COMPARATIVE ASSESSMENT OF GRID-TIED AND ISOLATED PV/HYBRID ENERGY SYSTEMS FOR GRID-CONNECTED FACILITIES: CASE OF MASIA DEVELOPMENT CENTRE AND VUWANI SCIENCE CENTRE ENERGY SYSTEMS

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2025

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DEDICATIONS

This dissertation is dedicated to my family, whose steadfast support, encouragement, and moral guidance have been indispensable throughout my academic journey. Their commitment has been a constant source of strength and motivation in pursuing this work.

I also dedicate this dissertation to the Almighty God, in gratitude for His guidance, protection, and providence, which have sustained me throughout this endeavour.

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ABSTRACT

The study underscores the significance of a sustainable energy system for national progress, particularly highlighting the increasing adoption of solar photovoltaic (PV) in South Africa. Solar PV integration into the current power generation systems offers financial and ecological benefits, but determining the optimal configuration, especially in areas with an existing utility grid, is challenging. A walk-through energy audit was conducted at the Masia Community Development Centre and the Vuwani Science Centre to establish accurate energy demand profiles. Using the Hybrid Optimisation Model for Multiple Energy Resources (HOMER), the study analysed load

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characteristics for two sites: the Masia Community Development Centre and the Vuwani Science Centre. Results show that grid-connected (GC) systems outperform off-grid (OG) systems in technical and economic terms, as evidenced by their lower net present cost (NPC) and levelized cost of energy (LCOE) values, alongside higher power output. However, GC systems' reliance on grid electricity, often derived from non-renewable sources, increases greenhouse gas emissions. Among the evaluated configurations, the Photovoltaic-Grid-Converter (PV/Grid/Conv) architecture emerged as the most cost-effective, delivering low NPC, LCOE, and operating costs of R1,852,811.00, R1.63, and R20,878.56, respectively, for Masia, and R2,969,068.00, R1.07, and R83,039.74 for Vuwani. When scaled to Masia's total facility demand, values reached R15,768,780.00 NPC, R1.90 LCOE, and R365,062.00 operating costs. Despite its efficiency, the PV/Grid/Conv system struggles with nighttime supply. It is vulnerable to load shedding, suggesting the advantage of incorporating PV/Battery/Grid/Converter (PV/Batt/Grid/Conv) systems for enhanced reliability in critical applications. The off-grid (OG) systems remain vital for remote locations where grid extension is impractical, enabling sustainable electrification, reduced fossil fuel dependence, and greater energy independence. This analysis offers valuable guidance for energy planners and system designers, balancing economic performance, environmental impact, and reliability in PV system deployment.

Keywords—Homer, grid-tied, stand-alone, hybrid, renewable energy source

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LIST OF ABBREVIATIONS

RESs	Renewable energy sources
CO_2	Carbon dioxide
PV	Photovoltaic
AC	Alternate Current
DC	Direct current
LCOE	Levelized Cost of Energy
NPC	Net present cost
GC	Grid-connected

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OG	Off-Grid
PV-DG	Photovoltaic-diesel generator
DG	Diesel Generator-Grid
GPS	Geographical position system
NREL	National Renewable Energy Laboratory
NASA	National Aeronautics and Space Administration
HOMER	Hybrid optimisation of multiple energy resources / (Hybrid Optimization Model for Electric Renewables)
SBP	Selling back price
O&M	Operation and Management
PV/Grid/Conv	Photovoltaic-Grid-Converter
PV/Batt/Grid/Conv	Photovoltaic-Battery-Grid-Converter
PV/Batt/Conv	Photovoltaic-Battery-Converter

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CHAPTER 1: INTRODUCTORY BACKGROUND

1.1 Introduction

Despite its rapid economic growth within Southern Africa, South Africa confronts a significant challenge in ensuring energy security. This challenge is exacerbated by increased prosperity, a burgeoning population, urbanisation, and heightened per capita energy consumption, all of which have escalated energy demand. As attributed by Sen et al. (2016) and Garg et al. (2015), the power-generating sector in South Africa is currently confronted with unprecedented challenges, predominantly stemming from its reliance on coal and the escalating costs associated with coal-based energy production. Amidst the prevailing energy crisis, characterised by soaring energy costs, dwindling fossil fuel reserves, and mounting concerns over global climate change, the imperative for national-scale adoption of renewable energy has never been more critical (Sen, et al., 2016; Garg, et al., 2015; Prasad & Raturi, 2017; Lal & Raturi, 2012; Raturi, et al., 2016; Franklin, 2017). This is particularly pressing for countries where limited resources and severe power shortages impede economic prospects and industrial growth (Chand, et al., 2019). Notably, in countries like South Africa, despite the abundance of coal and uranium deposits, the global trend of discouraging CO_2-emitting resources due to their environmental impact leaves these countries with scant options but to enhance the proportion of clean technologies within their energy mix to meet consumption needs (Masrur, et al., 2021).

The acceptance of photovoltaic (PV) technology as a viable renewable energy source in South Africa has been bolstered by escalating electricity prices and the unpredictability of power outages (Prasad & Raturi, 2017; Lal & Raturi, 2012; Masrur, et al., 2021). The observed decline in solar technology costs further amplifies the share of PV in the country's energy matrix, facilitating both rural and urban electrification and propelling sustainable development through renewable energy sources (RESs) (Lal & Raturi, 2012; Masrur, et al., 2021). Moreover, the increased reliance on electricity generated from fossil fuels is exacerbating South Africa's carbon footprint, with adverse implications for public health (Hansen, et al., 2000). Predominantly dependent on coal for electricity, coal constituted 84.4% of its electricity production in 2021, with clean energy resources contributing a mere 13.7%, it becomes imperative for South Africa to diminish its dependency on coal-generated electricity in favour of alternative energy sources (Garg, et al., 2015; Prasad & Raturi, 2017; Lal & Raturi, 2012).

Beyond the necessity to reduce reliance on fossil fuels, owing to their finite availability in some regions, it is crucial to recognise the detrimental environmental consequences of their utilisation.

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The combustion of fossil fuels for energy not only emits CO_2, contributing to the greenhouse effect but also plays a significant role in the depletion of the ozone layer (Chand, et al., 2019). These processes are associated with numerous environmental repercussions, including acid rain, air pollution, and land pollution from excavation operations. Concurrently, global efforts are underway in developing and researching renewable energy technologies, including biogas, hydro, wind, solar, and nuclear energy (Lal & Raturi, 2012; Raturi, et al., 2016; Chand, et al., 2019). Integrating renewable energy sources (RESs) into existing power generation systems offers remarkable economic and environmental benefits, enabling significant fuel savings and substantial reductions in carbon dioxide emissions.

Alternative sources of energy, particularly solar photovoltaics (PV), possess the capacity to revolutionise global energy systems, presenting a transformative potential for our world. As technology improves, PV systems become increasingly efficient and effective. There are three categories of solar systems: stand-alone (off-grid), grid-tied (on-grid), and hybrid. Each category comes with its requirements for assembly, challenges in installation, and opportunities for cost savings, as outlined in Table 1, (Masrur, et al., 2021; Chand, et al., 2019). Households often face obstacles when adopting PV systems, such as a lack of information and understanding.

Identifying the best-suited type of solar system for each situation is crucial. This study adopts the generic framework used by Mathew, et al., (2022) for PV-based microgrid sizing to simulate the alternative and optimal system configuration for the two cases. The affordable and effective utilisation of PV as a renewable energy technology can be achieved by determining the optimal design size strategy. Utilising optimisation techniques for sizing can be highly beneficial, ensuring a smart investment and the maximisation of solar systems, battery banks, or the grid to reliably and efficiently satisfy power requirements (Alturki, 2022; Liu, et al., 2010).

Table 1: Components of grid-tied, off-grid, and hybrid solar systems

Grid-tied solar system	Standalone(off-grid) solar system	Hybrid solar system
➢ Solar panels ➢ Power meter ➢ Grid inverter or Microinverters	➢ Solar panels ➢ Charge controller ➢ Battery bank ➢ Off-grid Inverter ➢ DC disconnect switch (additional)	➢ Solar panels ➢ Charge controller ➢ Battery bank ➢ Grid-tied Inverter ➢ Power meter

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		➢ DC disconnect switch (and others)

Table 1 shows the components of the grid-tied, Stand-alone (off-grid) hybrid solar systems (Bhatia, 2018). The facility's ability to run independently from the electrical grid should be considered when designing a PV system, which calls for batteries or other on-site energy storage technologies (Bhatia, 2018; Tomar & Tiwari, 2017) . With this massive increase in the adoption of solar photovoltaic technology, there is a need to clearly show the advantages and drawbacks of the available system configurations in their optimised form (Masrur, et al., 2021). The longevity (lifespan), maintenance, and configuration complexity of a solar PV system are all impacted by adding more components. The grid-tied system without a battery bank/storage has a longer life span than other systems and requires less maintenance due to fewer components and decreased system complexity. (Bhatia, 2018).

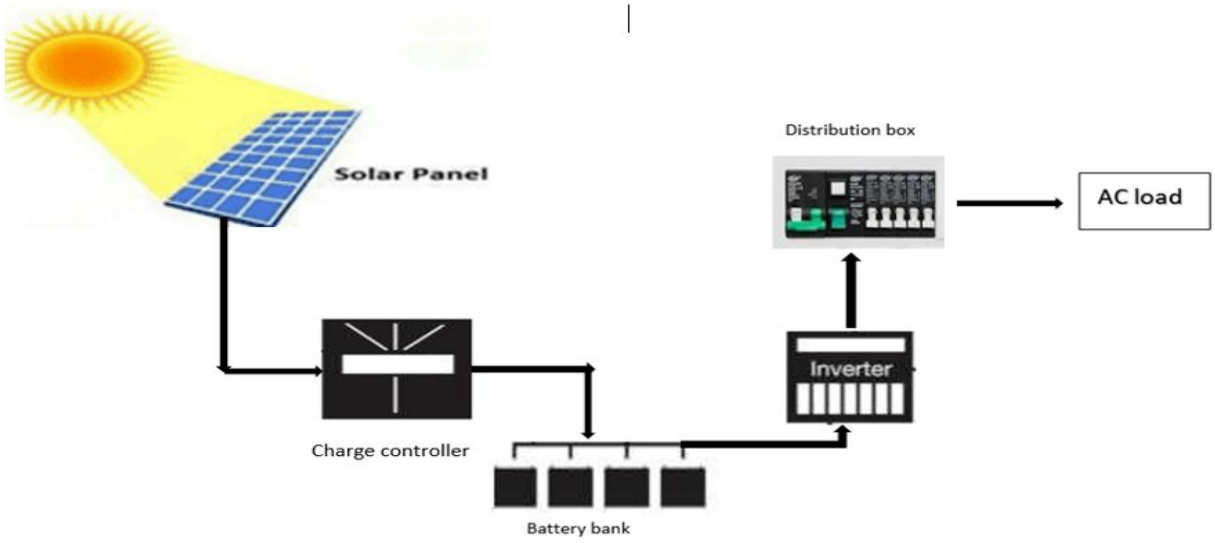


Figure 1: Stand-Alone/Off-Grid Solar PV System (Ali, et al., 2018)

The diagram in Figure 1 illustrates an off-grid/stand-alone photovoltaic system (PV system) consisting of a solar panel, battery bank, charge controller, and inverter. An off-grid/stand-alone solar PV system is an independent solar installation that operates with a battery backup system and is not connected to the power grid (Bhatia, 2018). The electricity produced by photovoltaic (PV) modules and stored in batteries is direct current (DC). An inverter converts this DC electricity into alternating current (AC). Following this conversion process, the AC electrical current is distributed to the residential infrastructure for various loads' consumption (Franklin, 2017;

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Sukamongkol, et al., 2002). In the development of a battery-dependent system, it is imperative to meticulously evaluate all electrical loads intended to be powered by the solar photovoltaic (PV) system, alongside devising an appropriate contingency strategy to address potential system failures in energy production or distribution (Torcellini, et al., 2006; Franklin, 2017; Islam & Mamun, 2017). Incorporating loads exceeding the system's designed capacity undermines its efficiency and necessitates a period of dormancy, allowing the battery bank to replenish its charge from the photovoltaic array. This approach underscores the importance of comprehensive planning and system design in renewable energy applications, ensuring reliability and sustainability. Comprehensive planning and system design in renewable energy applications ensure reliability and sustainability (Franklin, 2017; Boxwell, 2010).

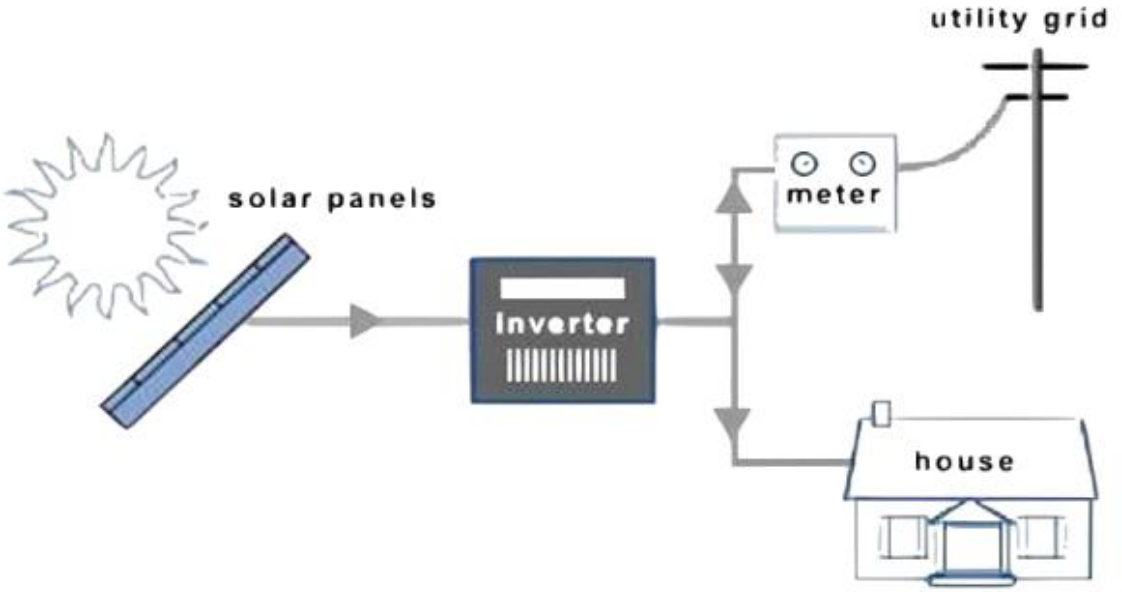


Figure 2: Grid-tied solar PV system (Maddileti & Cherukuri, 2019)

The schematic representation provided in Figure 2 elucidates the components of a grid-tied photovoltaic (PV) system, comprising a solar panel, an inverter, and a power meter. This configuration typifies a solar energy installation interconnected with the electrical grid, distinguished by its operation without a battery backup mechanism (Bhatia, 2018). Among the diverse solar energy systems, grid-tied PV installations have witnessed a precipitous growth trajectory, attributed to their efficiency and practicality in energy generation and distribution.

In the operational dynamics of a grid-tied solar PV system, the conversion of sunlight into electricity is initiated by solar panels, which harness solar energy to produce direct current (DC) electricity. This DC electricity is subsequently directed to an inverter, where it transforms

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alternating current (AC) electricity, rendering it compatible with residential or building utilization (Sen, et al., 2016; Garg, et al., 2015; Torcellini, et al., 2006). A notable feature of this system is its capacity to export surplus electricity back to the local utility grid. This mechanism, often facilitated through net metering policies, enables the accrual of credits against future electrical consumption, offering a financially viable and environmentally sustainable energy-use model.

Moreover, the seasonal variability in electricity production, characterised by a higher yield during summer months, accentuates the benefits of net metering by allowing for a reduction in electrical costs during the winter (Franklin, 2017; Tomar & Tiwari, 2017). This cyclical balance underscores the efficacy of grid-tied PV systems in contributing to a more sustainable and economically favourable energy landscape.

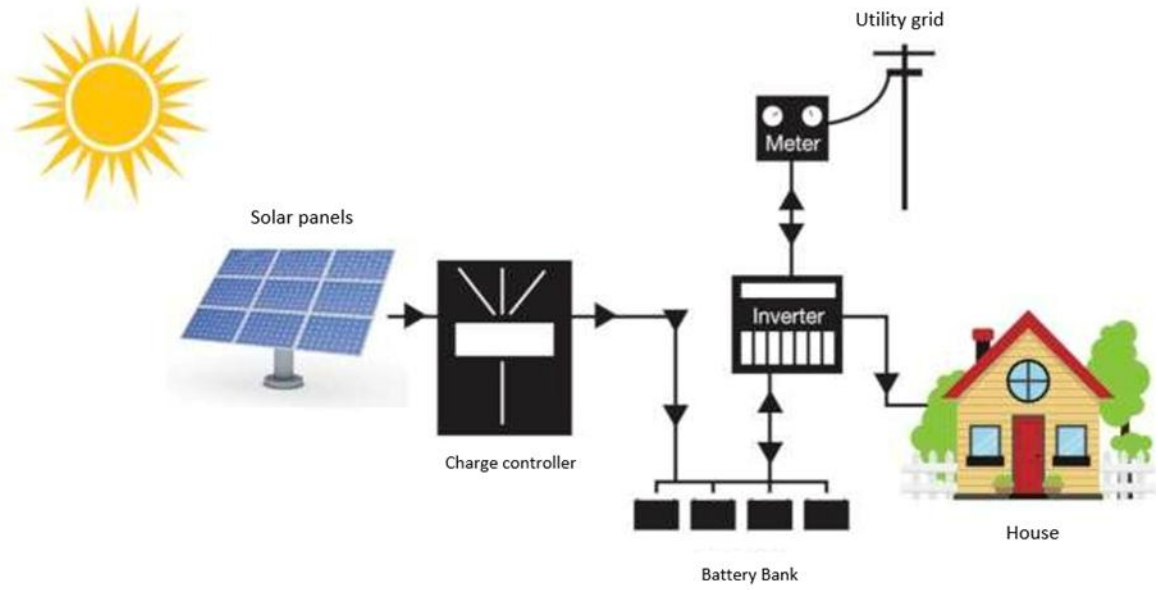


Figure 3: Hybrid solar energy system (Ahmed, et al., 2000)

A hybrid solar energy system combines stand-alone/off-grid and grid-tied PV systems (Franklin, 2017; Sukamongkol, et al., 2002). It uses solar-generated energy primarily to satisfy the electrical demands of homes/buildings, with surplus energy exported back to the utility grid. (Bhatia, 2018; Tomar & Tiwari, 2017). The system also draws electricity from the grid during periods of low solar generation and charges battery storage units. (Franklin, 2017; Torcellini, et al., 2006). Although installation costs are high, hybrid solar energy systems offer long-term benefits through net metering and the assurance of an uninterrupted power supply, especially during load-shedding (Tomar & Tiwari, 2017).

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1.2 Problem Statement

Solar photovoltaic (PV) technology is widely acknowledged for its efficiency, economic viability, and pivotal role in fostering sustainable development and global electrification (Sen, et al., 2016; Chand, et al., 2019) . The increase in the adoption of photovoltaic (PV) systems, especially in regions like South Africa, highlights their crucial role in advancing the transition to sustainable energy solutions. However, the decision regarding selecting the most suitable PV system configuration, whether to opt for a grid-tied PV system or a standalone PV/battery hybrid system, is not merely important; it is essential. This choice has profound implications for energy planners, policymakers, and facility managers.

Within this context, a pressing need exists to elucidate the intricate trade-offs and considerations guiding the deployment of PV systems in their optimised configurations. This requires thoroughly evaluating the parameters influencing system size and design decisions. Consequently, this study aims to analyse and compare two illustrative cases systematically: the grid-tied and stand-alone PV/fuel cell/battery hybrid systems deployed at the Vuwani Science Centre and Masia Development Centre in Vhembe District of South Africa, respectively. Drawing insights from the distinctive operational contexts of these facilities, a comparative scenario analysis is conducted to delineate optimal operational dispatch strategies.

This study proposes a comprehensive techno-economic optimisation framework in response to the challenges posed by load shedding at the distribution level. Leveraging industry-standard simulation tools such as PVSYST and HOMER, the study aims to simulate the performance of hybrid renewable energy systems, incorporating photovoltaic arrays, inverters, and energy storage units configured to operate both off-grid and grid-tied. A vital part of this framework is adopting an innovative, rule-based energy management strategy to optimise how and when we use our energy resources.

Central to optimisation is the judicious sizing of critical components, specifically photovoltaic arrays, fuel cell units, and batteries. This task will be accomplished by applying the Grasshopper optimisation algorithm, guided by a multi-criterion decision-making approach. Parameters such as loss of power supply probability, levelized cost, and payback period will inform the optimisation process, ensuring that system configurations align with technical exigencies and economic viability.

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1.3 Aim and Objectives

Aim: To conduct a comparative assessment of grid-tied and isolated PV/hybrid energy systems for grid-connected facilities, with a focus on the Masia Development Centre and Vuwani Science Centre energy systems, aiming to elucidate the optimal configuration and operational strategies for integrating renewable energy sources to mitigate the adverse impacts of load shedding while ensuring economic viability and technical feasibility.

Objectives:

To collect data on the study area and installed power systems. To process the collected data for input in simulation platforms (HOMER and PVSYST) and simulate the currently installed systems.

To run simulations to determine the alternative and optimal configuration of the installed systems that give the lowest Levelized Cost of Energy (LCOE) and net present cost (NPC) of power systems.

1. To propose the optimal operation strategy of the off-grid configuration and compare it with the grid-connected based on the total power production, economic parameters like cost of energy (LCOE) and net present cost (NPC), and greenhouse gas emissions.

1.4 Significance of the Study

This study provides valuable guidance for selecting the most appropriate PV system configuration suitable for specific situations. It identifies a set of parameters and develops a decision algorithm to optimise energy provision while minimising the annualised cost of the system. Integrating renewable energy sources (RESs) into existing power generation systems has yielded significant economic and environmental benefits, including substantial reductions in carbon dioxide emissions and fuel consumption (Chand, et al., 2019) This study will assist facility managers, households, and policymakers in understanding the most effective renewable energy configurations, supporting broader sustainability goals, energy security, and economic, environmental, and technological advancement. This study will facilitate the transition toward a more sustainable and resilient energy future by addressing these critical factors.

1.5 Research Background

Energy from the sun is essential for all living organisms. As concerns about global warming and carbon dioxide emissions mount, reducing dependency on fossil fuels becomes imperative (Hansen, et al., 2000) .Solar energy, primarily from the sun, presents a promising solution to the

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global energy crisis. Solar photovoltaic (PV) technology is particularly notable for its sustainability, efficacy, and economic viability, positioning it as a primary solution for long-term electrification and development challenges worldwide (Sen, et al., 2016). The increasing adoption of solar PV technology, especially in regions like South Africa, underscores its pivotal role in transitioning towards a more sustainable energy system.

1.6 Research Motivation

The motivation for conducting this research arises from the urgent need for sustainable energy solutions in the face of global environmental challenges and the pursuit of energy security. Sustainable energy and development are intrinsically linked to incorporating energy resources such as photovoltaic solar systems into existing energy-producing systems. Despite considerable interest in integrating renewable energy systems into the current energy generation system, there remains a dearth of studies on the comparative assessment of different configurations of solar photovoltaic systems for grid-connected facilities. This research addresses this gap by identifying the most suitable system configuration for specific load characteristics, especially in areas where the utility grid is available, thereby minimising losses due to non-optimal design and operation. Understanding how these technologies perform under various configurations can guide energy planners in making informed decisions that enhance energy resilience. Additionally, evaluating the potential of off-grid and hybrid systems supports the empowerment of communities through sustainable electrification and promotes energy independence. As energy costs continue to rise, economic viability assessment of different configurations can reveal the long-term financial implications of grid-tied versus isolated systems, aiding stakeholders in making economically sound decisions. Hence, this study will contribute to the body of knowledge necessary for a more sustainable energy future.

