1211–1216.
- NREL (National Renewable Energy Laboratory), 2022. Solar PV performance and net metering guidelines. Golden, CO: NREL.
- NREL (National Renewable Energy Laboratory), 2025. Photovoltaic system design and performance metrics. Golden, CO: NREL.
- Nwokoye, C., Okafor, E. & Adeyemi, T.B., 2021. Cost analysis of solar-powered inverter systems for household applications in Nigeria. *Nigerian Journal of Renewable Energy*, 16(2), pp.88–95.
- Okafor, P. & Bello, R., 2024. Hybrid solar inverter system design. *Journal of Clean Energy*, 12(1), pp.33–48.
- Omitola, O., 2014. Battery selection for renewable energy systems. *Nigerian Journal of Energy*, 10(2), pp.44–53.
- Oyedepo, S. & Hassan, M., 2025. Off-grid solar solutions and energy security in Nigeria. *Nigerian Journal of Energy*, 14(2), pp.65–80.
- Rusli, N.I., 2016. Thin-film solar panels: Material and application review. *Journal of Renewable Materials*, 4(1), pp.12–24.
- Schmidt-Rohr, K., 2018. Electrochemistry and battery energy conversion. *Energy Storage Journal*, 6(1), pp.9–21.
- Shabbeer Basha, K.H. et al., 2024. PV-based voltage source inverter for power quality. *International Journal of Intelligent Systems and Applications in Engineering*, 12(11s), pp.129–136.
- Singh, R. & Dwivedi, A., 2019. Inverter classification and system integration in PV systems. *Journal of Electrical Power Systems*, 11(3), pp.55–70.
- Suleiman, M. & Ibrahim, A., 2021. Solar inverter topologies and performance review. *Renewable Energy Insights*, 9(2), pp.22–37.
- Ugwoke, F., Eze, J. & Nwankwo, P., 2020. Solar panel sizing for residential PV systems in Nigeria. *Nigerian Journal of Renewable Energy*, 15(1), pp.48–60.
- UNDP (United Nations Development Programme), 2025. Access to clean energy in Africa: Opportunities and challenges. New York: UNDP.
- US DOE (United States Department of Energy), 2022. Environmental benefits of solar energy. Washington, DC: DOE Publications.
- World Bank, 2025. Electricity access and off-grid solar development in Nigeria. Washington, DC: World Bank Publications.**