1.7 Assumptions of the Study

This study assumes that each case study will evaluate grid-tied and isolated photovoltaic (PV)/hybrid energy systems under the same environmental and load conditions to ensure a fair comparison. A nominal discount rate of 8.0% and an inflation rate of 5.9% are considered (SARB, 2024; CPI, 2023) . The grid-tied system is assumed to sell surplus energy to the grid at a fixed rate of R1.20 while purchasing electricity at a higher rate of R2.95 per kWh (Eskom, 2023), reflecting typical utility pricing structures. It is assumed that energy storage banks are integrated into the isolated system to ensure a stable power supply. The project's lifespan is 25 years, considering system degradation and maintenance costs. Economic and technical factors, NPC,

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LCOE, operational costs, efficiency, and reliability are analysed to determine the optimal system configuration for grid-connected facilities. The simulations considered the monocrystalline ART solar panel, the Freedom Won Lite Home 30/24 LiFePO4 battery, and an Apex inverter. Table 2 below shows the Cost and Lifetime Analysis of System Components used in the simulation.

Table 2: Cost and Lifetime Analysis of System Components

Components	Cost /kW	Replacement cost	O&M per Kw	Lifetime(Years)
Solar panel	R13 500.00	R13 500.00	R500.00	25
Inverter	R10 600.00	R10 600.00	R500.00	10
Battery	R8 000.00	R8 000.00	R500.00	10

1.8 Overview of Thesis Structure

Chapter One introduces the thesis by outlining the problem statement, research aim and objectives, significance of the study, research background, and motivation behind the research. Chapter Two comprehensively reviews related studies, identifies knowledge gaps, critically assesses previous approaches, and develops a theoretical framework to guide empirical investigation. Chapter Three details the data collection process, PV solar system configuration, study area, load assessment, mathematical models, and analysis methods, followed by a discussion of the research approach. Chapter Four presents data/results from the two study areas and compares simulation results from HOMER software, focusing on energy generation dynamics, economic metrics, and emission dynamics. Finally, Chapter Five summarises the study's results and examines their implications for the energy landscape.

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CHAPTER 2: LITERATURE REVIEW

2.1 Power Supply in South Africa

The power supply in South Africa, which predominantly relies on fossil fuels, requires significant improvements in reliability and sustainability. The ongoing, unpredictable power outage has witnessed this. South Africa's energy plan is an integrated energy resource plan that provides an energy mix that includes Coal, wind, hydro, Solar, etc. (DME, 2021; ENERGY, 2003). Under its IRP, South Africa plans to add 2.5GW of hydropower capacity, 6GW of solar photovoltaic (PV) capacity, 14.4GW of wind power capacity, and 2GW of energy storage capacity. In 2020, it was reported that 84.39% of the population had access to electricity in South Africa. However, many of the users of the Grid frequently experience disruptions, voltage fluctuations, blackouts (which may continue for days or weeks), and ongoing load scheduling. (Torcellini, et al., 2006). Due to this, many people and businesses have purchased various fossil fuel-based generators with varying capacities to generate their electricity due to frequent grid interruptions. This pattern can result in fatalities and negatively impact the economy and ecology. Industrial consumers often opt for generators to solve the challenges of unreliable power supply. As a consequence of these interruptions, some people may relocate their firms/businesses to other countries because they find the capital and maintenance costs of these generators to be too exorbitant, which can lead to economic growth retard (Boxwell, 2010). These issues highlight the vulnerabilities present in the system and emphasise the need for improvements to ensure a more reliable and stable electrical supply.

In 2019, South Africa experienced its worst year of load shedding, according to the Council for Scientific and Industrial Research (CSIR), with blackouts persisting for 530 hours. Stage 6 load shedding was implemented for the first time, and this was expected to continue for two to three years, depending on government decisions and actions (Mataboge, et al., 2021). The ongoing increase severely hampers the nation's economic growth due to power outages or load shedding. This situation was reportedly a result of insufficient generating capacity (South Africa produces around 47,000MW against an installed generation capacity of 52,000MW), operation failures, maintenance issues, and breakdowns at poorly maintained power stations (Mataboge, et al., 2021). Several nations, such as South Africa, have implemented regulations and financial incentives to boost their renewable energy capacity; the objectives are to tackle environmental issues, curtail atmospheric pollution, and address energy-related challenges. Consumers in South Africa have also had to deal with the steadily rising cost of electricity and the unreliability

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of the Grid since 2007 due to insufficient electricity output; as a result, utilising hybrid renewable energy systems (HRESs) has become more common.

In South Africa, the National Energy Act, 2008 (Act 34 of 2008) guarantees the availability of various energy supplies in sustainable amounts and at reasonable costs. (DME, 2021). In addition, the Act provides for the increased use of renewable energies, contingency energy supplies, the holding of strategic energy feedstock and carriers, and adequate investment in energy infrastructure (DME, 2021). Considering the abundant renewable energy sources (RES) almost everywhere in South Africa, the country is in the best position to harness all these energy resources to ensure a healthy ecosystem. However, the fluctuating nature of RES, especially solar photovoltaic (PV) and wind, poses a significant challenge; integrating these renewable energy sources will serve as a better option for energy sustainability (Asamoah, et al., 2022; Adebanji, et al., 2021). Solar photovoltaic (PV) is a promising renewable energy solution recommended to address long-term electrification and development issues worldwide; it is a direct and straightforward solution that can effectively meet the energy needs of communities (Chand, et al., 2019; Sen, et al., 2016).

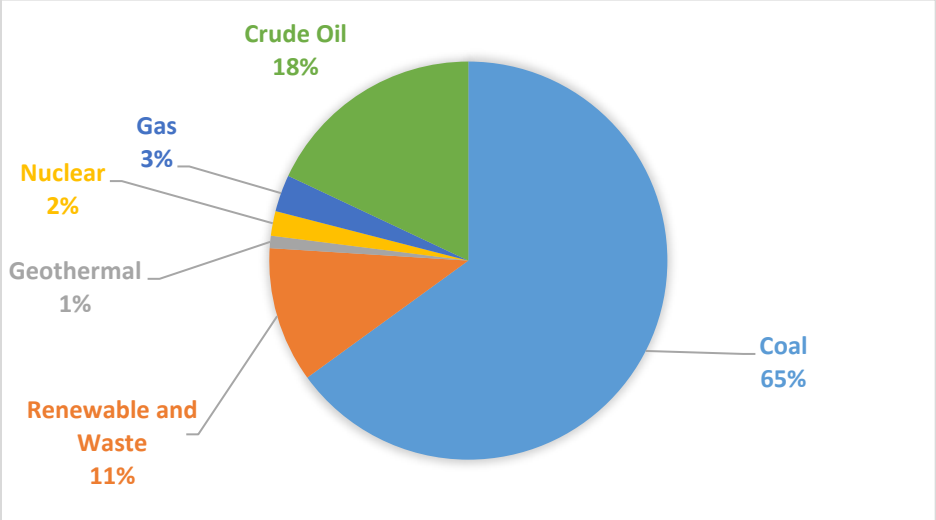


Figure 4: Power supply pie chart 2018 *(DME, 2021)*

2.2 South Africa's Renewable Energy Policy Formulation

Reducing the detrimental effects of the generation and consumption of energy in South Africa on the country's economy, society, and environment requires investments in energy efficiency and renewable energy (Winkler, 2005). Unfortunately, renewable energy sources comprise only a tiny fraction of primary energy production and a smaller percentage of commercial energy

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consumption. To address this problem, it is necessary to explore various renewable energy implementations (ENERGY, 2003). Reliable and affordable energy for domestic purposes and businesses is fundamental, underpinning everyone's standard of living. Renewable energy produced from natural resources will help avoid unexpected power interruptions and promote the country's sustainable growth, as most natural resources are available domestically. Based on the study, these local resources might provide energy supply security independent of occasional global difficulties (ENERGY, 2003).

Climate change is recognised as one of the biggest environmental threats worldwide today. Reducing fossil fuel usage via implementing renewable energies would significantly decrease damaging emissions, thus reducing South Africa's impact on climate change (ENERGY, 2003; DME, 2021). To boost both commercial and residential PV roof segments, vital to bolstering the economy and positively influencing the existing power supply in South Africa, a national legal framework for commercially viable net-metering schemes must be established. Implementing solar PV systems is complicated because different municipalities have varied legislation regarding connecting dispersed renewable energy generators to the community grid. However, the certainty of feed-in tariffs remains to be determined regarding the amount of renewable electricity ensured to be delivered under local conditions despite the guarantee, according to developers (Winkler, 2005). According to *Winkler (2005, diversity of energy supply guaranteed quality,* considering the fixed quantity set by portfolio standards (Winkler, 2005).

Setting targets and coordinating essential supporting actions like power purchase agreements, Grid access, and creating a stable market for sustainable energy technology are all part of a renewable energy obligation that should be considered (Chalmers, 2001; Winkler, 2005). Funding to support commercial and residential PV roof segments is necessary since renewable electricity technologies must contend with substantially lower tariffs for electricity locally and internationally (Chalmers, 2001; ENERGY, 2003). Prospective sources from abroad and those found locally will require identification to establish South Africa's best eventual renewable energy mix (Winkler, 2005).

Some local governments have approved using solar energy surplus to reduce consumption costs in some places, while a two-way metering scheme has been adopted in other areas. With this method, energy consumption is invoiced at fixed rates, and customers who install rooftop solar panels are reimbursed at different rates for the energy they sell back into the electric Grid. However, municipalities like the City of Cape Town offer a strange reverse-free tariff scheme, implying that owners of rooftop solar energy systems can sell any extra energy back to the electric

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Grid and recuperate costs incurred through energy use (Marais, 2019; Elsässer, et al., 2018). After surplus energy is purchased at the authorised City SSEG feed-in tariffs, qualified commercial electricity users can receive payment in one of the following ways: One way to offset costs is to apply it to your power account, rates account, or another account (Elsässer, et al., 2018).

2.3 Benefits of Solar PV System

PV solar systems provide usable solar electricity through photovoltaics. It is made up of multiple parts, such as solar PV panels that gather solar energy and transform it into DC electrical current, a solar inverter that changes the DC electrical current output into AC electrical current, and mounting, cabling, and further electrical accessories that enable the system to work. Solar energy systems have several environmental, economic, and social benefits. As a result of solar PV, countries in developing regions can increase their energy independence, diversify their energy sources, and enhance the security of their energy supply (Tsoutsos, et al., 2005). Furthermore, deregulation of energy markets will be enabled, as well as an acceleration of rural electrification.

Photovoltaic (PV) is one of the most sustainable and environmentally friendly ways of generating electricity and offers several environmental benefits, such as minimising air and water pollution while reducing the need for conventional resources. However, a PV system is a renewable and clean energy source that achieves environmental benefits. In *2013, Almaktar et al.* documented that photovoltaic (PV) systems do not generate noise, air, or water pollution during operation (Almaktar, et al., 2013). Applying grid-connected and grid-interactive hybrid PV systems allows cities to support aesthetic and more environmentally friendly concepts. In contrast, off-grid systems enable remote areas to reinforce aesthetic and more ecologically/environmentally friendly concepts. According to *Tsoutsos et al. (2005)*, the primary environmental benefits of grid-connected and hybrid PV Technologies are reducing greenhouse gas emissions and avoiding hazardous gas emissions (Tsoutsos, et al., 2005).

In grid-connected areas/facilities, Grid-tied PV reduces the electricity demand and supply from the Grid, which eases the burden on the local power grid (Almaktar, et al., 2013; Oladigbolu, et al., 2021; Gbadamosi & Nwulu, 2022). Furthermore, grid-tied PV technology has shallow maintenance requirements and minimal maintenance costs during its life span, as it comprises few components. Off-grid and hybrid PV systems have high installation costs, maintenance costs, and system complexity due to additional components compared to the grid-tied (Okedu, et al., 2015; Bhatia, 2018). The Grid-tied and hybrid PV can support the country's economy and create job opportunities (Pillai, et al., 2014). Moreover, the solar industry creates business opportunities

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for installers of PV power systems, manufacturers, product distributors, engineering and architectural companies. Under economic benefits, solar PV systems are comparatively costly to install in buildings; therefore, countries like the United States provide several financial incentives, including tax credits, cash rebates, net metering, solar set aside, and solar renewable energy credits, which perform as critical drivers to enhance the PV demand (Burns & Kang, 2012).

Comparatively, in 2014*, Polo & Haas found that grid-tied PV systems are more beneficial than separate PV power plants because of zero requirements for additional land, fewer expenses on supporting structures, and* an indirect energy conservation impact due to the participation of consumers in their electricity supply (Polo & Haas, 2014). In 2015, *Kumar and Sudhakar* assessed the output produced by a 10 MW grid-connected solar photovoltaic power plant in Ramagundam, Telangana. The solar plant configuration was designed with a seasonal tilt, and its performance was studied seasonally and annually. The results of the plant output were compared with the simulation values derived from PVsyst software and PV-GIS. As a result, it was demonstrated that grid-connected PV systems are the perfect clean-energy option for large-scale generation. (Kumar & Sudhakar, 2015).

Table 3: Benefits of solar PV systems

Environmental Benefits	Economic Benefits	Social benefits
➢ Minimising water and air pollution and emitting zero noise	➢ Reduce the electricity supply-demand from the Grid	➢ Increase of national energy independence.
➢ Promoting more aesthetically pleasing and environmentally friendly building practices.	➢ Low maintenance cost throughout its lifespan	➢ Energy supply security and diversification.
➢ generating zero carbon emissions while in operation	➢ Create job opportunities	➢ Support of the deregulation of energy markets.
➢	➢ Grid-tied PV consumers are provided financial incentives (such as feed-in tariffs, net metering, and capital subsidies).	➢ Acceleration of rural electrification in developing nations.

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		➢ Creating both rural and urban electrification

Furthermore, in 2013, *Annisa & Mustaqimah* embarked on a pioneering simulation study focused on designing a hybrid energy system for hydrogen production within Malaysia, leveraging climatic data from Johor Bahru over a calendar year. This investigation revealed that a hydrogen-based system possesses the intrinsic capacity to operate independently of the grid, offering significant benefits from both technical and economic perspectives. This system is deemed particularly suitable for coastal residential applications, serving as an efficient energy carrier, contingent upon reducing costs associated with wind turbine and hydrogen system technologies to their minimal feasible levels.

2.4 Comparative Assessment of On-Grid and Off-Grid Hybrid Systems

Existing studies indicate that both on-grid and off-grid hybrid systems, which typically integrate a combination of solar, wind, and hydropower, possess distinct advantages and disadvantages, with no single configuration emerging as universally optimal. Various comparisons of renewable energy systems have been made in recent years to overcome the energy problem.

In 2020, *Bankole A. et al*. published a research paper illustrating the superiority of grid-connected hybrid power systems over their off-grid counterparts. This study provided empirical evidence that, contingent on the geographical location, grid-connected hybrid systems offer superior performance and economic benefits compared to off-grid hybrid systems. The study underscores the significance of integrating renewable energy sources with the existing grid infrastructure to enhance the efficiency and cost-effectiveness of sustainable energy solutions.

In 2015, *Okedu et al. conducted* a comparative study of on-grid and off-grid Tied Integrated Diesel Solar PV Generation Systems. These studies collectively highlight the evolving understanding and advancements in hybrid energy systems, demonstrating their potential to offer more sustainable, efficient, and economically viable energy solutions. Their research unveiled significant advantages of employing the proposed hybrid system for powering small, isolated villages. Notably, it was found that such a system could effectively compete with conventional energy sources by lowering operational costs and minimising pollutant emissions. Additionally,

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outcomes derived from the HOMER software indicated that the on-grid system presented a more promising approach.

The earlier studies of different solar energy systems have consistently shown that the grid-tied and hybrid energy systems offer superior energy reliability and investment returns. This is primarily attributed to the diversification of energy sources that contribute to the system's overall energy output. In a related study conducted in 2020, *Bankole A. and colleagues* conducted a comparative analysis of off-grid versus grid-connected hybrid power systems. The findings revealed that, depending on the geographical location, the grid-connected hybrid power system exhibits superior technical and economic performance compared to its off-grid counterparts. Specifically, grid-connected (GC) systems demonstrated a decrease in net present value (NPC) and cost of energy (COE), along with an enhancement in power production capacity.

Building upon this knowledge, in 2018*, Usman et al. employed the hybrid optimisation* model for the electric renewable (HOMER) program to assess the feasibility of a grid-connected PV-DG hybrid system for a faculty building in New Delhi, India. The investigation explored three scenarios: PV-Grid hybrid, PV-DG hybrid, and grid-connected systems. The analysis concluded that a hybrid PV-Grid system is the most cost-effective strategy, achieving a COE of Rs 8.84/kWh.

In recent scholarly endeavours, *Oladigbolu et al. (2021)* embarked on a comprehensive study aimed at evaluating the techno-economic feasibility of deploying hybrid energy systems (HES) consisting of solar photovoltaic (PV), wind turbines, diesel generators (DG), and battery storage to energize a remote rural health clinic located in the northern region of Nigeria. The investigation leveraged the capabilities of the HOMER software tool to simulate various configurations, ultimately identifying that the combination of a 5.43 kW PV system, a 2 kW diesel generator, a 3.06 kW power converter, and a battery array comprising ten units emerged as the superior option. This configuration distinguished itself by demonstrating the lowest Net Present Cost (NPC) at $16,457 and the most competitive Levelized Cost of Energy (LCOE) at $0.259/kWh when juxtaposed against alternative setups such as PV/wind/battery, DG/battery, PV/battery, and DG-only systems. This optimal HES excelled economically and showed commendable environmental performance, evidenced by its carbon dioxide emissions totalling 1304 kg/year. This figure notably undercuts the emissions associated with DG/battery and DG-only systems by a margin of 80% to 82.5%, underscoring the HES's potential to marry cost-efficiency with environmental stewardship (Oladigbolu, et al., 2021).

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Furthering the discourse on sustainable rural electrification, in 2022, *Gbadamosi and Nwulu* delved into the strategic configuration of hybrid energy systems dedicated to electrifying community healthcare facilities in secluded areas of Nigeria. Their research illuminated the significant benefits of renewable energy sources in optimising electricity generation's production costs and emissions footprint. The study underscores the pivotal role of integrating diesel generators, wind turbines, solar photovoltaic arrays, and battery storage solutions in crafting a resilient, cost-effective, and environmentally conscious energy infrastructure for rural healthcare services.

2.5 Technological and Economic Aspects of Hybrid Systems

Advancements in technology, including smart meters (which control the flow of electricity from the grid to the battery and vice versa) and energy management systems (which optimise energy use from diverse sources), play a vital role in optimising hybrid systems. According to research by *Jacobson et al*. (2015), these technologies can significantly improve the efficiency of hybrid systems by actively managing the power flows among renewable sources, the grid, and storage systems.

On-grid hybrid systems integrate renewable energy with the conventional grid, allowing seamless transitions and enhancing energy stability. These systems enable grid-connected facilities to sell excess energy back to the grid, reducing operational costs and improving efficiency (Olatomiwa, et al., 2015). Hybrid off-grid systems effectively enhance energy security, especially in remote areas facing frequent grid disruptions (Adebanji, et al., 2021). Integrating renewable energy sources with battery storage provides reliable energy access independent of the central grid.

Incorporating various renewable energy technologies into existing hybrid systems has notably improved renewable energy's economic and technological aspects. In 2020, the study by Acakpovi et al. highlighted the financial advantages of wind/hydrogen/fuel-cell systems compared to traditional wind/battery storage systems. By employing HOMER software for simulating these integrated systems, researchers have shown that the Hybrid Renewable Energy System 1 (HRES 1) demonstrates superior financial viability, evidenced by its lower levelized cost of electricity (COE) and net present cost (NPC). This highlights the economic benefits of using hybrid technologies, which can offer long-term savings despite higher initial costs.

Moreover, the technological complexity of incorporating photovoltaic, wind energy, and hydrogen fuel cell technologies into one cohesive system highlights significant potential for enhancing energy generation capabilities. As explored by Khan and Iqbal (2005) and Sawle et al. (2016),

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such systems are particularly advantageous for isolated communities, providing autonomous power generation solutions. While the wind/battery storage system (HRES 2) showed a more significant energy storage capacity, it fell short in financial metrics, underscoring a critical trade-off between economic efficiency and environmental impact. Thus, hydrogen fuel cell technology advancement presents a promising direction toward economically viable and environmentally friendly energy storage solutions.

*Khan & Iqbal (*2005 and *Samaniego, et al. (*2008 demonstrated a highly reliable wind/hydrogen/fuel cell hybrid power system for continuous constant power delivery for one year by simulating various fuel cell operating schemes using TRNSYS 15 software, studied the design (Khan & Iqbal, 2005; Samaniego, et al., 2008). *El-Shatter et al. (2006* also considered the design of a wind/hydrogen/fuel cell hybrid power system. PV was added to the hybrid system, increasing design complexity to a higher level (El-Shater, et al., 2006).

2.6 Barriers to Renewable Energy Implementation

Since the start of the 21st Century, sustainable power (renewable energy) has been a massive area of examination for researchers (Kariuki, 2018). However, despite the practical and convincing technologies developed by scientists for renewable energy, the transition from non-renewable energy use has been slow and uncertain, particularly in developing nations (Kacare, et al., 2022; Kariuki, 2018). The further use of renewable energy must be facilitated by removing significant obstacles. The top concerns that need immediate attention are: To offer substantial energy to major enterprises or urban regions, many renewable energy technologies still need to be more affordable than traditional energy sources due to their higher capital costs. Technologies for renewable energy need a significant initial investment and maybe long-term assistance before they can be commercially adopted (Beck & Martinot, 2004; Adebanji, et al., 2021). There needs to be more shopper mindfulness on the advantages and opportunities of environmentally friendly power. The centralised development of conventional energy sources, specifically electricity generation, gas supplies, and, to some extent, the provision of liquid fuel, underpins the economic and social energy services system.

Monetary, legal, administrative, and hierarchical barriers should be overcome to conduct environmentally friendly power advances and foster industries. Critical energy infrastructure like the national electricity grid, some infrastructure for liquid fuels, and gas infrastructure do not have open, non-discriminatory access (Ashaye & Alharahsheh, 2019; Simon, et al., 2011). Apart from over-reliance on fossil fuels, most people can also attribute their reluctance to adopt renewable

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energy technologies to several other categories of barriers, including political and regulatory barriers, technical barriers, social-cultural barriers, financial and economic barriers, and market-related barriers (Ashaye & Alharahsheh, 2019; Kariuki, 2018). These barriers are in addition to the excessive reliance on fossil fuels, which are cheaper than most renewable energy technologies. Combining all these factors hampers the development and use of renewable energy sources. For example, most nations cannot adjust and foster sustainable power because of the tremendous initial capital costs expected to be set up (Ashaye & Alharahsheh, 2019; Winkler, 2005; Kariuki, 2018).

2.6.1 Summary of Barriers to Renewable Energy Implementation

1. **High Initial Costs:** Energy storage devices, such as batteries, battery banks, and solar panels, require improvements for better adoption due to their high initial costs. Though the long-term running costs are often lower than fossil fuels, the initial investment can be a substantial barrier for individuals, businesses, and government (Luthra, et al., 2015).
2. **Intermittency and Reliability:** Numerous renewable energy sources, like wind and solar power, must be revised more consistently. This implies that they are not constantly accessible and that the time of day and the weather affect how much they produce. The fluctuation can make providing a steady and dependable energy supply complex, particularly without efficient energy storage options (Yaqoot, et al., 2016).
3. **Infrastructure and Grid Integration:** To switch to renewable energy, energy grid systems and infrastructure must undergo substantial modifications. This entails expanding the Grid with additional transmission lines, modernising existing infrastructure, and incorporating distributed energy sources. This may be an intricate and expensive procedure that frequently calls for political backing and regulation modifications (Luthra, et al., 2015).
4. **Energy Storage Challenges:** When renewable energy sources are not producing energy, energy storage is essential for preserving a steady and uninterrupted energy supply. Developing efficient and affordable energy storage systems is a significant problem because existing technologies, such as batteries, may have limited capacity and are still extremely expensive (Gissey, et al., 2018).
5. **Policy and Regulatory Barriers:** Government policies and regulations can aid or hinder the adoption of renewable energy sources. Permitting procedures, inconsistent incentives, and subsidies are a few factors that can impede the development of renewable energy.

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Moving toward greener energy sources may also need to be improved by subsidies for fossil fuels and opposition from strong interest groups (Luthra, et al., 2015)

CHAPTER THREE: METHODOLOGY

3.1 Introduction

The success of any project hinges on the alignment of both its technical and financial parameters. For any venture powered by solar energy, key technical aspects include careful site selection, accurate estimation of solar irradiation and load profiles, and choosing the right solar PV modules along with a suitable monitoring system. Additionally, incorporating a battery bank, considering the lifespans of PV modules, optimizing the configuration, and establishing maintenance protocols, among other relevant factors, are crucial to the venture's effectiveness (Bhatia, 2018; Masrur, et al., 2020; Rahman, et al., 2012). This study focuses on the comparative analysis of a standalone PV/Battery hybrid and a Grid-Tied PV (without battery storage) energy system, taking the cases of the Masia Development Centre and Vuwani Science Centre energy systems, respectively. The grid-tied Vuwani PV system serves as the main power supply to power critical loads, an on-site power generator designed to provide power to specific loads in the building, not feeding any power to the grid to reduce the electricity bill (Masrur, et al., 2020; Ma, et al., 2019). This setup reduces reliance on the grid and enables the PV system owner to become a prosumer, a producer, and a consumer (Rahman, et al., 2012).

The financial viability of solar power systems connected to the grid largely depends on local factors, such as regulations like net metering and available incentives, as noted by Ma et al. 2019. The Levelised Cost of Energy (LCOE) and the Net Present Cost (NPC) are the leading financial indicators used to evaluate these systems (Oladigbolu, et al., 2021; Lambert, et al., 2006; Dash, et al., 2018). For the simulation and optimisation of hybrid PV systems, a robust and user-friendly tool, HOMER, is indispensable for analysing their technical and economic performance. HOMER's ability in techno-economic modelling has facilitated evaluating energy systems across diverse climatic conditions (Masrur, et al., 2020; Rahman, et al., 2012). The most economically viable hybrid renewable energy system (HRES) design is developed by determining optimal and

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near-optimal values, leveraging the components' technical and financial characteristics alongside site-specific meteorological data (Rahman, et al., 2012). This research uses HOMER software to conduct its investigation, thereby underscoring its methodological approach with process steps depicted in the flow chart shown in Figure 5.

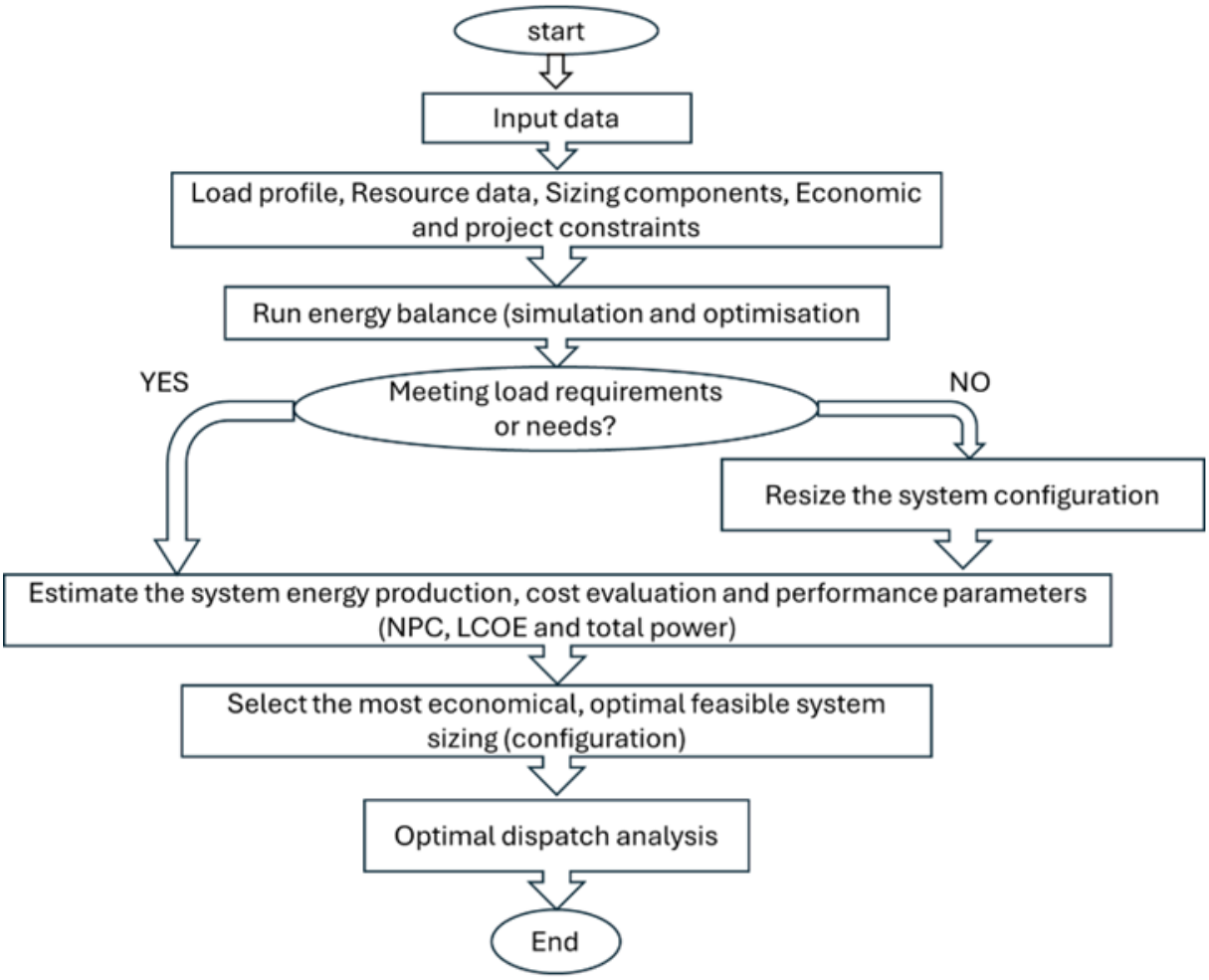


Figure 5: A flow chart of the steps followed for the simulations *(Alturki, 2022)*, *(Masrur, et al., 2020) (Rahman, et al., 2012)*.

3.2 Data Collection

Data was collected from the Vuwani Science Centre and the Masia Community Development Centre, focusing on their energy systems. The energy audit and data-gathering process spanned approximately 4.5 weeks and was designed to ensure accuracy, comprehensiveness, and site-specific customisation. Input load data for the simulation tools were obtained through precise on-site measurements, providing a robust basis for analysis. Additionally, meteorological data for

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2023 were sourced from NASA's Atmospheric Data Centre, incorporating location-specific satellite-derived information. Monthly solar irradiation data for the same period were acquired from the National Renewable Energy Laboratory (NREL), further enhancing the reliability of the simulations.

3.3 Configuration of the Photovoltaic Solar System

3.3.1 Masia Community Development Centre

The Masia Community Development Centre operates a photovoltaic (PV) system with a rated capacity of 19.8 kWp, consisting of 36 ARTsolar ART550-144MHA monocrystalline modules. The array is configured in two parallel strings of 18 modules each, yielding a voltage at maximum power (Vmp) of approximately 756 V (18 × 42.0 V) and an open-circuit voltage (Voc) of about 897 V (18 × 49.85 V). The combined current output at maximum power is approximately 26.2 A (2 × 13.09 A). The strings are integrated through a DC combiner box equipped with overcurrent and surge protection devices, after which the power is regulated by four maximum power point tracking (MPPT) charge controllers operating in parallel. These units condition the high-voltage DC into a 48 V DC bus for energy management.

Energy storage is provided by a 48 V, 40 kWh lithium-ion battery bank, comprising two 20 kWh modules connected in parallel, which ensures continuity of supply during periods of low solar irradiation and at night. The stored energy is converted to alternating current by three 8 kW inverters operating in parallel to supply a three-phase 400/230 V AC output. The system design incorporates high-voltage strings within the 1500 V operational limit, comprehensive DC-side protection, distributed MPPT regulation, and substantial battery storage, thereby ensuring stable and reliable electricity provision for the facility’s diverse loads.

The PV modules are roof-mounted at a tilt angle of 4° and oriented towards the northwest. Although this configuration is dictated by structural constraints, it results in reduced solar capture relative to the optimal north-facing orientation at the site’s latitude (≈22°–25°). Nevertheless, under normal operating conditions, the system sufficiently meets the energy demand of the facility. A 5-kW hydrogen fuel cell has also been installed on-site; however, it is not yet operational and is therefore excluded from the present system analysis. Figure 6 illustrates the system configuration, and Table 4(a) summarises the module specifications.

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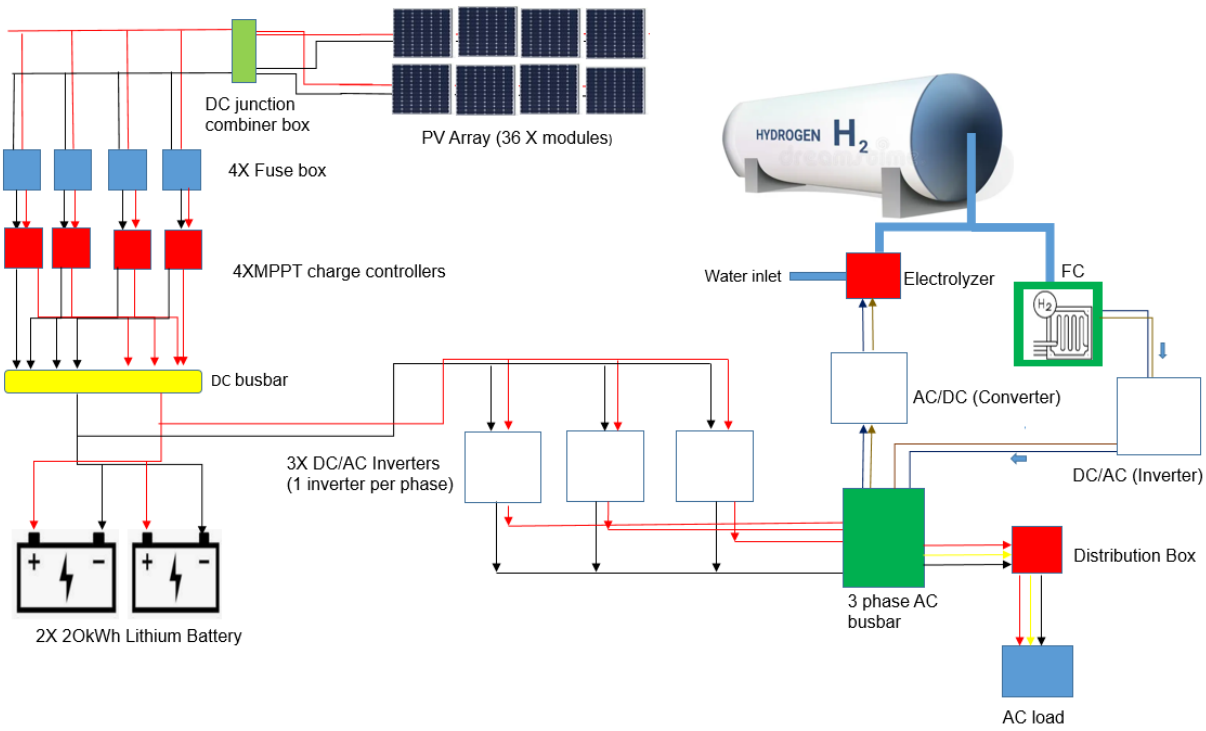


Figure 6: Masia Community Development Centre System Layout

3.3.2 Configuration of the Vuwani Science Centre Solar System

The solar photovoltaic (PV) system at the Vuwani Science Centre consists of 20 polycrystalline solar panels, each with a peak power output of 255 W. These panels are connected in parallel, resulting in a total system capacity of 5.1 kW peak. The system includes a single 5 kW inverter but does not incorporate battery storage.

The PV panels are mounted on aluminium steel structures on the ground roof and oriented northeast to optimise sunlight exposure throughout the day, ensuring minimal shading. The system is designed to supply power to preselected loads while the local electricity grid meets additional demand.

Figure 7 illustrates the PV system layout at the Vuwani Science Centre, with detailed module specifications in Table 4(b).

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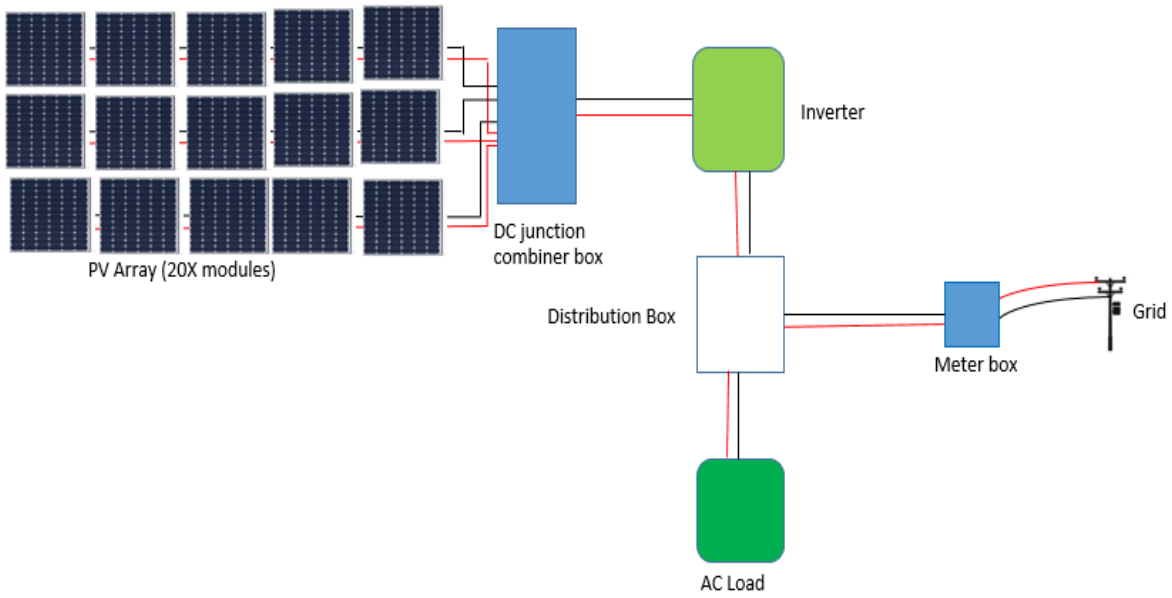


Figure 7: Vuwani Science Centre Current System Layout

Table 4:Module specification installed for (a) Masia Community Development centre and (b) Vuwani Science centre

Module manufacture	(a)	ARTsolar	(b)	EnerSoLI
Model		ART550-144MHA		ES-250
Open Circuit Voltage		49.85 V		37.5 V
Max power voltage		42.00 V		30.4 V
Maximum System(DC) Voltage		1500 V		1000 V
Short Circuit Current		13.97 A		8.86 A
Maximum power Current		13.09 A		8.39 A
Peak Power(Pmax)		550 W		255 W

3.4 Description of Study Area

This study examines two key locations: the Masia Community Development Centre and the Vuwani Science Centre, both situated in the Collins Chabane Local Municipality of Limpopo Province, South Africa. The Masia Community Development Centre is located at 23°11'03.5"S, 30°18'37.6"E, while the Vuwani Science Centre is located at 23°8.1'S, 30°25.3'E. These facilities are vital community hubs that provide essential services and educational opportunities. The Masia

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Community Development Centre serves as a centre for various community activities and supports local engagement and empowerment initiatives. The Vuwani Science Centre, on the other hand, plays a pivotal role in promoting scientific literacy and fostering interest in technology, particularly among educators and learners.

As these facilities seek to enhance service delivery and long-term sustainability, analysing and simulating their energy systems is crucial. This study explores energy optimisation strategies that ensure both centres' efficient, reliable, and cost-effective power supply.

3.5 System Architecture

The hybrid energy system, comprising photovoltaic (PV) panels, a battery bank, and an inverter, was modelled using the HOMER software under grid-connected and off-grid scenarios. The solar, converter, battery, and grid components were selected within the Homer platform to determine the optimal system configuration. HOMER was employed to simulate various energy system configurations, identifying the most cost-effective solution based on the net present cost (NPC) and levelised cost of energy (LCOE). The national grid and PV modules function as primary energy generators, which are crucial in optimising the hybrid power system for reliability and efficiency.

3.6 Load Assessment

Assessing energy demand is a fundamental aspect of comparing and optimising energy systems. This study adopted a three-pronged methodological approach, consisting of:

1. On-site inspections to evaluate existing infrastructure,
2. Questionnaire administration to gather user input on energy consumption patterns, and
3. Energy flow analysis to identify facility conservation opportunities (Barzola-Monteses & Espinoza-Andaluz, 2019).

Comprehensive data on appliance usage, including power ratings and operational durations, were systematically collected and integrated into HOMER software. The software facilitated simulations to generate daily, seasonal, and annual load profiles, providing a detailed understanding of energy consumption trends. This analysis was instrumental in determining the required load capacity for the optimal hybrid system, whether grid-tied or stand-alone.

The total energy consumption (E_T) of the facility's appliances is calculated as follows:

$$E_T = \sum_{i=1}^{m} n \times p_i \times T_i = \sum_{i}^{m} E_i = E_1 + E_2 + \cdots + E_m \qquad \text{(Equation 3.1)}$$

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Where:

E_T = total energy consumed by the facility,

n = number of loads (appliances) in usage,

p_i = power rating of the load i and

T_i = duration of usage for load and

E_i = total energy consumed by the appliance i

This equation stands for the total energy consumption across all appliances, forming the foundation for designing an optimal hybrid system architecture that effectively addresses the facility's energy needs.

3.7 HOMER Modeling

A crucial tool for power system design, the HOMER computer model makes it easier to compare different power-generating methods (Lambert, et al., 2006). It evaluates a power system's life-cycle cost, including all costs associated with its development, operation, and maintenance throughout time while simulating its physical behaviour. According to Lambert et al. (2006), the HOMER optimisation model makes it possible to assess several design options according to their technical and financial feasibility. It also contributes substantially to comprehending and measuring the impacts of uncertainties and changes in input parameters.

3.7.1 PV generator model

A photovoltaic (PV) generator converts solar energy into electrical energy, which can be consumed locally or injected into the grid after serving onsite loads (Zhao, et al., 2020). The PV generator consists of two primary subsystems: the PV cells within the PV Module, which convert solar radiation into electrical energy, and the power-electronics-based energy conversion system, which involves exploring how energy is conditioned and optimized for various applications.

The power generated by the solar PV panels is expressed as follows (Adebanji, et al., 2021; Okedu, et al., 2015):

$$P_{PV} = P_{R-PV}\left[\frac{G}{G_{ref}}\right]\left[1 + K_T\left(T_c - T_{ref}\right)\right] \quad \text{(Equation 3.2)}$$

Where:

P_{PV} = power generated by PV panels.

P_{R-PV} = rated power at reference condition.

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G = solar radiation in $^{W}/_{m^2}$,

G_{ref} = solar radiation at a reference condition and is given by $G_{ref} = 1000\,^{W}/_{m^2}$,

T_{ref} = total cell temperature at reference conditions ($T_{ref} = 25℃$),

K_T = temperature coefficient of the PV panels,

T_c = cell temperature given by ($T_c = T_{amb} + (0.02256 \times G)$), with T_{amb} the ambient Temperature in ℃,

The PV-rated power, can be determined using eq (3.2), (Okedu, et al., 2015):

$$P_{R-PV} = {(E_L \times SF)}/{(\eta_R \times \eta_V \times PSH)} \quad \text{(Equation 3.3)}$$

Where

E_L = daily load energy,

SF = stacking factor accounting for resistive and PV temperature losses,

η_R and η_V = efficiencies of solar charging regulators and bidirectional inverters, respectively.

PSH = peak sunshine hours.

3.7.2 Battery model

The battery model is integral to the design of battery-powered systems (Dash, et al., 2018; Koutroulis, et al., 2006). It facilitates the prediction and optimisation of critical battery parameters such as lifetime, charging/discharging rate, and state of charge. (Tomasov, et al., 2019).

The storage capacity for the lithium-ion battery is estimated in HOMER using the Equation. 3.3 (Asamoah, et al., 2022; Okedu, et al., 2015):

$$C_{Wh} = {(E_L \times AD)}/{(\eta V \times \eta B \times DOD)} \quad \text{(Equation 3.4)}$$

Where: DOD is the allowable depth of discharge of the battery, AD is the number of autonomy days, and ηB is battery efficiency

The battery capacity, C(t), at a point in time *t*, is calculated by HOMER with the equation (Koutroulis, et al., 2006):

$$C(t) = C(t-1) - \eta_{batt}\left(\frac{P_B(t)}{V_{Bus}}\right)\Delta t \quad \text{(Equation 3.5)}$$

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Where: $C(t-1)$ Battery capacity at the previous increment

: $P_B(t)$ Battery input /output power given by

$$P_B(t) = E_g(t) - E_i(t)$$

HOMER estimates the lifetime of the battery with the equation (Lambert, et al., 2006; Asamoah, et al., 2022; Okedu, et al., 2015):

$$R_{batt} = Min\left(\frac{N_{batt} \times Q_{liftime}}{Q_{thrpt}}\right) \times R_{batt.f} \quad \text{(Equation 3.6)}$$

Where:

R_{batt} = the storage bank life (yr);

N_{batt} = the number of batteries in the storage bank,

$Q_{liftime}$ = the lifetime throughput of single storage (kWh);

Q_{thrpt} = the annual storage throughput (kWh/year);

$R_{batt.f}$ = the storage float life (year).

According to the central assumption that lifetime throughput is independent of cycle depth, HOMER may calculate the battery bank's remaining life by observing the quantity of energy passing through it without considering the depth of the numerous charge-discharge cycles (Tomasov, et al., 2019).

3.7.3 Financial metrics

HOMER requires the annual interest rate as a key input for assessing the economic viability of a hybrid system (Acakpovi, et al., 2020). The interest rate is calculated using:

$$i = \frac{i_0 - f}{1+f} \quad \text{(Equation 3.7)}$$

Where:

i = real interest rate

i_0 = nominal interest rate

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f = annual inflation rate

For this study, a nominal interest rate of 8% and an inflation rate of 5.9% were considered (CPI, 2023; SARB, 2024).

The Net Present Cost (NPC) and the Levelised cost of Electricity (LCOE) are the primary financial metrics indicators used (Lambert, et al., 2006; Dash, et al., 2018). NPC is the present value of all costs over the system's lifetime minus the present value of all income. HOMER calculates NPC using:

$$NPC = \frac{C_{ann.tot}}{CRF(i,N)} \quad \text{(Equation 3.8)}$$

Where:

$C_{ann.tot}$ = total annualised cost.

$CRF(i,N)$= capital recovery factor

The capital recovery factor $CRF(i,N)$ is determined by (Lambert, et al., 2006; Dash, et al., 2018; Asamoah, et al., 2022) :

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N-1} \quad \text{(Equation 3.9)}$$

Where

i = real interest rate, and

N = period/number of years.

LCOE, a key metric for comparing electricity generation costs, is calculated as:

$$LCOE = \frac{C_{ann.tot}}{E_{prim}+E_{def}+E_{grid.sales}} \quad \text{(Equation 3.10)}$$

Where:

$C_{ann.tot}$ = total annualised cost,

E_{prim} = total amount of primary load that the system serves per year,

E_{def} = total amount of deferrable load that the system serves per year,

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$E_{grid.sales}$ = amount of energy sold to the Grid per year.

The system's average cost per kilowatt hour of usable electrical energy generated is known as the Levelised cost of energy (Alturki, 2022). The Levelised energy cost is frequently a handy metric for comparing the costs of various systems, but HOMER ultimately uses the total NPC as its primary economic measure of merit. Instead of using a Levelised cost of energy in its optimisation approach, HOMER ranks the system configurations based on NPC (Lambert, et al., 2006; Dash, et al., 2018). The total NPC is preferred as the primary economic measure of merit since it excludes any definitional ambiguity.

3.8 Software

The comparative analysis of various solar energy systems for grid-connected facilities was performed using HOMER (Hybrid Optimisation of Multiple Electric Renewables) software. This software facilitates the re-design, resizing and technical and financial evaluation of grid-tied and standalone PV/hybrid energy systems, considering various energy resource availability scenarios and technology options.

3.9 Research approach

Solar resource data from the two study areas were collected, analysed, and converted to monthly and annual datasets. HOMER software was utilised in sizing the hybrid components (PV, battery, and inverter) and model system configurations with and without grid connectivity (Hansen, et al., 2000). The simulations determined the optimal configuration with the lowest LCOE and NPC (Adebanji, et al., 2021; Zhao, et al., 2020). The best-performing off-grid system was compared with its grid-connected counterpart based on power output, economic parameters, and greenhouse gas emissions (Zhao, et al., 2020).

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CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents a comparative analysis of the simulation outcomes obtained using HOMER software, focusing on the grid-tied hybrid microgrid system architecture. The input load data was derived from measurements conducted in the study area to ensure accuracy and reliability. Additionally, meteorological data was sourced from NASA's Atmospheric Data Centre, utilising location-specific satellite-derived information. Monthly solar irradiation data was obtained from the National Renewable Energy Laboratory (NREL). Essential parameters such as utility energy tariffs and the selling back price (SBP) for the grid-tied setup were integrated into the input dataset to ensure a comprehensive evaluation.

4.1 Results presentation

This section outlines the simulation results for various power system configurations utilising Homer software. The optimal configuration was identified based on key performance indicators, such as the Levelised Cost of Energy (LCOE) and Net Present Value (NPV). Additional considerations included independence from centralised power systems and the system's resilience, reliability, and enhanced autonomy.

4.1.1 Simulated Hybrid System Architecture for Study Sites.

A hybrid energy system comprising photovoltaic (PV), grid, battery, and converter components was simulated for both study sites: The Masia Community Development Centre and the Vuwani Science Centre. Both facilities have access to the local grid. Currently, the Masia facility is powered by a PV system; however, its grid connection is yet to become operational.

Figures 8 and 9 display the simulated architectural designs for the Masia Community Development Centre's hybrid systems, along with the current connected load and total facility load. The daily average energy demand at the Masia Community Development Centre is 50.11 kWh, with a peak power requirement of 9.79 kW. In contrast, the total facility load has an average energy demand of 426.60 kWh daily and a peak power of 64.78 kW. Additionally, Figure 10 shows the energy demand at the Vuwani Science Centre, which has a daily average energy demand of 197.13 kWh and a peak power of 61.44 kW.

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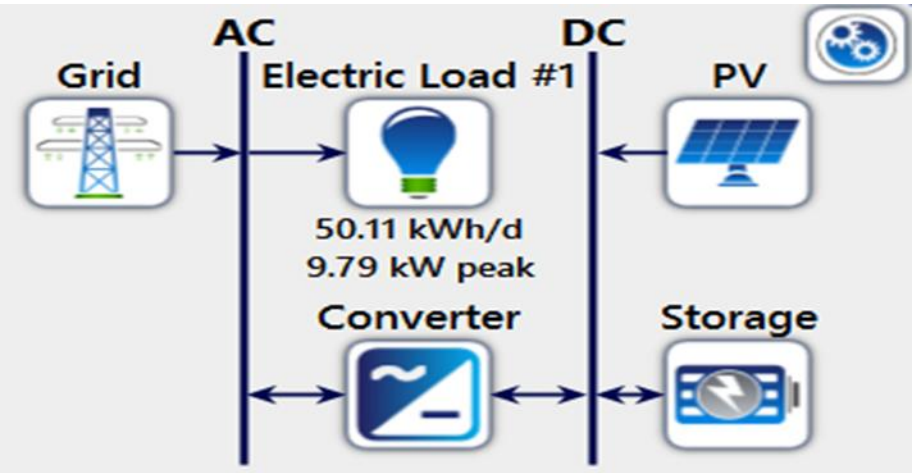


Figure 8: Hybrid system architecture for Masia community development centre, total Facility Load

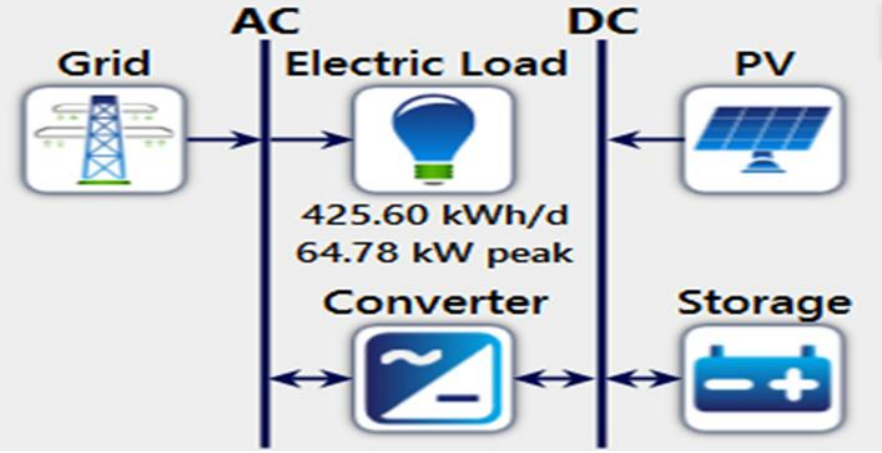


Figure 9: Hybrid system architecture for Masia community development centre energy system

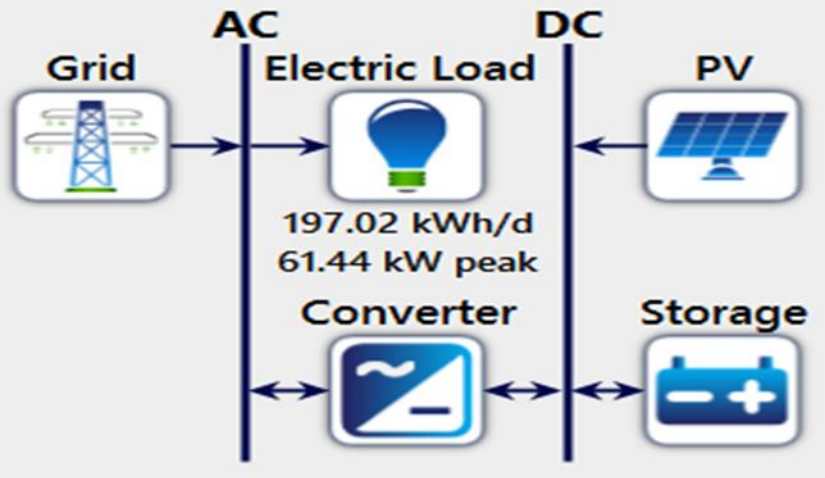


Figure 10:Hybrid system architecture for Vuwani science centre energy system

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4.1.2 Renewable Resource Assessment

4.1.2.1 Solar resources

The Masia Community Development Centre receives an average solar irradiation of 5.85 kWh/m^2/day. Figure 11 below presents the monthly solar irradiance and clearness index from the National Renewable Energy Laboratory (NREL). Providing valuable insights into the site's solar energy potential throughout 2023. The daily solar irradiation, depicted by the blue bars, ranges from 3.93 to 6.5 kWh/m²/day, with the highest values observed in January, November, and December. This indicates a robust solar potential during the summer months. The lowest irradiation is recorded in June at 3.93 kWh/m²/day, aligning with the winter season and shorter daylight hours. The clearness index, represented by the orange line, ranges from 0.501 to 0.650. The highest values occur in July at 0.650, while the lowest are found in February at 0.501 and December at 0.518.

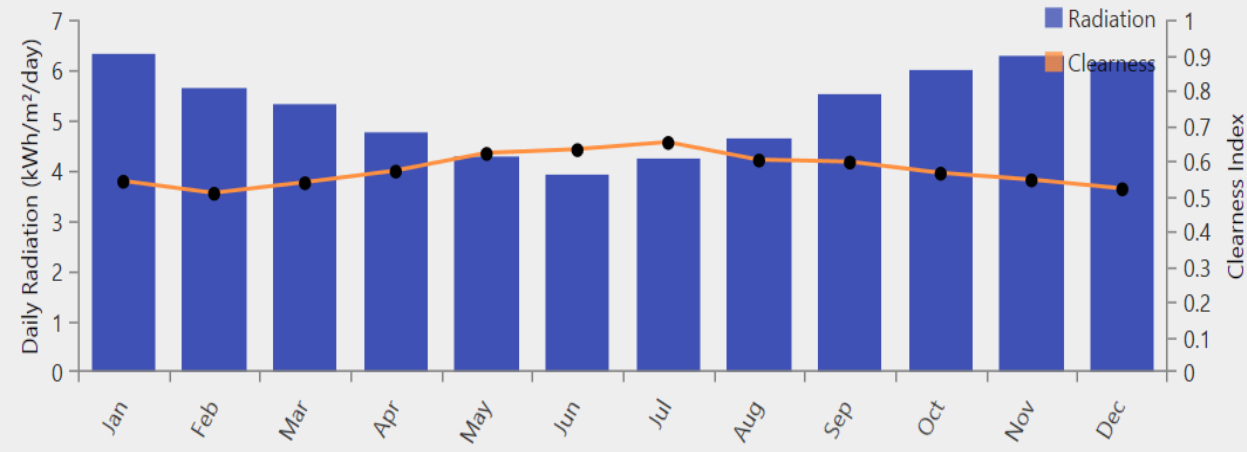


Figure 11: Solar irradiation and clearness of the Masia community development centre.

Figure 12 displays the solar irradiation and clearness index for the Vuwani Science Centre in 2023, from the National Renewable Energy Laboratory (NREL). The highest recorded irradiation was 6.34 kWh/m²/day in January, with a clearness index 0.540. Daily solar irradiation varied between 3.93 kWh/m²/day and 6.34 kWh/m²/day. Even during the lower months of May, June, and July, irradiation remained above 3.50 kWh/m²/day, indicating a strong solar profile throughout the year. The clearness index fluctuated between 0.506 and 0.649, with July exhibiting the highest values corresponding to increased solar irradiation. Minor dips in irradiation were noted in March and September, likely due to occasional cloud cover. The consistent solar radiation and clear atmospheric conditions make the Vuwani Science Centre an excellent candidate for solar photovoltaic (PV) systems, ensuring reliable energy generation throughout the year.

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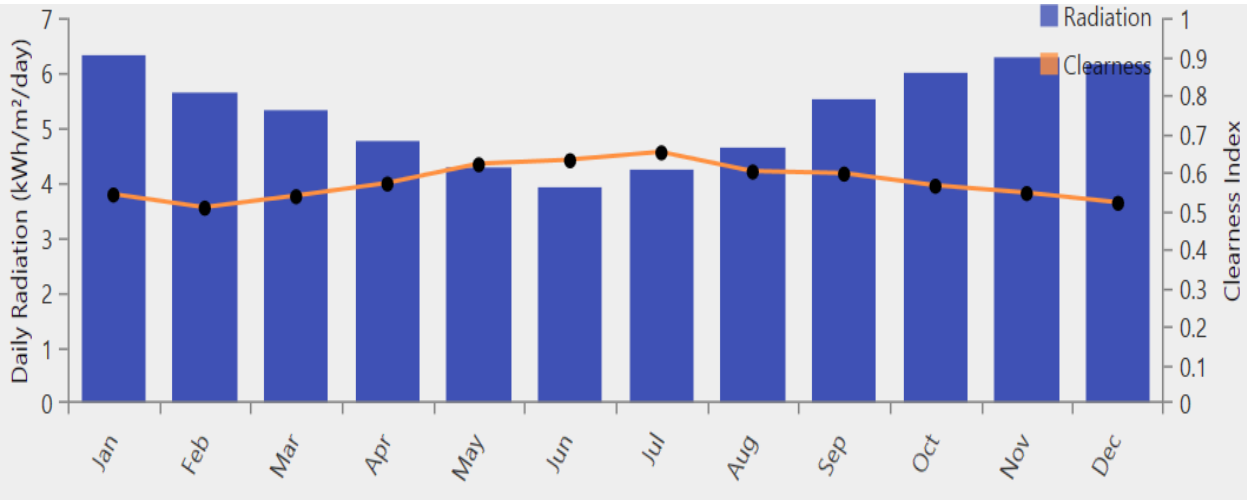


Figure 12: Solar irradiation and clearness of Vuwani Science Centre.

4.1.2.2 Temperature Analysis

Figure 13 shows that the temperature fluctuated throughout the year, with the lowest daily average of 15.58°C noted in July and the highest reaching 25.54°C in January at the Masia Community Development Centre. Figure 14 details the average daily temperatures (°C) across the year, revealing a clear seasonal pattern. The warmest temperatures, peaking between 24°C and 25°C, occur in January, February, November, and December. In contrast, the coolest temperatures, around 16°C, are observed in June and July. This pattern reflects the Southern Hemisphere's winter season, characteristic of regions like South Africa, with December being the warmest month and July the coldest. The climate cycle consists of summer from November to February and winter from June to July, emphasising the importance of temperature variations in evaluating the performance of microgrid systems.

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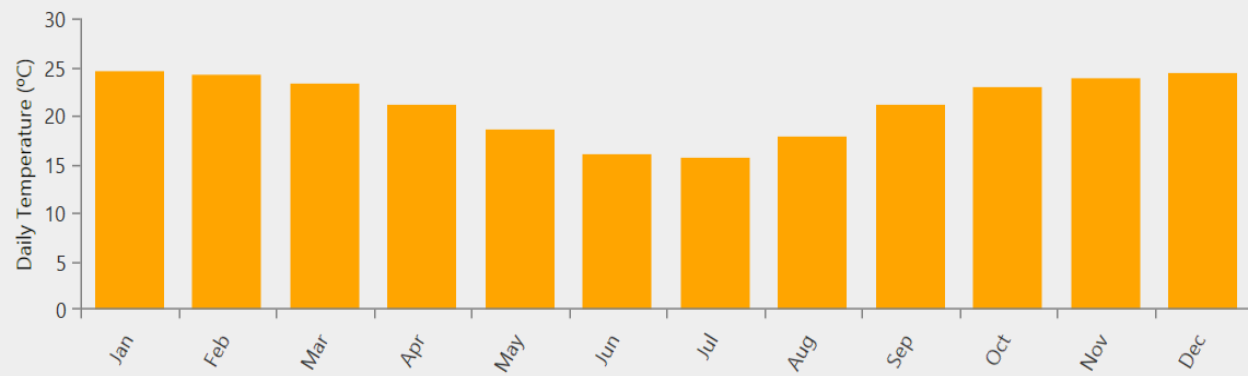


Figure 13: Monthly Temperature for Masia Community Development Centre

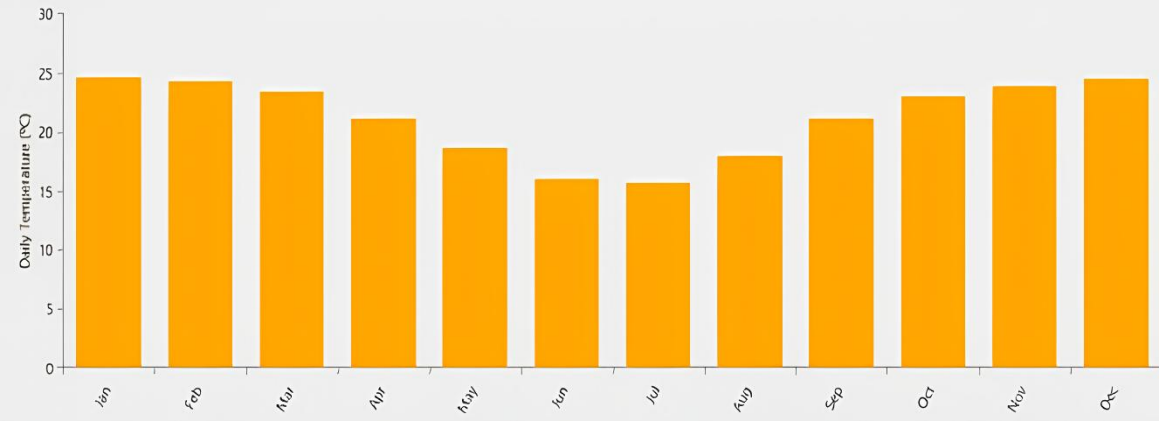


Figure 14 Monthly Temperature for Vuwani Science Centre

4.1.3 Energy consumption assessment

Energy audits were conducted at both facilities to assess energy consumption patterns, optimise energy usage, and improve sustainability. The results provide stakeholders with the information to make informed decisions about energy efficiency improvements and investments. Table 5 lists the primary appliances connected to the photovoltaic (PV) systems at the Masia Community Development Centre, including their power ratings and operational hours. Table 6 presents the total load requirement at the Masia Community Development Centre, while Table 7 provides an overview of the Vuwani Science Centre's electrical load.

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Table 5: Facility electrical load Masia (Connected load)

Electrical Load	Quantity n	Power rating P (kW)	Usage T(hours)	Energy $E = nPT$ (kWh)
Compact Fluorescent Light	31	0.018	8	4.464
Spotlight 1(motion sensor)	4	0.004	12	0.196
Spotlight 2(motion sensor)	1	0.002	12	0.024
Borehole Pump	1	2.2	8	17,6
Pressure pump 1	1	1.1	8	8.8
Pressure pump 2	1	0.75	8	6
Computer Laptop	5	0.065	6	1.95
Cell phone Charger	7	0.005	4	0.14
Kettle	1	2	0.5	1
HP Printer	1	0.021	3	0.063
Total				40.237

Table 6: Total Facility electrical load for Masia Community Development Centre

Electrical Load	Quantity n	Power rating P (kW)	Usage T(hours)	Energy $E = nPT$ (kWh)
Compact Fluorescent Light	258	0.018	8	37.152
Spotlight 1(motion sensor)	4	0.004	12	0.196
Spotlight 2(motion sensor)	1	0.002	12	0.024
Borehole Pump	1	2.2	8	17,6
Pressure pump 1	1	1.1	8	8.8
Pressure pump 2	1	0.75	8	6
Computer Laptop	5	0.065	6	1.95
Cell phone Charger	7	0.005	4	0.14
Kettle	1	2	0.5	1
HP Printer	1	0.021	3	0.063
Light bulb (indoor)	92	0.009	8	6.624

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Light bulb (outdoor)	72	0.009	12	7.776
Wall lamp	22	0.060	12	15.840
Spotlight 1	68	0.070	12	57.120
Spotlight 2	6	0.060	12	4.32
Air conditioner	25	1.165	6	174.75
Hand dryer	11	2.60	2	57.2
Bibliotheca	1	0.375	24	9.000
Total				405.555

Table 7: Facility electrical load for Vuwani Science centre

Electrical Load	Quantity n	Power rating P (kW)	Usage T(hours)	Energy $E = nPT$ (kWh)
Compact Fluorescent Light (indoor) magnetic	104	0.058	8	48.256
Compact Fluorescent Light (outdoor) magnetic	13	0.058	12	9.048
Spotlight	1	0.15	12	1.8
Light bulb	11	0,005	12	0.66
Desktop	21	0.45	6	56.70
Screen monitor	21	0.345	6	43.47
Refrigerator	1	0.1896	24	4.5504
Kettle	2	2.2	0.2	0.88
Platinum printer	1	0.550	4	2.2
Pixma printer	1	0.340	4	1.36
Lap top	5	0.26	8	10.4
HP printer	1	0.06	4	0.24
HP scanner	1	0.60	4	0.24
Cell phone	6	0.04	3.	0.912
Microwave	1	1.550	0.6	0.93
Photocopier	1	1.344	4	5.376
Total				197.0224

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4.1.4 Daily and seasonal load profiles

This subsection presents the daily and seasonal load profiles for Masia Development, the Community Development Centre, and the Vuwani Science Centre. The observed daily load profile reveals a distinct and consistent pattern of energy consumption concentrated between mid-morning and late afternoon, indicating that these facilities operate primarily during daytime hours. Energy demand remains steady throughout the day but drops sharply to near zero during the evening and overnight, highlighting minimal or no activity outside operational hours.

The seasonal load profile further reinforces the predictability of energy usage across the year. Monthly energy consumption remains stable with only minor fluctuations in daily demand, suggesting that seasonal changes do not significantly influence usage. Peak demand levels are sustained throughout the year, while off-peak demand frequently drops to near zero, reflecting periods of inactivity. This consistent and non-seasonal load pattern underscores the need for energy systems optimised for daytime operation, with a strong potential for integration with solar energy solutions and minimal reliance on energy storage during non-operational periods.

Figures 15 and 16 below illustrate the daily and seasonal energy demand for the Masia Community Development Centre. The centre has an average daily energy consumption of 50.11 kWh, demonstrating its significant energy requirements for various activities and services. It reaches a peak load of 9.79 kW during periods of high demand, resulting in a load factor of 0.21.

The seasonal profile, represented in a box-and-whisker plot, shows a stable average load ranging from 2 kW to 3 kW throughout the year, indicating consistent energy use. Although the interquartile range indicates minimal variation, a slight increase in variability is observed from June to September. Peak demand consistently remains between 8 and 11 kW year-round, reflecting high maximum usage with slight seasonal fluctuation. In contrast, the minimum demand approaches 0 kW during off-peak periods.

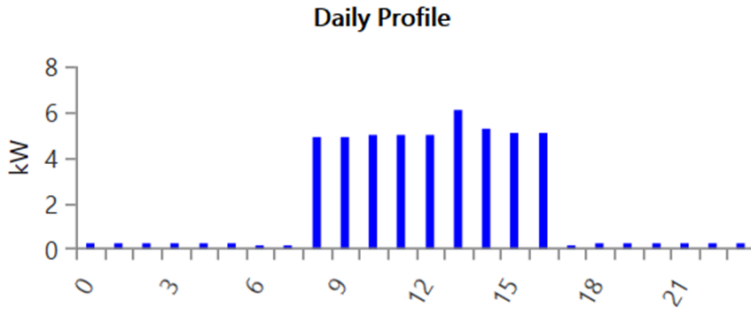


Figure 15: Daily load profile for Masia Community Development Centre's current facility load

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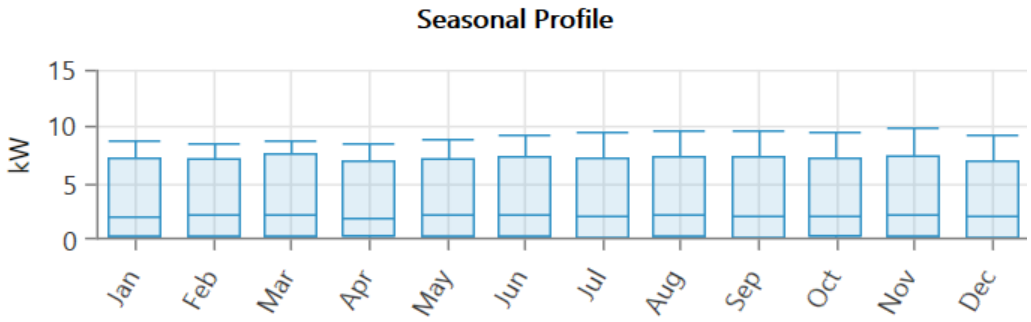
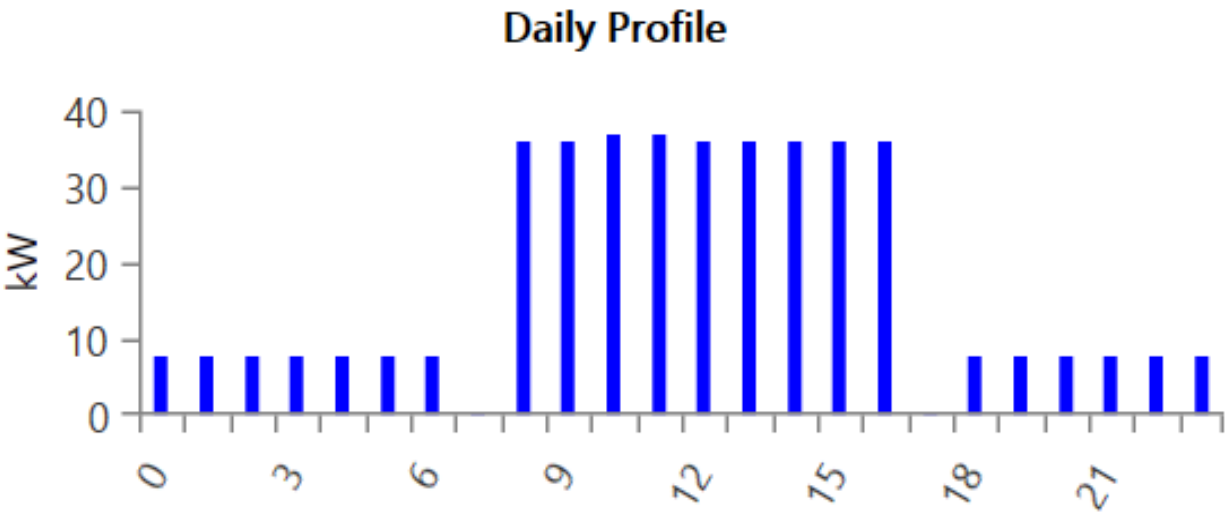


Figure 16: Seasonal load profile for Masia Community Development Centre's current facility load

Figures 17 and 18 illustrate the energy demand patterns, both daily and seasonal, of the Masia Community Development Centre, shedding light on the facility's comprehensive load requirements. The centre experiences an average daily energy consumption of approximately 405.56 kWh, peaking at a demand of 97.31 kW, resulting in a load factor of 0.17. This suggests a significant disparity between average and peak usage. The seasonal analysis, represented by a box and whisker plot, reveals a remarkably stable average load of 17kW to 18 kW throughout the months, indicating consistent operational energy needs year-round. Although the interquartile range is narrow, pointing to minimal daily fluctuations, a slight increase in variability is observed during the winter months. Remarkably, peak loads remain high and stable, oscillating between 60 and 64 kW regardless of seasonal changes, underscoring the facility's continuous need for substantial capacity. The minimum demand often plummets to 0 kW during inactivity, starkly illustrating the contrast between operational and idle times in the facility's daily energy profile and the need for effective energy management strategies during off-peak hours.



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Figure 17: Daily load profile for Masia Community Development Centre energy system total facility load

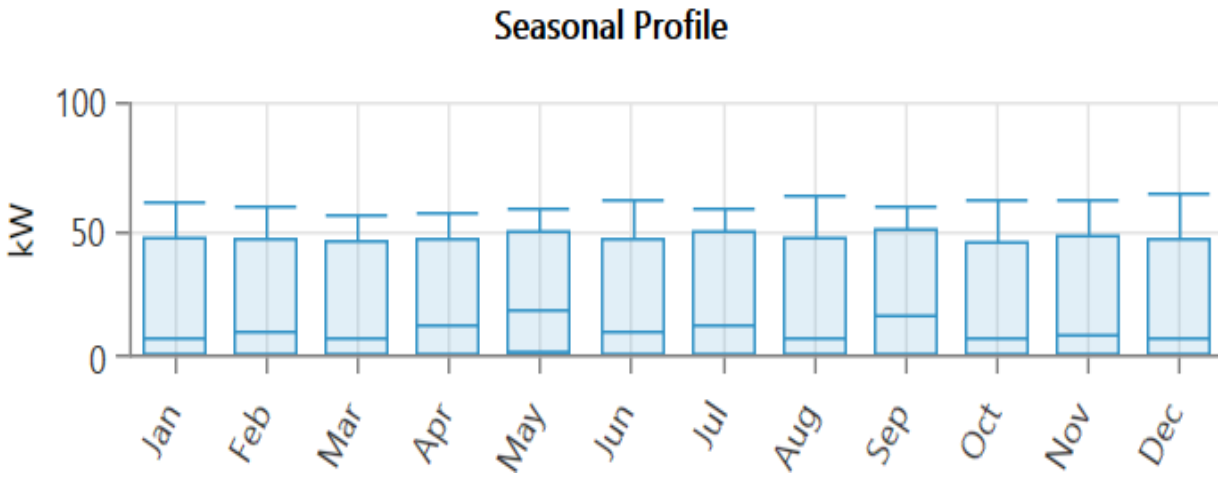


Figure 18: Seasonal load profile for Masia Community Development Centre energy system total facility load

Figures 19 and 20 illustrate the daily and seasonal energy demand profiles for the Vuwani Science Centre, revealing key load characteristics. The centre's average daily energy demand is 197.02 kWh, with a peak load of 61.44 kW and a load factor of 0.25, indicating moderate variability between average and peak usage. Seasonal demand, shown in a box-and-whisker plot, maintains a stable average load between 8 kW and 10 kW year-round, signifying consistent operational energy requirements. Peak loads remain high across all seasons, fluctuating between 44 and 46 kW, highlighting the need for reliable, high-capacity power. Conversely, minimum demand frequently drops to zero during non-operational periods, underscoring the disparity between active and idle hours and emphasising the necessity for efficient energy management solutions to optimise performance during low-demand times.

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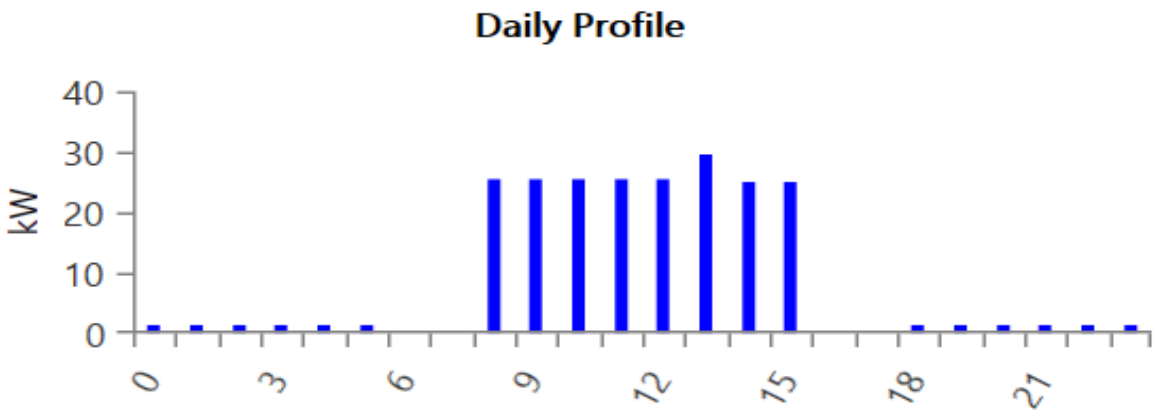


Figure 19: Daily load profile for Vuwani Science Centre energy system

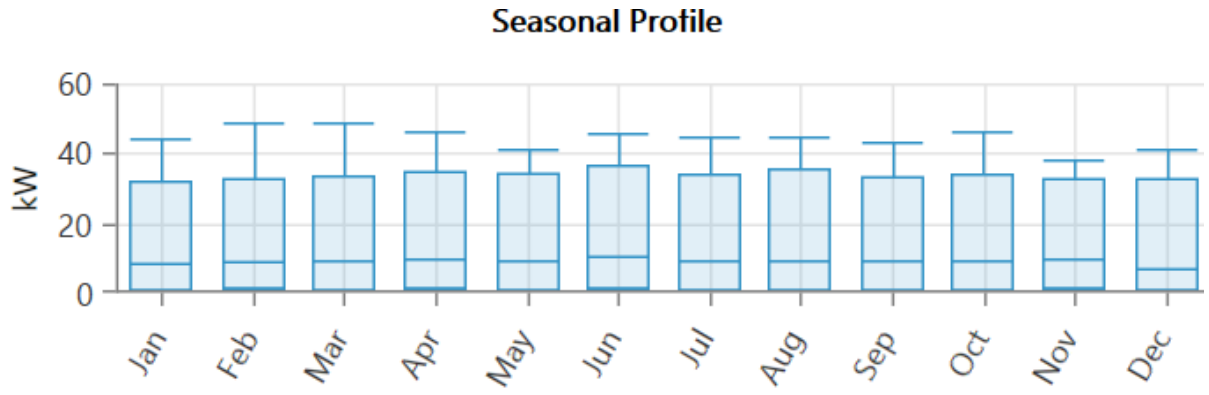


Figure 20: Seasonal load profile for Vuwani Science Centre energy system

4.2 Results Discussion

4.2.1 Optimisation results and optimal sizing of the simulated hybrid power system

HOMER software optimised the hybrid power system, incorporating essential factors such as load profiles, solar radiation data, component costs, and operational limitations. HOMER analysed different system configurations, concentrating on both technical performance and financial aspects. Its specialised functionality allowed it to balance costs and reliability, ensuring a dependable energy supply while reducing the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). The optimal configurations were chosen based on their ability to meet energy demand, even without grid power. They incorporated a cost-effective and technically feasible setup considering capital expenses, renewable energy share, and battery autonomy.

The subsequent sections will present further analysis and discussions regarding the optimisation results. These sections will detail the proposed hybrid systems' component sizing and cost

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implications and comprehensively compare the optimised system with other potential configurations.

4.2.1.1 Optimisation results and optimal sizing for Masia community development centre for the current connected load

The analysis explores various hybrid power system configurations designed to meet the energy needs of the Masia Community Development Centre. These systems supply electricity with photovoltaic (PV) panels, battery storage, grid connections, and inverters. Each scenario differs regarding net present cost (NPC), Levelised cost of electricity (LCOE), and operational expenses, aiming to achieve an optimal balance between initial investment and long-term sustainability. The primary objective is to ensure energy security, particularly during load-shedding events. The optimal outcomes and dimensions for the Masia Community Development Centre are delineated in Table 8, presented below.

Configuration 1, which consists of PV, grid, and inverter components without battery storage, stands out as the most cost-effective option, featuring the lowest NPC and LCOE. The negative operational cost suggests potential revenue from selling surplus energy back to the grid. This means the system's operational costs are lower than its revenues. This situation arises due to the low demand compared to capacity, allowing the savings and potential profits from selling excess energy to surpass operational expenses. However, the lack of battery storage restricts its functionality during outages. In contrast, configuration 5 includes an 8 kWh battery, which raises both NPC and LCOE slightly while enhancing reliability during grid disruptions. Although it remains economically viable, the additional cost associated with the battery makes it a less appealing option compared to configurations 1 to 4. Configuration 5, which has the lowest battery storage, does not provide adequate support for the facility during power outages. Configurations 6,7, and 8 utilise larger battery capacities of 40 kWh, resulting in even greater energy resilience. However, these cases also come with higher Net Present Costs (NPCs) and Levelized Costs of Energy (LCOEs), highlighting the trade-off between increased reliability and cost.

Configurations 7 and 8, with extensive battery storage of capacity 40, entail significant costs, leading to NPCs and LCOEs that are less economically feasible for most applications. While these high-capacity batteries ensure continuous power during prolonged outages, their substantial initial and operational costs affect profitability. The most economical choice recommended is configuration 1 for efficient installations in a grid-connected facility with no power interruptions,

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while configuration 5 balances cost and resilience. Configurations 1 to 4 cater to those facilities which does not require more excellent energy. Configurations 9 to 12 have battery capacities of 160 to 240 kWh, providing some energy autonomy but limited resilience for on-grid use. Their large battery banks may prevent energy shortages during prolonged cloudy periods or high demand. Configuration 12 with grid connection prioritises energy security over cost, making it ideal for on-grid environments where uninterrupted power is crucial. With a larger battery storage capacity of 240 kWh, this scenario can maintain power during prolonged periods without solar generation despite higher Net Present Costs (NPC) and Levelised Cost of Energy (LCOE). This ensures continuous operation without grid dependence.

The optimal rated capacity for the solar PV array is 30 kW, providing PV penetration of 253% with operating hours of 4,388 hours per year and a levelised cost of R0.576 per kWh. The power converter has a capacity of 30 kW, with 4,388 hours of operation per year, energy input of 46,035 kWh/year, energy output of 45,069 kWh/year, and losses of 967 kWh/year. The grid capacity is 999,999 kW, with energy purchased from the grid amounting to 2,914 kWh/year and energy sold back to the grid at 14,520 kWh/year.

Table 8: Optimised Component Sizes of the Proposed Hybrid Power System for Masia's current connected load.

System configuration	Architecture	PV (kW)	Batt (kWh)	Grid (kW)	Conv (kW)	NPC (R)	LCOE (R)	OC (R)	Energy purchased (kWh)	Energy sold (kWh)
1	PV/Grid/Conv	19.8	0	999 999	20	R1 852 811.00	R1.63	R20 878.56	2 914	14 520
2	PV/Grid/Conv	30	0	999 999	30	R1 884 740.00	R1.14	R15 532.47	2 075	29 082
3	PV/Grid/Conv	19.8	0	999 999	24	R2 017 667.00	R1.77	R24 701.85	2 914	14 520
4	PV/Grid/Conv	30	0	999 999	40	R2 296 880.00	R1.40	R25 090.71	2 075	29 082
5	PV/Batt/Grid/Conv	19.8	8	999 999	24	R2 305 389.00	R2.15	R30 541.41	1 138	12 550
6	PV/Batt/Grid/Conv	40	24	999 999	24	R2 477 703.00	R1.24	R22 771.90	51.	39 431
7	PV/Batt/Grid/Conv	30	40	999 999	24	R3 477 683.00	R1.22	R50 553.32	45.8	26 819
8	PV/Batt/Conv	19.8	40	999 999	20	R3 659 803.00	R3.52	R60 677.90	328	11 655
9	PV/Batt/Conv	19.8	160	999 999	30	R9 928 200.00	R9.66	R202 160.60	0	11 291
10	PV/Batt/Conv	30	240	999 999	30	R13 514 250.00	R8.63	R276 992.60	0	26 778
11	PV/Batt/Conv	40	240	999 999	40	R13 603 980.00	R6.50	R273 387.60	0	41 914
12	PV/Batt/Conv	30	240	999 999	34	R13 679 100.00	R8.73	R270 815.00	0	26 778

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4.2.1.2 Optimisation results and optimal sizing for Masia Development Centre for the Total facility loads.

The ideal hybrid power system architecture results for trying to power the whole of the Masia Community Development Centre are shown in the table below. The best or winning configuration appears at the top of configuration 1. This configuration is the best fit due to its cost-effective Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and operational costs. In exploring the findings and comparisons, it's clear that Case 1 stands out with an NPC of R15, 768,780.00 and an LCOE of R1.90. Its operational cost shows a surplus of R365,062.00, driven by the sale of excess energy back to the grid and high temperatures received in the area, where 48,300 kWh was purchased, and 71,283 kWh was sold. This surplus indicates that the system meets the energy demands of the Masia Community Development Centre and generates additional revenue, making it highly economical. This configuration proves to be highly economical and efficiently uses solar power and grid resources during peak daylight hours.

In a close second position are configurations 2 to 5, which present a similar setup but with slightly varying operational costs and energy balance metrics. These energy balance metrics refer to the ratio of energy purchased from the grid to the energy sold back to the grid, which measures the system's self-sufficiency and ability to contribute to the grid. It also showcases high cost-effectiveness, with configuration 2 having an NPC of R17,404,210.00 and an LCOE of R1.98. This configuration remains viable despite not including battery storage, reflecting a high confidence level in the project's financial sustainability.

While configurations 1 to 5 present significant economic advantages in maintaining a balance between NPC, LCOE, and operational costs, their lack of battery storage hampers their ability to meet power demands during grid interruptions, such as nighttime load shedding. These interruptions, which occur when the grid is not supplying power, necessitate using battery systems for comprehensive energy security. Implementing battery systems is a crucial and immediate step toward ensuring the reliability of the Masia Community Development Centre's energy supply.

Configurations 6 to 9 involve adding battery banks to enhance energy reliability during grid outages while maintaining moderate net present costs (NPC) and levelised cost of electricity (LCOE). However, costs also rise significantly as battery capacity increases, impacting economic viability. Configurations 10 to 12 focus on off-grid energy security, featuring large battery storage capacities of 1,128 to 1,600 kWh for uninterrupted operation during low solar generation. Although they have higher NPC and LCOE values (R12.12 to R16.10), these configurations ensure essential energy independence and reliability in remote areas.

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In contrast, configurations 1 and 2 emerge as the most economical, ideal for cost-sensitive applications. However, configurations 6 to 9 balance cost and energy resilience. A moderate-sized battery bank offers a viable solution for improving reliability at a reasonable price, providing a reassuring balance between financial viability and energy resilience. This approach assures operational sustainability, making the PV/Grid/Conv structure with added battery support the recommended model for the hybrid power needs of Masia.

Table 9: Optimised Component Sizes of the Proposed Hybrid Power System for Masia's Total Facility Load.

System configuration	Architecture	PV (kW)	Batt (kWh)	Grid (kW)	Conv (kW)	NPC (R)	LCOE (R)	OC (R)	Energy purchased (kWh)	Energy sold (kWh)
1	PV/Grid/Conv	130	0	999 999	72.7	R15 768 780.00	R1.90	R365 062.00	48 300	71 283
2	PV/Grid/Conv	130	0	999 999	125	R17 404 210.00	R1.98	R398 232.20	43 300	85 100
3	PV/Grid/Conv	100	0	999 999	100	R18 142 610.00	R2.44	434 856.90	55 241	48 261
4	PV/Grid/Conv	130	0	999 999	150	R18 475 800.00	R2.10	R421 994.10	48 300	85 100
5	PV/Grid/Conv	90	0	999 999	100	R19 541 990.00	R2.78	R476 688.30	58 737	37 164
6	PV/Batt/Grid/Conv	100	48	999 999	68.7	R19 571 970.00	R2.79	R466 749.70	46 318	36 299
7	PV/Batt/Grid/Conv	130	88	999 999	75.5	R20 284 00.00	R2.59	R462 217.50	35 052	58 929
8	PV/Batt/Grid/Conv	130	176	999 999	75	R24 655 920.00	R3.30	R555 977.30	25 300	48 757
9	PV/Batt/Grid/Conv	100	337	999 999	100	R36 281 080.00	R5.90	R827 638.20	22 925	12 621
10	PV/Batt/Conv	0	1128	0	137	R67 370 060.00	R12.12	R1 432 223.00	0	0
11	PV/Batt/Conv	0	1464	0	119	R83 680 530.00	R14.87	R1 783 694.00	0	0
12	PV/Batt/Conv	0	1600	0	129	R90 867 790.00	R16.10	R1 938 810.00	0	0

4.2.1.3 Optimisation of Results and optimal sizing for Vuwani Science Centre.

To ensure the efficient sizing and optimisation of component selection within a hybrid power system for sustainable energy, they emphasised the importance of evaluating both the levelised cost of energy (LCOE) and the net present cost (NPC). It was essential to assess these factors to make informed decisions and ascertain the system's cost-effectiveness and sustainability over time. HOMER simulation software was utilised in simulations, which aided in choosing system configurations that minimised NPC and LCOE, marking them as the most effective and favourable solutions. According to the outcomes presented in Table 10, the best result for the hybrid power system architecture was demonstrated in configuration 1, listed in the first row of Table 10. This case, featuring a PV/Grid/Conv configuration, was singled out as the superior choice for the

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proposed micro-grid energy system due to its NPC of R2,968,068.00, an LCOE of R1.07, and an annual operational cost (OC) of R83,039.74. With a renewable fraction of 90.7%, this configuration was highlighted as optimal; however, during nighttime and grid outages, the system might fail to support facility loads, as observed from configuration 1 to configuration 4.

Given the region's frequent and unpredictable power outages, the current 5 kW hybrid energy system architecture of PV/Grid/Conv was reviewed, and it was concluded that it is not the best option for providing a consistent energy supply to facilities. The hybrid energy systems, ranging from configurations 5 to 8 and configurations 9 to 12, emerged as more fitting solutions for both facilities and households in South Africa. The most viable options are configurations 5 and 7, employing PV/Batt/Grid/Conv configurations. These cases presented NPCs of R4,949,102.00 and R5,221,413.00, LCOEs of R1.89 and R1.95, and operation costs of R154,425.20 and R162,963.20, respectively.

Additionally, with an optimal capacity of 57.8 kW, the solar PV array allowed a PV penetration rate of 186% across 4,386 operating hours yearly, fully satisfying the current load demand with a levelized cost of 0.729 R/kWh. The grid, having a total capacity of 999,999 kW, was utilised to purchase 13,274 kWh/year of energy. In contrast, 70,155 kWh/year of energy was sold back to the grid, underscoring a balanced and efficient energy exchange.

Table 10: Optimised Component Sizes of the Proposed Hybrid Power System for Vuwani Science Centre.

System configuration	Architecture	PV (kW)	Batt (kWh)	Grid (kW)	Conv (kW)	NPC (R)	LCOE (R)	OC (R)	Energy purchased (kWh)	Energy sold (kWh)
1	PV/Grid/Conv	57.8	0	999 999	58.1	R2 962 068.00	R1.17	R83 039.74	13 274	70 155
2	PV/ Grid /Conv	66	0	999 999	77.5	R 3275 166.00	R1.05	R85 068.80	11 743	87 874
3	PV/ Grid /Conv	66	0	999 999	93	R3 698 436.00	R1.18	R100 367.00	11 743	87 874
4	PV/ Grid /Conv	198	0	999 999	93	4 255 206.00	R0.708	R37 735.81	7 060	235 464
5	PV/Batt/Grid/Conv	57.7	64	999 999	46.3	R4 949 102.00	R1.89	R154 425.20	13 371	62 209
6	PV/Batt/Grid/Conv	55.8	64	999 999	57.5	R5 106 815.00	R1.88	R159 214.30	13 769	66 647
7	PV/Batt/Grid/Conv	57.8	72	999 999	48.7	R5 221 413.00	R1.95	R162 963.20	13 311	64 731
8	PV/Batt/Grid/Conv	62.7	72	999 999	42.1	R5 256 494.00	R2.03	R164 115.20	12 614	60 714
9	PV/Batt/Conv	81	176	0	85.3	R10 915 610.00	R7.09	R366 740.90	0	0
10	PV/Batt/Conv	91.6	176	0	93	R11 477 290.00	R8.35	R384 971.30	0	0
11	PV/Batt/Conv	87.2	208	0	93	R12 387 600.00	R9.01	R417 209.50	0	0
12	PV/Batt/Conv	66	352	0	66	R15 592 910.00	R11.35	R530 337.60	0	0

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4.3. Electric energy production

This section discusses how the electrical energy in Photovoltaic (PV) hybrid energy systems was analysed, looking at the variations in electricity production throughout the year and conducting a detailed comparison between the electrical power supplied by the grid and that produced by the PV system. This includes considering the changes and fluctuations that occur over the entire year.

4.3.1 Actual energy production from the installed PV system in Masia Community Development Centre.

In Figure 21, the graph presents the real-time electricity generation of the current hybrid energy system. The system can shut down inverters or reduce power output to align with energy demand or system conditions. This balancing act aims to maintain photovoltaic (PV) system reliability while efficiently using available energy resources. Although these adjustments help keep the system stable, they also decrease potential energy and economic value due to curtailment.

The PV system's daily energy production over 289 days shows a variable yet active generation pattern, with a 10–15 kWh baseline and occasional spikes over 60 kWh. This variability suggests consistent energy production, likely from diffuse irradiance on cloudy days, while high-irradiance periods enhance output. The lack of a smooth seasonal trend indicates factors like intermittent cloud cover, partial shading from nearby structures, or dirt buildup affecting efficiency inconsistently.

Daily analysis revealed that the energy output from the solar PV system varied with the seasons, often producing more energy than the facility needs. Unfortunately, much of this excess energy is wasted due to the facility's low consumption, especially during periods of curtailment. Integrating a larger storage bank and connecting additional electrical loads to the PV system are recommended to tackle this issue. These enhancements aim to optimise energy utilisation, reduce waste, and ensure the hybrid energy system operates more efficiently.

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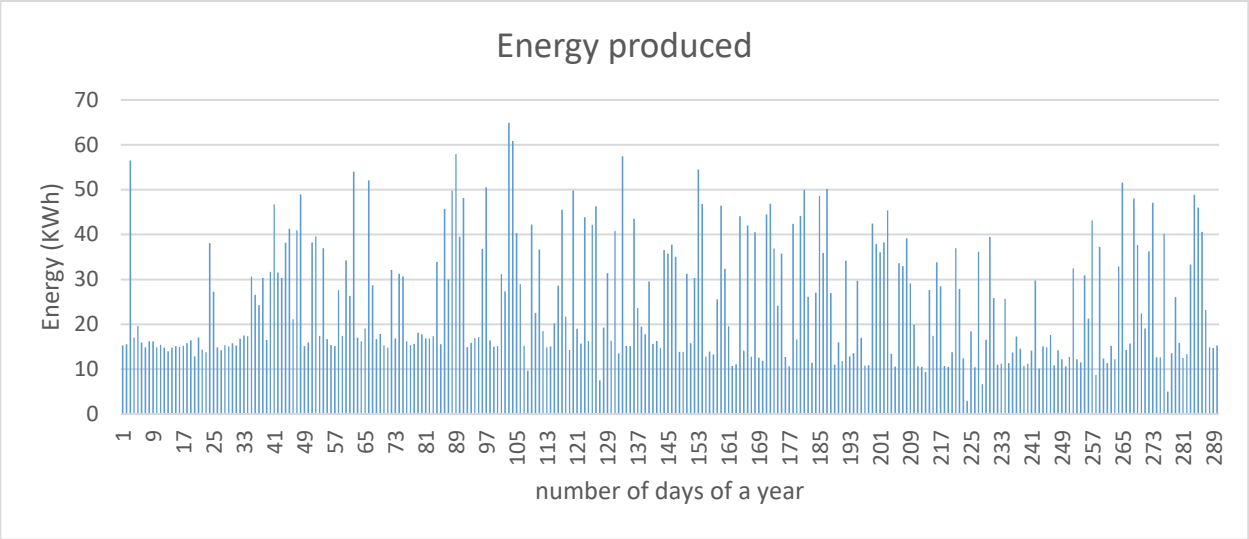


Figure 21: Actual energy production of Masia Community Development Centre

4.3.2 Energy production for the simulated hybrid energy system

This section delves into the intricacies of energy production within the hybrid energy systems examined in our case studies. This subchapter comprehensively explores the dynamics of energy generation in both scenarios, shedding light on the unique characteristics and synergies inherent in these hybrid systems.

4.3.2.1 Energy production for Masia community development centre energy system.

Based on a monthly analysis, Figure 22 illustrates how solar PV and national grid systems generate varying amounts of electricity yearly. Solar PV generates the highest amount of electricity, while the National Grid serves as a backup, as simulated by Homer. Throughout the year, PV production, represented by orange bars, serves as the primary energy source, consistently generating between 3.4 MWh and 4.3 MWh each month. The lowest PV output occurs in February, possibly due to shorter daylight hours or seasonal weather conditions such as increased cloud cover. Grid electricity contributes only a minimal amount each month, remaining almost constant and serving as a supplementary source to cover shortfalls. The peak production occurs in August, September and October, reaching over 4.2 MWh, likely reflecting increased solar irradiance. Contributions from the grid, represented by green bars, are minimal across all months, highlighting the site's significant reliance on solar energy. The relatively stable PV output indicates an effective solar system, with seasonal fluctuations corresponding to

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variations in solar exposure. The findings suggest that the perfect grid-connected hybrid microgrid power system produces 48,355 kWh/yr annually with grid purchases of 2,066 kWh/yr, which accounts for 4.27% of total energy production, and 46,269 kWh/yr, which accounts for 95.7% of total energy production, with a renewable fraction of 95.6%.

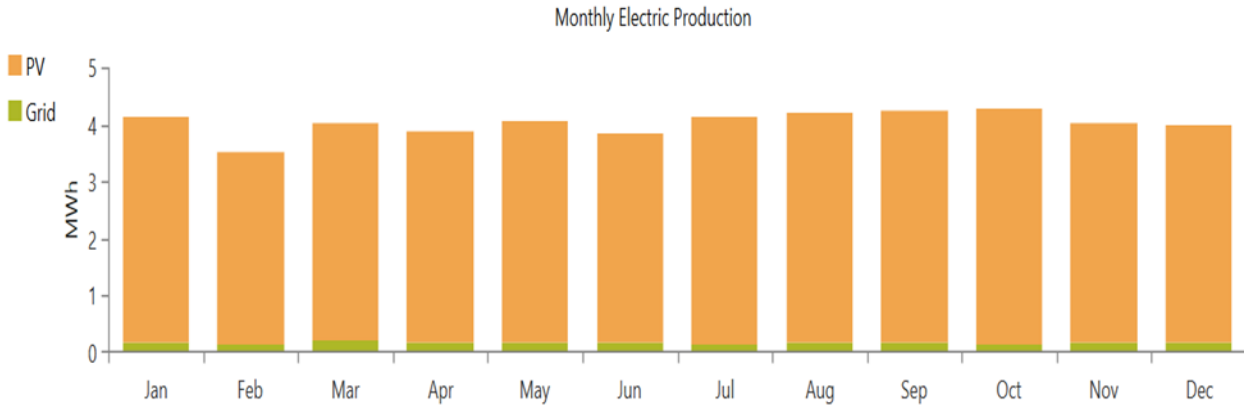


Figure 22: Monthly electricity production from the Grid and PV for the Masia development centre.

Figure 23 shows a daily photovoltaic (PV) power output over a year, with days on the x-axis, hours on the y-axis, and a colour scale indicating power levels from 0 to 30 kW. A clear bell-shaped pattern emerges, corresponding to longer daylight hours and higher solar irradiance during the middle of the year, where peak outputs frequently exceed 18 kW during midday, especially in spring and summer. The PV power output diminishes during winter, consistent with shorter days and reduced sunlight. The comprehensive diagrammatic map, or D-map, visualises these seasonal variations and highlights the system's performance across different conditions. Despite the evident decline in generation during winter, the system continues to produce sufficient electricity to meet the facility's load demands. This consistent performance, even under less favourable conditions, underscores the efficiency and resilience of the PV array in maintaining a reliable power supply year-round.

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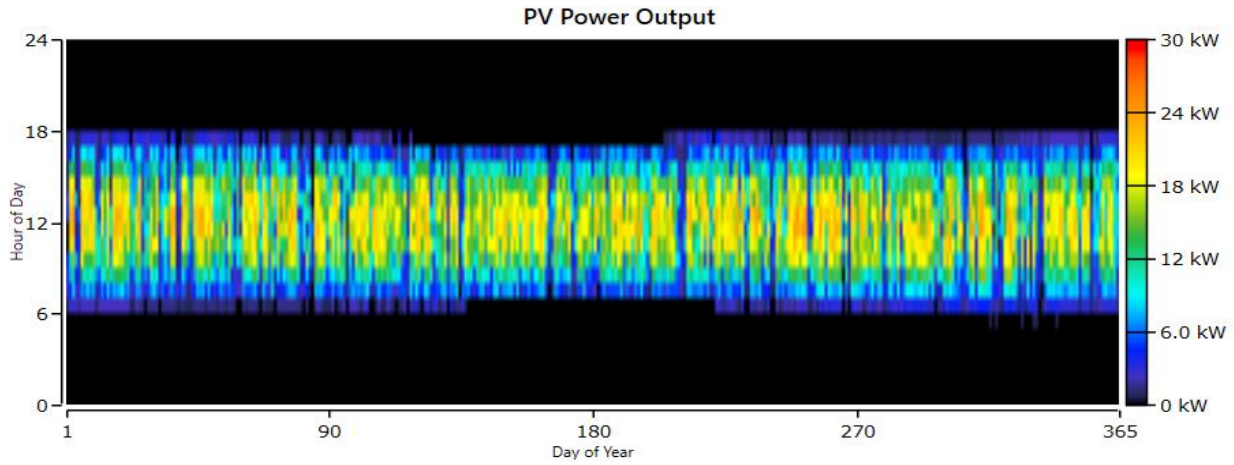


Figure 23: PV power output for the Masia hybrid energy system

Figure 24 shows daily energy transactions to the grid over a year, indicating that a significant proportion of energy exports occur during daylight hours, with a notable peak around midday. This pattern aligns closely with the photovoltaic (PV) system's output, showcasing the correlation between solar generation and grid exports. When solar irradiance is optimal, the facility experiences the highest energy sales between 15kW and 25kW during the spring and autumn. While energy production slightly declines during the shorter seasons, the facility exports significant amounts of electricity, indicating consistent overproduction. In winter, energy exports drop due to shorter days and lower solar output. However, the integrated battery storage system mitigates grid dependence at night, ensuring self-sufficiency. This surplus of energy positions the facility for potential energy credits from local utilities. It enhances its financial strategy under net metering policies, proving its energy-efficient approach and ability to capitalise on solar overproduction.

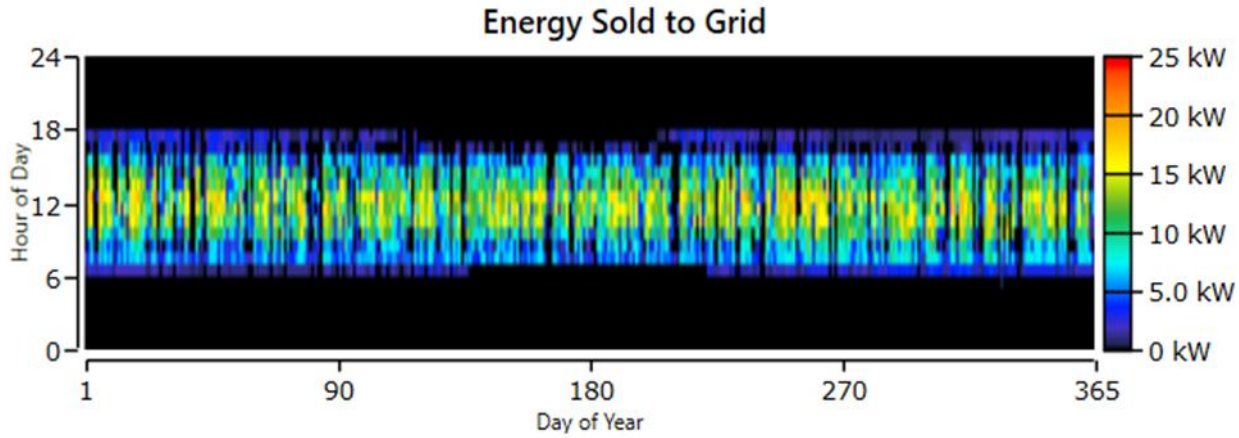


Figure 24:Energy sold back to the Grid in the Masia development centre

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Figure 25 below illustrates the patterns of energy purchased from the grid at the facility, emphasising the reliance on grid power during low or no solar generation, particularly in the early morning and evening hours. This dependence on grid power is most noticeable in winter when solar output decreases. During nighttime, energy purchases from the grid typically remain below 4.2 kW, although they can occasionally spike to between 4.2 and 5.6 kW during poor weather conditions. While the solar system effectively meets the facility's energy demands during the day, it does not provide sufficient energy at night or during overcast conditions.

Energy purchases from the grid significantly decrease during late-night hours, likely due to lower electricity demand. This trend emphasises the facility's reliance on solar energy during daylight hours while highlighting the crucial role of grid power in bridging the energy gap during off-peak solar production times.

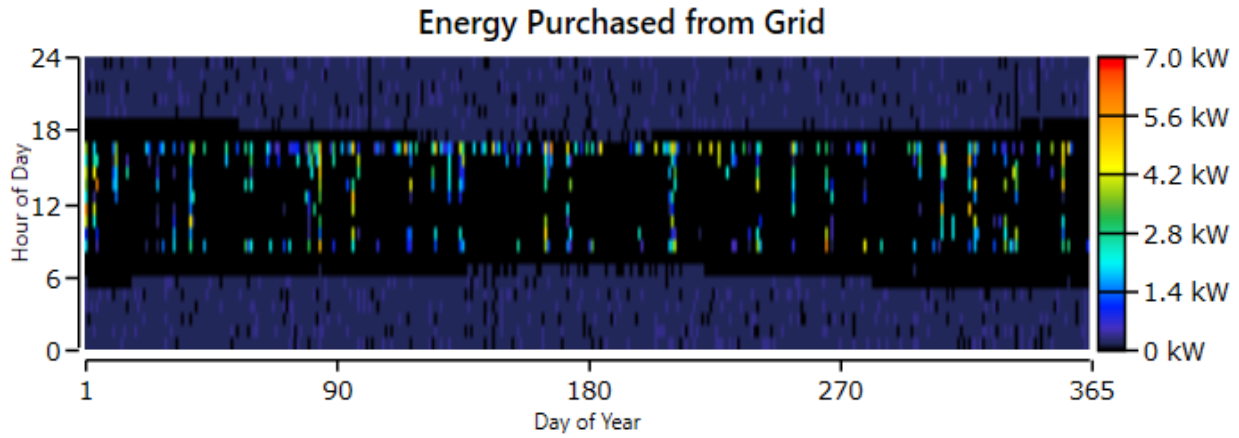


Figure 25: Energy purchased from the Grid for the Masia development centre

4.3.2.2 Energy production for the Masia Community Development Centre energy system for the total facility load.

Considering the total electrical consumption of the facility, Figure 26 illustrates the monthly fluctuations in electricity generation from the solar PV system compared to the national grid. The output from the solar PV system demonstrates a clear peak and consistently surpasses that of the grid. Notably, even during the prolonged heavy rainfall in February, which adversely affected the energy production of the PV array, the hybrid power system reliably fulfilled the facility's energy needs, ensuring uninterrupted functionality. The most efficient grid-connected hybrid microgrid configuration produced an impressive 274,418 kWh annually, with 199,118 kWh (80.5% of the total) derived from solar PV and 48,300 kWh (19.5% of the total) sourced from grid

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purchases. The renewable fraction stands at an impressive 78.6%, Demonstrating the system's effectiveness in fulfilling the facility's energy requirements.

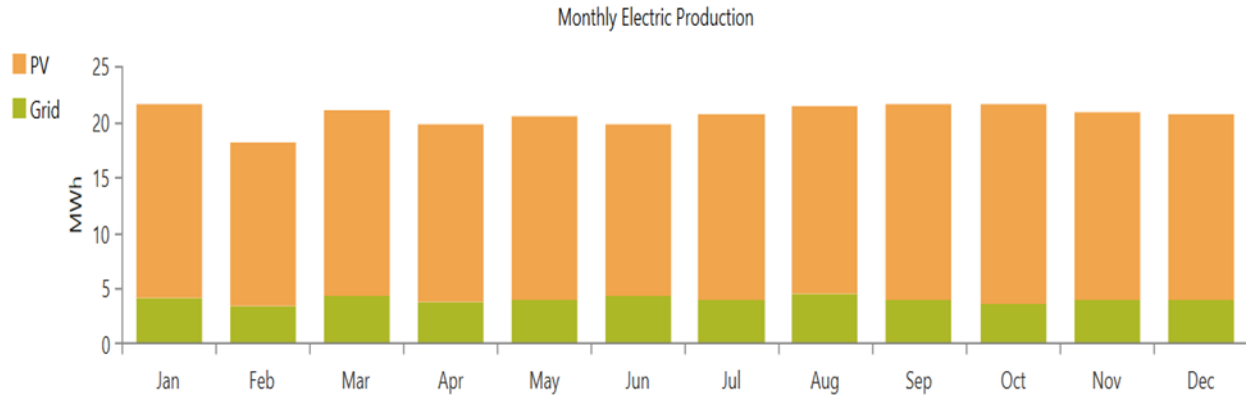


Figure 26: Monthly electric energy production from the Grid and PV for the Masia development centre, total facility load

Figure 27 illustrates how annual photovoltaic (PV) power generation varies under different conditions, showing a notable reduction during winter due to shorter daylight hours. Despite this, the system reliably meets daily power demands, enhancing confidence in its dependability. The PV array's ability to maintain a steady supply even during less favourable weather conditions, particularly in winter, further boosts its reliability and longevity. A seasonal pattern shows a bell shape, with production peaking from spring to early autumn. During this time, high output is consistent between 8 AM and 4 PM, reaching its peak around midday.

The photovoltaic (PV) system, with a capacity of 130 kW, produces an average power of 22.7 kW, equivalent to 546 kWh daily and 4,388 hours annually. This results in a capacity factor of 17.5 % and a PV penetration rate of 128%. The levelized cost of electricity is 0.567 R/kWh, reflecting the average price per unit of electricity over the system’s lifespan, a key aspect in evaluating its economic viability. Notably, the system is designed to perform well in challenging winter conditions, ensuring a reliable and sustainable energy supply.

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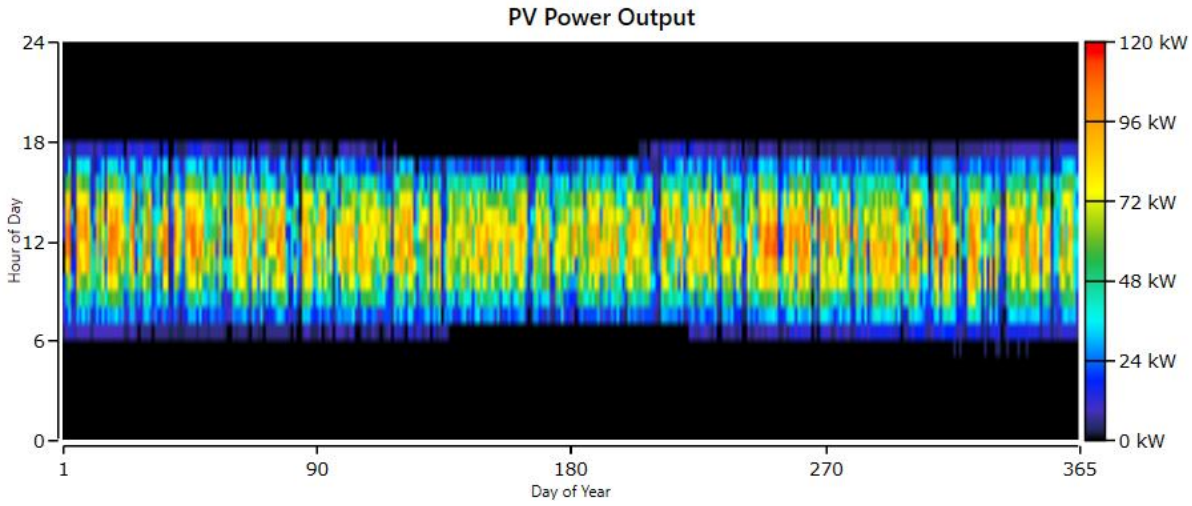


Figure 27: PV power output for the Masia hybrid energy system, total facility load

Figure 28 illustrates the daily energy transactions at the Masia Development Centre throughout the year based on the total facility load. The data shows that the centre sells energy back to the grid during the day, with zero sales occurring at night. During periods of "load shedding," which refers to situations when less power is available, the facility relies on its batteries and grid supply to meet its energy needs. A substantial amount of energy is sold back to the grid around midday when the solar panels generate the most power. However, sales decrease in winter due to shorter daylight hours.

The Centre significantly reduces energy costs by effectively utilising its solar power system. It sells energy at a lower price while purchasing it back at a higher rate, making this a wise financial strategy leading to considerable economic gains. More importantly, the centre's strategic use of solar power optimises energy consumption and decreases its reliance on the grid. Peak energy sales occur around noon, with no sales at night, creating a sustainable energy model.

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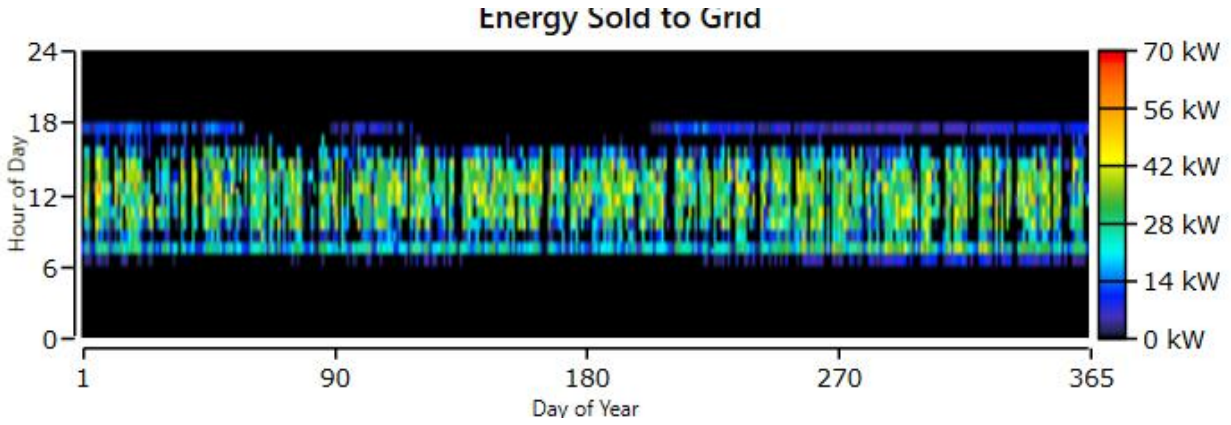


Figure 28: Energy sold back to the Grid in the Masia development centre, total facility load

Figure 29 provides a comprehensive daily annual energy transfer from the grid to the Masia Development Centre. The pattern reveals that energy purchases are generally low and sporadic, with intensity peaking up to 50 kW, primarily outside daylight hours before 7 AM and after 4 PM when the photovoltaic (PV) system is inactive or generates minimal output. During the daytime, especially from spring through autumn, grid reliance significantly drops due to the PV system's peak performance in supplying the facility's energy demands. Conversely, nighttime hours and winter months have marked increases in grid energy use, aligning with reduced solar availability caused by shorter days and less favourable weather conditions. This trend corresponds with the facility's lower internal activity at night, resulting in decreased but still present energy demand.

The energy transfers from the grid occur throughout the 24 hours, though skewed toward the night, and reflect a well-structured hybrid strategy. The Masia Centre efficiently leverages solar energy during sunlight hours. It taps into the grid only as needed, particularly in low PV output periods, suggesting the presence of a complementary energy storage system (e.g., battery bank). This balanced and proactive energy management approach ensures operational stability while minimising grid dependence and maximising renewable energy utilisation.

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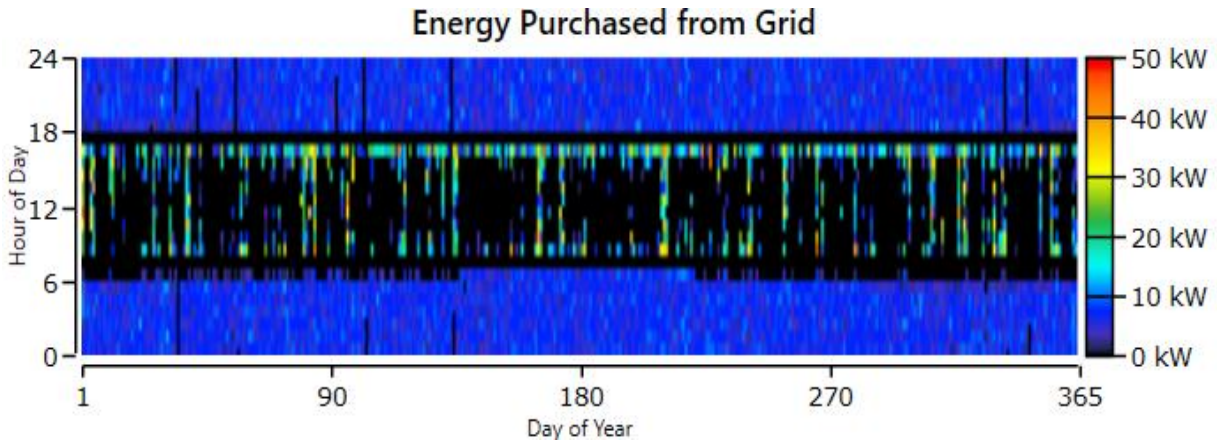


Figure 29: Energy sold back to the Grid in the Masia development centre, total facility load

4.3.2.3 Energy production for the Vuwani science centre energy system

Figure 30 below depicts the monthly electricity generation from photovoltaic (PV) solar energy and the Grid, measured in megawatt hours (MWh) over a year. Throughout all months, PV consistently represents the larger share of production, as evidenced by the prominent orange sections of each stacked bar. At the same time, the Grid, shown in green, maintains a minor yet steady contribution. Peak production occurs in July and August, reaching 14 MWh, which suggests optimal solar generation due to seasonal advantages such as reduced cloud cover. The lowest output in February was below 10.8 MWh, with some support from the Grid. Notably, grid contributions slightly increase from September to December, likely offsetting the diminished solar efficiency during these months.

The sustained and relatively high contribution of PV throughout the year highlights the system's firm reliance on solar energy, emphasising its effectiveness and seasonal dependency. Meanwhile, the Grid serves as a stabilising supplementary source. This hybrid approach showcases a well-balanced energy strategy for maintaining reliable electric production year-round. The study reveals that the optimal grid-connected hybrid microgrid power system achieves an annual production of 147,124 kWh, with 13,274 kWh (9.02% of the total output) sourced from grid purchases and 133,850% kWh (91.0% of total production) from solar PV. The renewable fraction stands at an impressive 90.07%.

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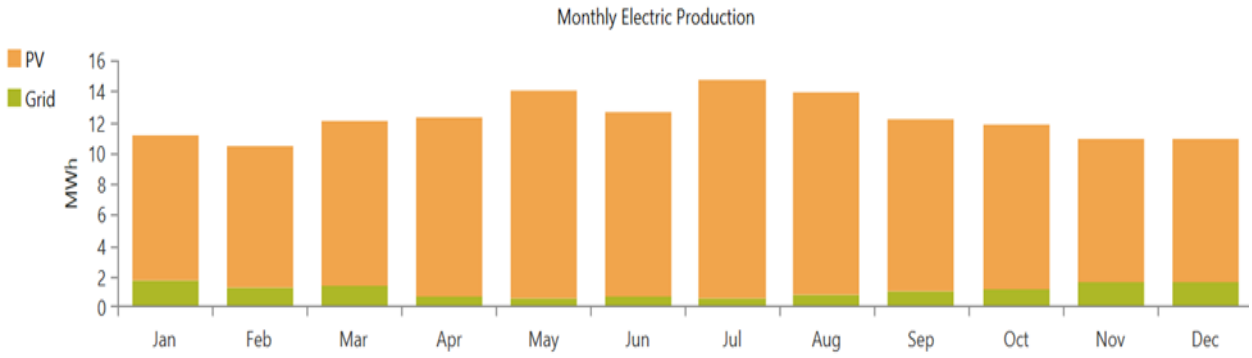


Figure 30: Monthly electric energy production from the Grid and PV for Vuwani science centre

Figure 31 presents a detailed visualisation of the photovoltaic system's performance (PV power output) throughout the year, with the horizontal axis representing the days (1–365) and the vertical axis showing the hours of the day (0–24). The colour gradient indicates PV power output intensity, from 0 kW (black) to 70 kW (red). The graph shows that PV generation peaks between 7:00 AM and 4:00 PM, with maximum production typically occurring from 10:00 AM to 3:00 PM, where output values range from 42 kW to 70 kW during sunnier months. There is a noticeable decline in output in winter, reflecting fewer sunshine hours, while summer and spring yield broader and more intense production due to increased solar availability. The figure highlights the system's reliance on seasonal and daily solar variations, achieving maximum output in mid-year and minimal production during nighttime.

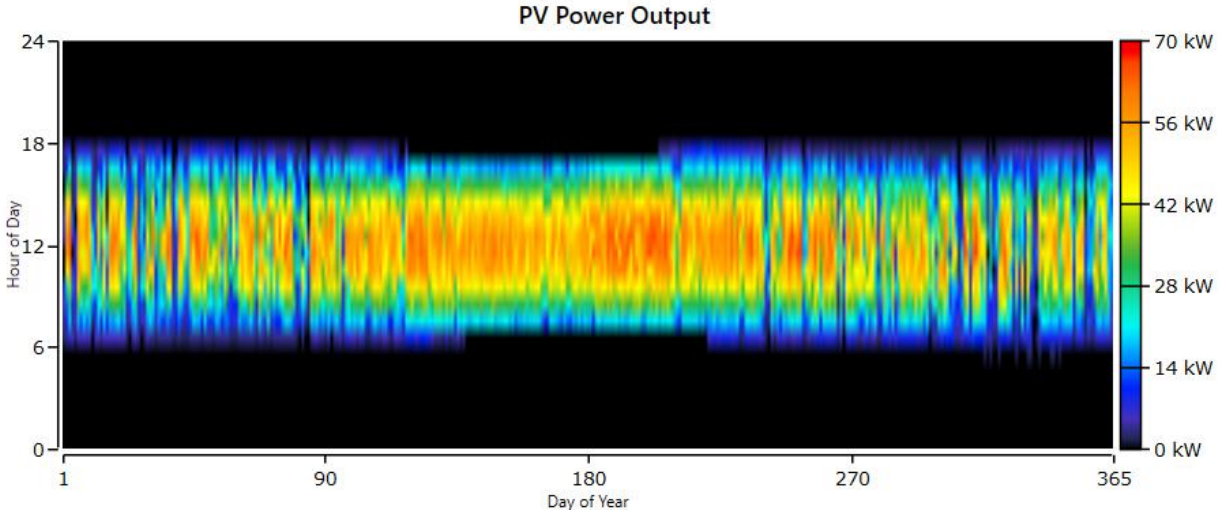


Figure 31: Power output for Vuwani science centre energy system.

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The graphical illustration of energy sold to the grid, shown in Figure 32, reveals a clear pattern of electricity exports from 8:00 AM to 5:00 PM, aligning with peak solar generation times where energy sales can reach up to 60 kW around midday. The photovoltaic (PV) system generates a substantial surplus of electricity during sunny hours, especially in the warmer months of spring and summer, while energy sales decline in winter due to lower solar irradiation and shorter daylight hours. At night, there are no energy sales to the grid, indicating that the system either prioritises self-consumption through battery storage or relies on the grid during low or no solar production periods. The observed energy export behaviour highlights a strategy to maximise solar energy use during the day while minimising grid sales, which are less economically favourable due to a lower feed-in tariff. This approach emphasises enhancing economic efficiency through on-site consumption, ultimately leading to a more effective use of solar energy resources.

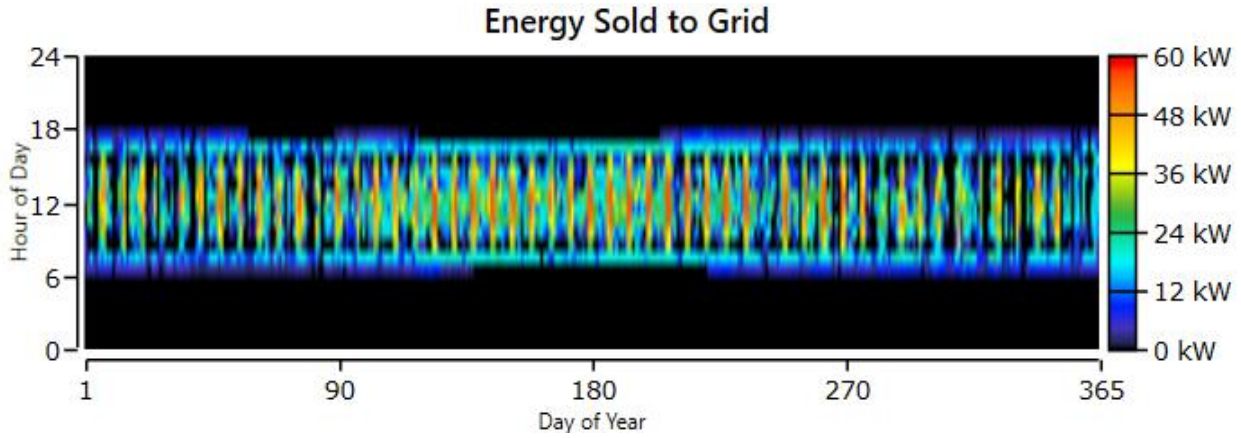


Figure 32: Energy sold back to the Grid for Vuwani science centre

The annual daily energy transfers from the grid to the facility are illustrated in Figure 33 below. Grid purchases mainly occur during daytime hours, especially from 6:00 to 18:00, which aligns with the facility's operational schedule. This pattern indicates that as internal energy demand rises, likely due to lighting and equipment use, the facility turns to grid electricity to meet its needs, especially during times of reduced solar generation. During the night, Grid purchases significantly decline, reflecting reduced building activity and the absence of workers. This decrease in demand also demonstrates the effectiveness of the facility's battery storage system in meeting nighttime energy requirements. The figure reflects a strategic energy management approach, where grid electricity is utilised mainly during peak daytime demand when storage is inadequate or solar output is variable, while nighttime hours experience minimal reliance on grid supply due to reduced consumption and effective demand management.

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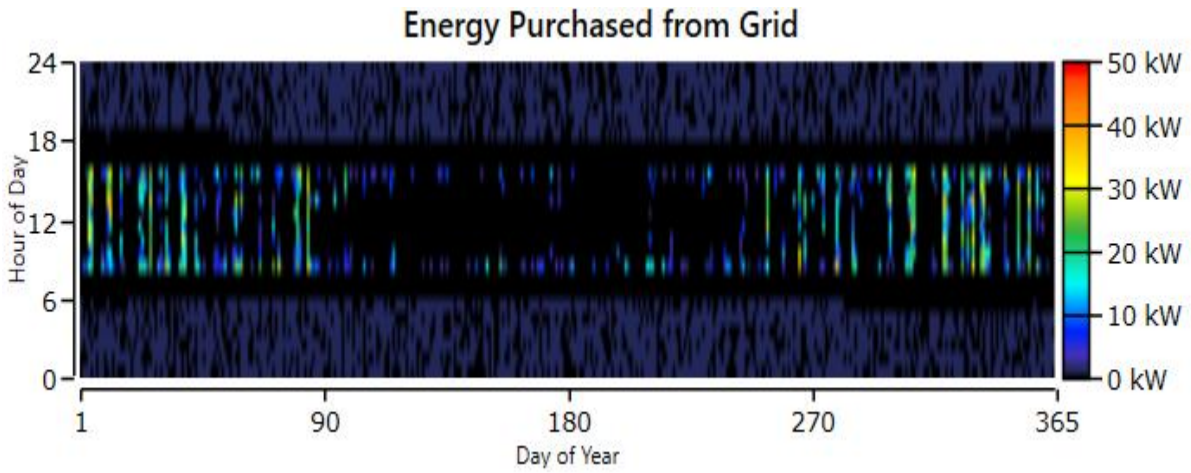


Figure 33: Energy purchased from the Grid for Vuwani science Centre

4.4 Emission dynamics

Tables 11,12, and 13 show that the Off-Grid option has zero or lower emissions when greenhouse gas emissions are examined between Off-Grid (OG) and Grid-Connected (GC) systems. The capacity of the Grid-Connected solar PV system to supply electricity to the erratic national Grid and the essential load demand is responsible for this phenomenon, which eventually results in increased emissions. Conversely, the off-grid solar PV system generates minimal emissions and is solely linked to local load needs; it has no communication with the national grid (Jacobson, et al., 2015).

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Table 11: Grid-Connected and Off-Grid emissions for Masia Development Centre Energy System

System Architecture	Grid-Connected (PV/Grid/Conv & PV/Batt/Grid/Conv)	Off-Grid (PV/Batt/Conv)
Carbon dioxide kg/yr	2797.44	0
Carbon monoxide kg/yr	1.457	0
Unburned hydrocarbons kg/yr	1.457	0
Particulate Matter kg/yr	1.04904	0
Sulphur dioxide kg/yr	24.769	0
Nitrogen oxides kg/yr	13.02558	0

Table 12: Grid-Connected and Off-Grid emissions for Masia Development Centre Energy System for the total facility load

System Architecture	Grid-Connected (PV/Grid/Conv & PV/Batt/Grid/Conv)	Off-Grid (PV/Batt/Conv)
Carbon dioxide kg/yr	46368	0
Carbon monoxide kg/yr	44.15	0
Unburned hydrocarbons kg/yr	24.15	0
Particulate Matter kg/yr	20.388	0
Sulphur dioxide kg/yr	420.55	0
Nitrogen oxides kg/yr	315.901	0

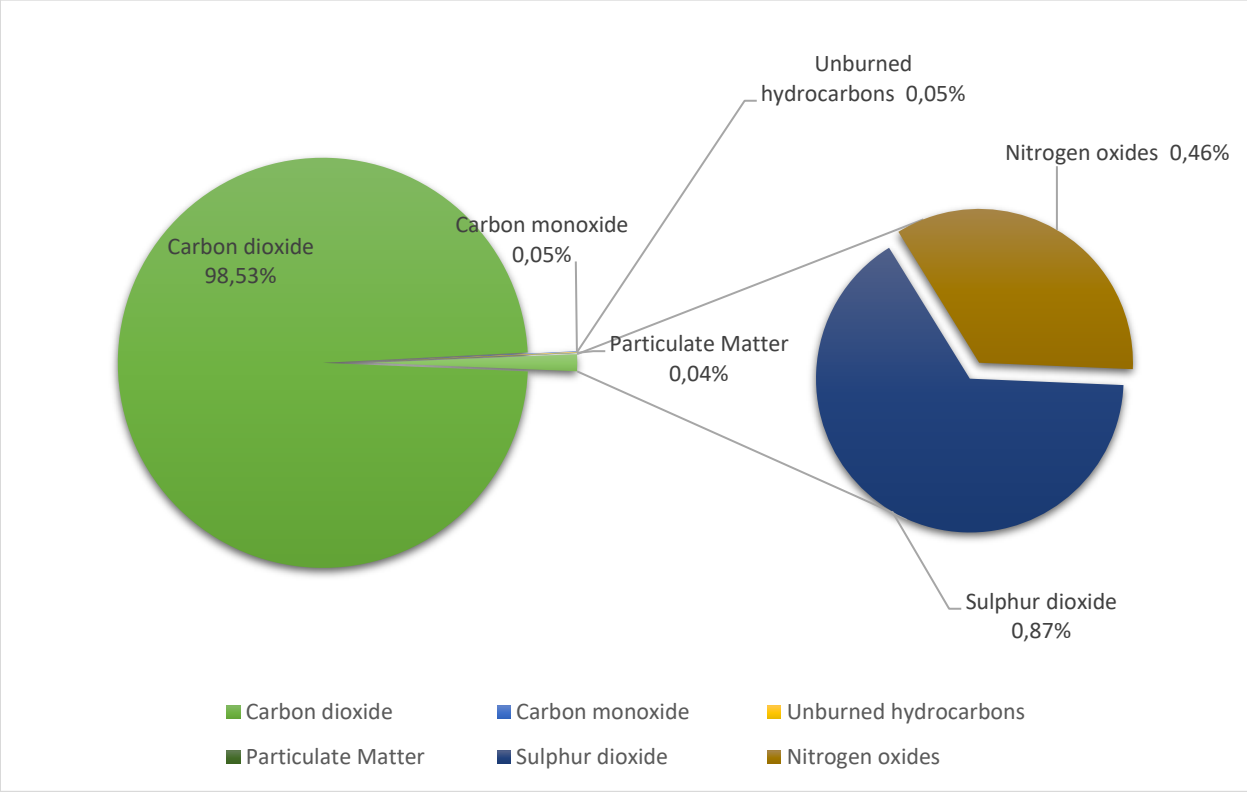
Table 13: Grid-connected and off-grid emissions for the Vuwani Science Centre's energy system

System Architecture	Grid-Connected (PV/Grid/Conv & PV/Batt/Grid/Conv)	Off-Grid (PV/Batt/Conv)
Carbon dioxide kg/yr	12843.04	0
Carbon monoxide kg/yr	26.637	0

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Unburned hydrocarbons kg/yr	26.637	0
Particulate Matter kg/yr	14.77864	0
Sulphur dioxide kg/yr	212.829	0
Nitrogen oxides kg/yr	89.33478	0

To delve deeper into the emissions dynamics, Figure 34 below details the total emissions associated with the grid-connected system design at the Masia Community Development Centre. The grid-connected system produces 2,797 kg of CO2 annually, representing 98.53% of total emissions. Sulphur dioxide (0.87%), nitrogen oxides (0.46%), unburned hydrocarbons (0.05%), Carbon monoxide (0.05%) and particle matter (0.04%) come in close succession. This startling finding emphasises how vital it is to reconsider how the current grid-connected technologies affect the environment. A targeted approach is necessary to minimise and lower this substantial input to the Centre's overall carbon footprint because of the predominance of carbon dioxide emissions.



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Figure 34:Total emissions from PV/Grid/Conv & PV/Batt/Grid/Conv for Masia community development centre

Considering the overall facility load, Figure 35 presents a detailed analysis of the emissions associated with the architectural design of the grid-connected system at the Masia Community Development Centre. A significant finding is that annual carbon dioxide emissions account for 98.25% of the total emissions. In contrast, other gases contribute much less: trace amounts of carbon monoxide(0.09%), unburned hydrocarbons(0.05%), and particulate matter(0.04%) of total emissions, while nitrogen oxides account for 0.67% and sulfur dioxide for 0.89%. This breakdown underscores the need for immediate and targeted environmental initiatives to mitigate the ecological impact of the grid-connected system, highlighting the crucial role of our professional colleagues and stakeholders in this endeavour.

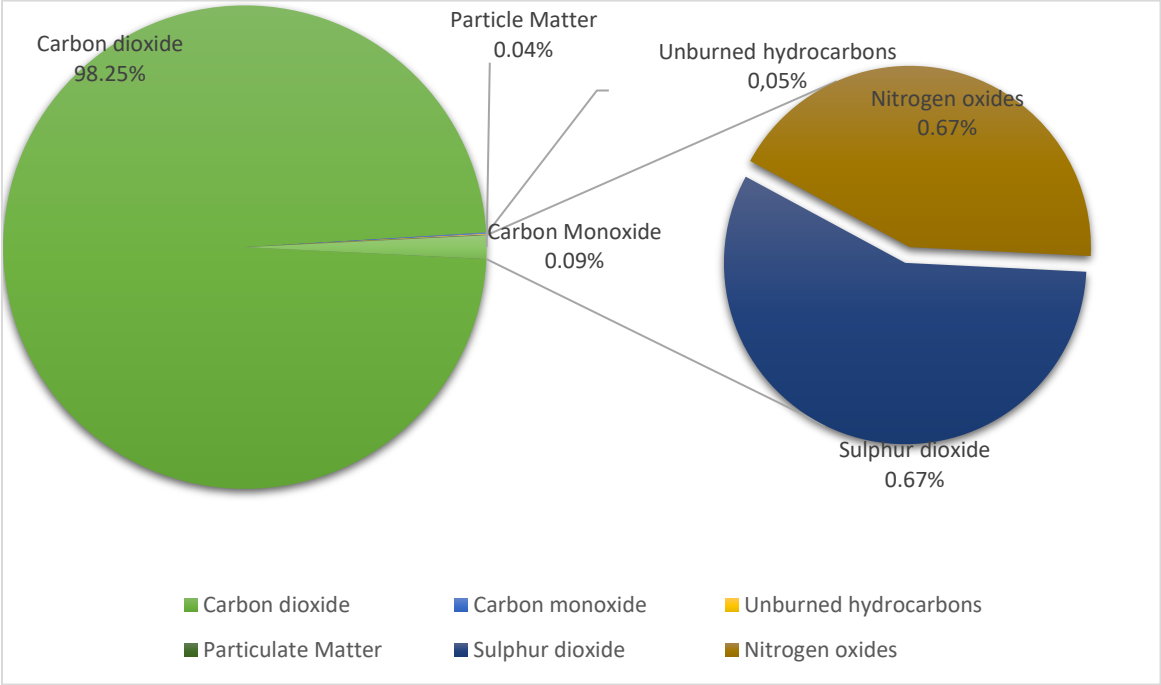


Figure 35: Total emissions from PV/Grid/Conv & PV/Batt/Grid/Conv for Masia community development centre, Total facility load

Figure 36 provides a detailed breakdown of the total emissions linked to the architectural design of the grid-connected system in the Vuwani Science Centre. A noteworthy finding is the significant annual production of 12,843.04 kg of carbon dioxide by the grid-connected configuration, constituting an astonishing 97.20 % of the overall emissions output.

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In addition to carbon dioxide, other major contributors to the emission profile include nitrogen oxides at 0.68%, sulfur dioxide at 1.61%, carbon monoxide at 0.20%, Unburned hydrocarbons at 0.20%, and particle matter at 0.11%. These figures shed light on the diverse composition of pollutants generated by the grid-connected setup, prompting a multifaceted approach to environmental management. Understanding the nuanced contributions of each gas is crucial for formulating targeted strategies to reduce the overall ecological footprint of the Vuwani Science Centre energy system.

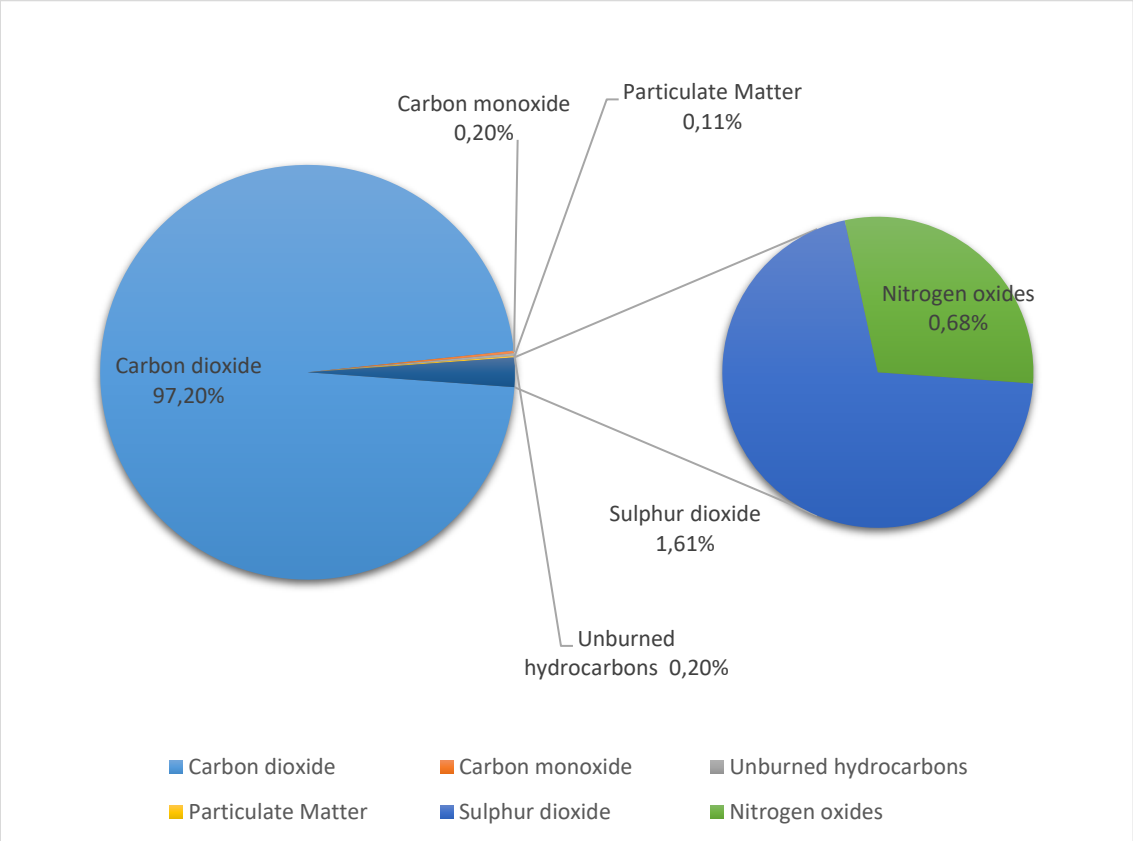


Figure 36: Total emissions from PV/Grid/Conv & PV/Batt/Grid/Conv for Vuwani Science Centre

This analysis demonstrates how much the grid-connected system contributes to carbon dioxide emissions, underscoring the necessity of thoroughly assessing how such energy schemes affect the environment. A thorough understanding of emissions composition facilitates adequate

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decision-making, emphasising the necessity of customised treatments. By targeting the distinct origins of contaminants, including carbon dioxide, nitrogen oxides, and sulphur dioxide, the Centre can implement efficient strategies to advance a hybrid energy system that is highly environmentally responsible and sustainable.

5. CONCLUSION

A comparative study evaluated Grid-tied and isolated PV/hybrid energy systems at the Masia Development Centre and Vuwani Science Energy Centre, focusing on metrics such as total power production, economic factors including Levelised Cost of Energy (LCOE), Net Present Cost (NPC), and greenhouse gas emissions. The findings revealed that the grid-connected (GC) system was technically and economically superior to the off-grid (OG) system, particularly in lower NPC and COE, and it also had increased power output. However, the GC system had higher greenhouse gas emissions due to its reliance on the grid, which often includes non-renewable energy sources.

The PV/Grid/Conv system architecture was both case studies' most economically viable and environmentally sustainable option. Its low Net Present Cost (NPC), competitive Levelised Cost of Energy (LCOE), and minimal operating expenses driven by the ability to export excess energy to the grid underscore its cost-effectiveness. For the current connected load at the Masia Community Development Centre, the system achieved an NPC of R1, 852,811.00, an LCOE of R1.63, and annual operating costs of R20,878.56. When scaled to the entire facility, it delivered an NPC of R15,768,780.00, an LCOE of R1.90, and yearly operating costs of R365,062.00, benefiting further from high local irradiance and the potential to integrate fuel cell technology. At the Vuwani Science Centre, the PV/Grid/Conv architecture achieved an NPC of R2, 969,068.00, an LCOE of R1.07, and annual operating costs of R83, 039.74. The PV/Grid/Conv system is highly effective for cost-efficient, sustainable energy in rural South Africa, excelling in performance and affordability. However, its dependence on grid availability limits nighttime reliability during outages. This situation highlights the advantage of integrating battery storage in PV/Batt/Grid/Conv configurations, which ensures a continuous supply during load shedding and enhances overall resilience.

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While the GC system is advantageous for grid-connected facilities, the study also emphasised OG systems' technical and economic viability of OG systems for isolated regions. Off-grid systems are particularly beneficial in remote areas where extending the grid may be impractical or costly, providing a sustainable and independent power source that leverages renewable energy to minimise dependence on fossil fuels. This approach can facilitate electrification in isolated settlements without the high costs and infrastructure requirements associated with grid expansion, highlighting OG systems as a viable solution for sustainable energy access in remote communities.

6. RECOMMENDATIONS

The study recommends off-grid (OG) hybrid systems for remote or rural areas where grid extension is not feasible. These systems promote broader electrification efforts, reduce environmental impact, and empower communities to generate electricity independently. By lowering reliance on non-renewable resources, OG systems support environmental sustainability while avoiding the financial and logistical challenges of expanding traditional grid infrastructure. For facilities with stable grid access, grid-connected (GC) systems are still the most cost-effective, delivering dependable power. However, due to frequent grid outages, the study suggests integrating PV/Battery/Grid/Converter systems to ensure excellent reliability during disruptions. Additionally, the study advocates for a net metering policy for rooftop photovoltaic (PV) owners, aiming to encourage renewable energy adoption, cut electricity costs, improve grid resilience, reduce greenhouse gas emissions, and stimulate economic growth.

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7. REFERENCES

Acakpovi, A., Adjei, P., Nwulu, M. & Asabere, Y., 2020. Optimal Hybrid Renewable Energy System: A Comparative Study of Wind/Hydrogen/Fuel-Cell and Wind/Battery Storage. *Hindawi,* Volume 2020, p. 15.

Acakpovi, A., Adjei, p., Nwulu, N. & Asabere, N., 2020. Optimal Hybrid Renewable Energy System: A Comparative Study of Wind/Hydrogen/Fuel-Cell and Wind/Battery Storage. *Hindawi:journal of Electrical and Computer Engineering,* Volume 2020, p. 15.

Adebanji, B. et al., 2021. Comparative study of off-grid and grid-connected hybrid power system: issues, future prospects, and policy framework. *Indonesian Journal of Electrical Engineering and Computer Science,* 22(2), pp. 752-759.

Ahmed, S., Ahshan, K. & Mondal, M., 2000. Rooftop solar: A sustainable energy option for Bangladesh. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) ,* 17(3), pp. 58-71.

Ajanovic, A. & Haas, R., 2018. Economic Prospects And Policy Framework For Hydrogen As Fuel In The Transport Sector.. *Energy policy,* Volume 123, pp. 280-288.

Ali, W. et al., 2018. Design considerations of stand-alone solar photovoltaic systems. Em: *2018 International conference on computing, electronic and electrical engineering (ICE Cube).* s.l.:IEEE, pp. 1--6.

Almaktar, M., Hasimah, A. & Mohammad, Y., 2013. Economic and Environmental Analysis of a Grid-connected Solar Photovoltaic System in Malaysia. *Indian Journal of Advanced in Electrical Engineering,* 1(1), pp. 11-32.

Alturki, A., 2022. Optimal design for a hybrid microgrid-hydrogen storage facility in Saudi Arabia. *Energy, Sustainability and Society,* Volume 12(1), pp. 1-17.

Alturki, A., 2022. Optimal design for a hybrid microgrid-hydrogen storage facility in Saudi Arabia.. *Energy, Sustainability and Society,* Volume 12(1), pp. 1-17.

© University of Venda

Annisa, F. & Mustaqimah, 2013. Developing a Model Using Homer for a Hybrid Hydrogen Fuel Cell System. *Rona Teknik Pertanian,* Volume 6.

Asamoah, S., Gyamfi, S., Uba, F. & Mensah, G., 2022. Comparative assessment of a stand-alone and a grid-connected hybrid system for a community water supply system: A case study of Nankese community in the eastern region of Ghana. *Scientific African,* Volume 19, p. e1331.

Ashaye, O. R. & Alharahsheh, H. H., 2019. Review of Drivers and Barriers to Development of Renewable Energy. *Cross Current International Journal of Economics, Management and Media Studies,* 1(6), pp. 114-123.

Barzola-Monteses, J. & Espinoza-Andaluz, M., 2019. *Performance analysis of hybrid solar/H2/battery renewable energy system for residential electrification..* Hong Kong, China , Elsevier, pp. 9-14.

Beck, F. & Martinot, E., 2004. Renewable energy policies and barriers. *Encyclopedia of Energy,* Volume 5, pp. 365-383.

Bhatia, A., 2018. *Design and Sizing of Solar Photovoltaic Systems.* Benoni, Johannesburg, South Africa: Continuing Education and Development, Inc. .

Boxwell, M., 2010. *Solar electricity handbook: A simple, practical guide to solar energy-designing and installing photovoltaic solar electric systems.* 2010 ed. Birmingham United Kingdom: Greenstream publishing.

Burns, J. E. & Kang, J.-S., 2012. Comparative economic analysis of supporting policies for residential solar PV in the United States: Solar Renewable Energy Credit (SREC). *energy policy,* Volume 44, pp. 217-225.

Chalmers, R., 2001. *Eskom's generation division gets new look,* Johannesburg, South Africa: Business Day,.

Chand, A. A. et al., 2019. Adoption of grid-tie solar system at residential scale. *Clean Technologies,* 1(1), pp. 224-231.

CPI, 2023. *Consumer Price Index,* Pretoria: Stats SA.

Dash, R., Behera, L., Mohanty, B. & Hota, P. K., 2018. *Cost and sensitivity analysis of a microgrid using HOMER-Pro software in both grid-connected and standalone mode.* Bhubaneswar, India., IEEE, pp. 3444-3449.

© University of Venda

DME, 2021. *THE SOUTH AFRICAN ENERGY SECTOR REPORT,* s.l.: Department of Mineral Resources & Energy.

Edenhofer, O. et al., 2011. special report on renewable energy sources and climate change mitigation. *IPCC,* pp. 1-41.

Elsässer, J., Hickmann, T. & Fee, S., 2018. The role of cities in South Africa's energy gridlock. *Case Studies in the Environment,* 2(1), pp. 1-7.

El-Shater, T. F., Eskander, M. N. & El-Hagry, M. T., 2006. Energy flow and management of a hybrid wind/PV/fuel cell generation system. *International Journal of Sustainable Energy,* 25(2), pp. 91-106.

ENERGY, O., 2003. *WHITE PAPER ON RENEWABLE ENERGY,* Pretoria: DME(Department of Minerals and Energy).

Eskom, 2023. *TARIFFS & CHARGES BOOKLET,* Johannesburg,: www.eskom.co.za/tariffs.

Franklin, E., 2017. *Types of Solar Photovoltaic Systems.* Tucson, AZ: College of Agriculture, University of Arizona .

Garcia, R. S. & Weisser, D., 2006. A wind–diesel system with hydrogen storage: Joint optimisation of design and dispatch. *Renewable energy,* Volume 31(14), pp. 2296-2320.

Garg, A., Naswa, P. & Shukla, P., 2015. Energy infrastructure in India: profile and risks under climate change. *Energy Policy,* Volume 81, pp. 26-38.

Gbadamosi, S. L. & Nwulu, N. I., 2022. Optimal Configuration of Hybrid Energy System for Rural Electrification of Community Healthcare Facilities. *Applied Sciences,* 12(9), pp. 42-62.

Ghouse, M., 2012. Fuel cells and their aplications.

Gissey, G. C., Dodds, P. E. & Radcliffe, J., 2018. Market and regulatory barriers to electrical energy storage innovation. *Renewable and Sustainable Energy Reviews,* Volume 82, pp. 781-790.

Hames, Y., Kaya, K., Baltacioğlu, E. & Turksoy, A., 2018. Analysis of the control strategies for fuel saving in the hydrogen fuel cell vehicles.. *Int. J. Hydrog. Energy,* p. 10810–10821.

Hansen, J. et al., 2000. Global warming in the twenty-first century : An alternative scenario. *Proceedings of the National Academy of Sciences,* 97(18), pp. 9875-9880.

© University of Venda

Islam, F. & Mamun, K., 2017. *Possibilities and Challenges of Implementing Renewable Energy in the Light of PESTLE & SWOT Analyses for Island Countries.* Cham, Germany: Springer.

Jacobson, M. Z. et al., 2015. 100\% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy \& Environmental Science,* 8(7), pp. 2093--2117.

Jain, J., Khambhawala, A. & Kumar, R., 2023. Hydrogen Towards a Sustainable Energy Future-The Indian Scenario.. *International Journal for Research in Applied Science & Engineering Technology (IJRASET),* 11(VII).

Kacare, M., Pakere, I., Gravelsins, A. & Blumberga, A., 2022. Impact Assessment of the Renewable Energy Policy Scenarios–a Case Study of Latvia. *Environmental and Climate Technologies,* 26(1), pp. 98-1019.

Kariuki, D., 2018. *Barriers to renewable energy technologies development,* Keele , UK: Keele University.

Kartik, J. & Karan, J., 2021. Hydrogen Fuel Cell: A Review of different types of fuel Cells with Emphasis on PEM fuel cells and Catalysts used in the PEM fuel cell. *International Journal of All Research Education and Scientific Methods (IJARESM),* 9(9).

Khan, M. & Iqbal, M., 2005. Dynamic modeling and simulation of a small wind-fuel cell hybrid energy system. *Renewable energy,* 30(3), pp. 421-439.

Koutroulis, E., Kolokosa, D., Potirakis, A. & Kazantzakis, K., 2006. Methodology for optimal sizing of standalone photovoltaic/wind-generator systems using genetic algorithms,. *Solar Energy,* Volume 80, pp. 1072-1088.

Kumar, B. S. & Sudhakar, K., 2015. Performance evaluation of 10 MW grid-connected solar photovoltaic power plant in India.. *Energy Reports,* Volume 1, pp. 184-192.

Lal, S. & Raturi, A., 2012. Techno-economic analysis of a hybrid mini-grid system for Fiji islands. *International Journal of Energy and Environmental Engineering,* Volume 3, pp. 1-10.

Lambert, T., Gilman, P. & Lilienthal, P., 2006. Micropower system modeling with HOMER. Em: F. A. Farret & M. G. Simões, edits. *Integration of Alternative Sources of Energy.* Hoboken, NJ, USA: John Wiley & Sons, pp. 379-385.

© University of Venda

Liu, G., Rasul, M., Amanullah, M. & Khan, M., 2010. *AHP and fuzzy assessment-based sustainability indicator for a hybrid renewable energy system.* Christchurch, New Zealand., Institute of Electrical and Electronics Engineers (IEEE), pp. 1-6.

Luthra, S., Kumar, S., Garg, D. & Haleem, A., 2015. Barriers to renewable/sustainable energy technologies adoption: Indian perspective. *Renewable and sustainable energy reviews,,* Volume 41, pp. 762-776.

Maddileti, T. & Cherukuri, L., 2019. Review on types of solar power systems. *Journal of Engineering Sciences.,* 10(10), pp. 1-4.

Marais, S., 2019. *Optimal Energy Management In A Smart Home, Based On Photovoltaic Systems Energy Feed-In Tariff: Case Of South Africa,* Free State: Central University of Technology.

Masrur, H. et al., 2020. Analysis of techno-economic-environmental suitability of an isolated microgrid system located in a remote island of Bangladesh. *Sustainability,* 12(7), p. 2880.

Masrur, H. et al., 2021. Assessing the Techno-Economic Impact of Derating Factors on Optimally Tilted Grid-Tied Photovoltaic Systems. *Energies,* 14(4), p. 1044.

Mataboge, M., Kidundhuhu, N., Mathumba, P. & Togba, A., 2021. *REGULATION FOR SUSTAINABLE FOR SUSTAINABILITY DEVELOPMENT GOAL 7,* Cape Town, South Africa: THE SOUTH AFRICAN POWER SECTOR.

Mathew, M. et al., 2022. Sizing approaches for solar photovoltaic-based microgrids: A comprehensive review. *Institute of Electrical Engineering and Technology (IET) Energy Systems Integration,* 4(1), pp. 1-27.

Ma, W., Fan, J., Fang, S. & Liu, G., 2019. Techno-economic potential evaluation of small-scale grid-connected renewable power systems in China. *Energy Conversion and management,* Volume 196, p. 430–442.

Okedu, K., Uhunmwangho, R. & Bassey, N., 2015. A Comparative Study of on and off Grid Tied Integrated Diesel Solar PV Generation System. *INTERNATIONAL JOURNAL OF ENGINEERING TECHNOLOGIES,* 1(1), pp. 19-25.

Oladigbolu, J. A.-T. Y. a. O. L., 2021. Comparative study and sensitivity analysis of a standalone hybrid energy system for electrification of rural healthcare facility in Nigeria.. *Alexandria Engineering Journal,* Volume 60(6), pp. 5547-5565.

© University of Venda

Oladigbolu, J. O., Al-Turki, Y. A. & Olatomiwa, L., 2021. Comparative study and sensitivity analysis of a standalone hybrid energy system for electrification of rural healthcare facility in Nigeria. *Alexandria Engineering Journal,* 60(6), pp. 5547-5565.

Olatomiwa, L., Mekhilef, S., Huda, A. N. & Sanusi, K., 2015. Techno-economic analysis of hybrid PV-diesel-battery and PV-wind-diesel-battery power systems for mobile BTS: the way forward for rural development. *Energy Science & Engineering,* 3(4), pp. 271--285.

Parida, B., Iniyan, S. & Goic, R., 2011. A review of solar photovoltaic technologies}. *Renewable and sustainable energy reviews,* 15(3), pp. 1625-1636.

Pillai, G. G., Putrus, G. A., Georgitsioti, T. & Pearsall, N. M., 2014. Near-term economic benefits from grid-connected residential PV (photovoltaic) systems. *Energy,* Volume 68, pp. 832-843.

Polo, A. L. & Haas, R., 2014. An international overview of promotion policies for grid-connected photovoltaic systems.. *Progress in Photovoltaics: Research and Applications,* 22(2), pp. 248-273.

Prasad, R. & Raturi, A., 2017. Grid electricity for Fiji islands: Future supply options and assessment of demand trends. *Energy,* Volume 119, p. 860–871.

Rahman, M. M., Islam, M. A., Karim, A. & Ronee, A. H., 2012. Effects of natural dust on the performance of PV panels in Bangladesh. *International Journal of Modern Education and Computer Science,* 4(10), p. 26.

Raturi, A., Singh, A. & Prasad, R., 2016. Grid-connected PV systems in the Pacific Island Countries.. *Renewable and Sustainable Energy Review,* Volume 58, p. 419–428.

Rondganger, L., 2023. The year we were plunged into darkness: A record 332 days of load shedding in 2023 and counting. *Independent OnLine (IOL) a leading platform for news, current affairs and content in South Africa.* , 11 December.

Samaniego, J. et al., 2008. Economic and technical analysis of a hybrid wind fuel cell. *Renewable energy,* 33(5), pp. 839-835.

SARB, 2024. *MONETARY POLICY REVIEW,* Pretoria: South African Reserve Bank (SARB).

Sawle, Y., Gupta, S. C., Kumar, B. A. & Meng, W., 2016. “PV-wind hybrid system: a review with case study. *Cogent Engineering,* Volume 3.

© University of Venda

Sen, S. et al., 2016. Renewable energy scenario in India: opportunities and challenges. *Journal of African Earth Sciences,* Volume 122, p. 25–31.

Simon, Müller, Brown, A. & Ölz, S., 2011. Policy Considerations for Deploying Renewables. Em: *Deploying Renewables.* Paris : International Energy Agency, pp. 65-106.

Sukamongkol, Y., Chungpaibulpatana, S. & Ongsakul, W., 2002. A simulation model for predicting the performance of a solar photovoltaic system with alternating current loads. *Renewable energy,* 27(2), pp. 237-258.

Suresh, V., Muralidhar, M. & Kiranmayi, R., 2020. Modelling and optimisation of an off-grid hybrid renewable energy system for electrification in a rural areas. *Energy Reports,* Volume 6, pp. 594-604.

Thanaa, F., Eskander, M. & El-Hagry, M. T. (., 2006. Energy flow and management of a hybrid wind/PV/fuel cell generation system. *Energy conversion and management,* Volume 47(9-10), pp. 1264-1280.

Tomar, V. & Tiwari, G. N., 2017. Techno-economic evaluation of grid-connected PV system for households with feed-in tariff and time of day tariff regulation in New Delhi–A sustainable approach. *Renewable and Sustainable Energy Reviews,* Volume 70, pp. 822-835.

Tomasov, M., Kajanova, M., Bracinik, P. & Motyka, D., 2019. *Overview of battery models for sustainable power and transport applications.* Stary Smokovec, Slovakia., s.n., pp. 548-555.

Torcellini, P., Pless, S., Deru, M. & Crawley, D., 2006. *Zero Energy Buildings: A Critical Look at the Definition.* Golden, CO (United States), National Renewable Energy Lab(NREL), pp. 550-39833.

Tsoutsos, T., Frantzeskaki, N. & Gekas, V., 2005. Environmental impacts from the solar energy technologiesEnergy policy. *Elsevier,* 33(3), pp. 289-296..

Usman, M., Khan, M., Rana, A. & Ali, S., 2018. Techno-economic analysis of hybrid solar-diesel-grid connected power generation system. *Journal of Electrical Systems and Information Technology,* 5(3), pp. 653-662.

Warrick, P. & Monique, L.-R., 2023. *Statistics of utility-scale power generation in South Afrrica (1 January - 31 December 2022),* Petroria: CSIR Energy Centre .

website., s.d. *"EERE ,Department of enegy".* [Online].

© University of Venda

Winkler, H., 2005. Renewable energy policy in South Africa: policy options for renewable electricity. *Energy policy,* 33(1), pp. 27-38.

Yaqoot, M., Diwan, P. & Kandpal, T. C., 2016. Review of barriers to the dissemination of decentralized renewable energy systems. .*Renewable and Sustainable Energy Reviews,* Volume 58, pp. 477-490.

Zhao, D., Qian, M., Ma, J. & Yamashita, K., 2020. Photovoltaic generator model for power system dynamic studies. *Solar Energy,* Volume 210, pp. 101-114.

© University of Venda