Cape Peninsula University of Technology

TECHNO-ECONOMIC FEASIBILITY STUDY OF A SOLAR PHOTOVOLTAIC SYSTEM WITH BATTERY BACKUP FOR COMMERCIAL APPLICATIONS

by

RUTENDO ROSE NZUWA

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Supervisor: Prof B Yan
Co-supervisors: Dr R Muvunzi and Prof S Krishnamurthy

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DECLARATION

I, Rutendo Rose Nzuwa, declare that the contents of this dissertation represent my own unaided work, and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

24 March 2025

Signed **Date**

ABSTRACT

This research study explores the techno-economic feasibility of implementing a solar photovoltaic (PV) system with battery backup for commercial use in Cape Town, South Africa. Addressing the energy challenges, particularly load-shedding, it determines system performance and cost-effectiveness. The primary research question revolves around identifying the optimal configuration of a solar PV system with battery backup, considering energy consumption patterns, and other site-specific factors like climatology data. Literature gaps in adequately addressing the techno-economic assessment of solar PV systems with battery storage for commercial use in South Africa exist. A literature review of the system components, effects of factors affecting technical performance as well as similar previous studies was conducted. The employed approach involves using simulation tools like PVSyst to determine the system's output and configuration and conducting a techno-economic analysis to determine its viability. The methodology involves using monthly electricity consumption data from a commercial site in Cape Town and utilising PVSyst to estimate energy yields, performance ratios, and system losses. The technical analysis formed the basis of system sizing and configuration, with a bill of quantities compiled to estimate system capital costs. The designed system, with an 82.2% performance ratio, includes two 50 kVA hybrid inverters, a 102 kWp solar panel array and 80 kWh energy storage. Economic analysis, using customised Excel worksheets, evaluated the project's net present value (NPV) of R45 358 870.35, internal rate of return (IRR) of 27.55% and a discounted payback period (DPP) of 3.4 years. Ethical considerations ensure transparency and integrity. Anticipated outcomes include insights into solar PV system yields, performance ratios, and economic viability, aiding decision-making for stakeholders and promoting renewable energy adoption. The findings aim to inform the adoption of renewable energy solutions in South Africa, contributing to the sustainable energy transition.

Keywords:

Techno-economic feasibility; solar photovoltaic system; battery backup; energy security; load-shedding; simulation tools; cost analysis; renewable energy.

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First and foremost, I would like to thank God the Almighty for His guidance and provision throughout this journey.

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LIST OF ABBREVIATIONS

AFDBG	African Development Bank Group
COGTA	Cooperative Governance and Traditional Affairs
CSIR	Council for Scientific and Industrial Research
FISE	Fraunhofer Institute for Solar Energy
IBR	Inverted box rib
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal rate of return
NPV	Net Present Value
SARB	South African Reserve Bank
PV	Photovoltaic

CHAPTER ONE

INTRODUCTION

1.0 Introduction and motivation

By 2030, a 21% surge in the total global energy demand is expected due to population growth (International Energy Agency, 2014). Singh *et al.* (2019) noted that energy is essential for industrialization and economic growth. Eskom, South Africa’s state-owned enterprise, has a monopoly in power generation with minimal competition from independent power producers. South Africa’s electricity supply mix is largely coal-dominated with a contribution exceeding 80% of the total energy whilst there is an increase in diesel usage (CSIR, 2023). Figure 1.1 shows South Africa’s electricity supply mix breakdown by energy sources.

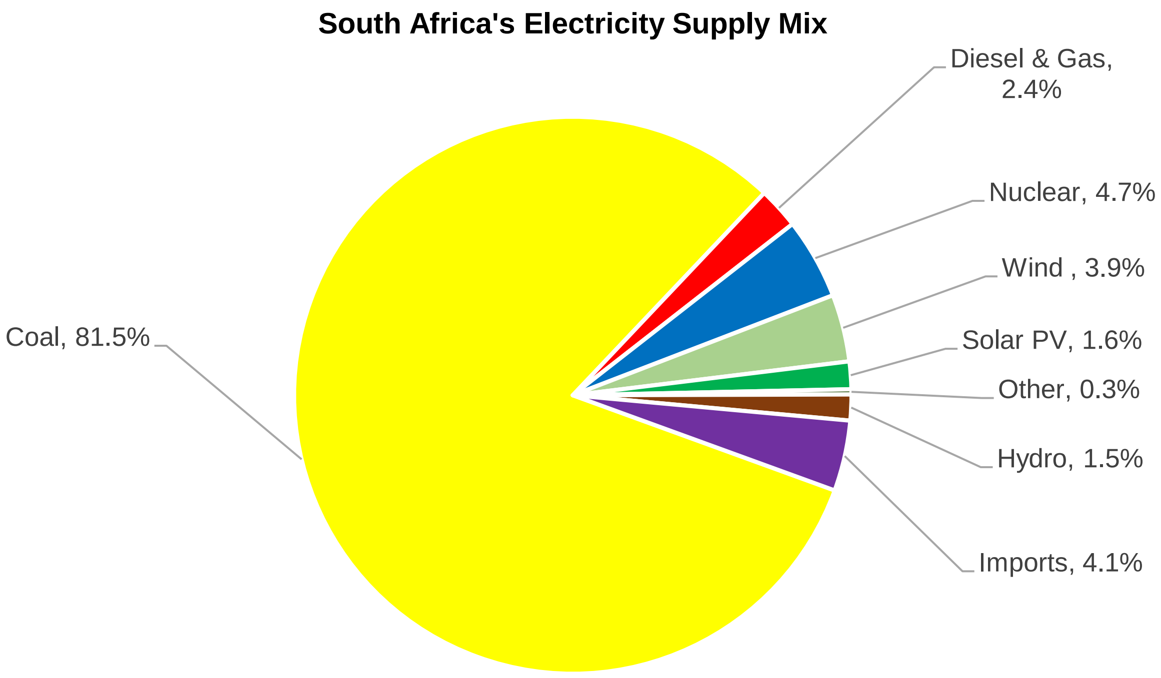

Figure 1.1 The electricity supply mix for South Africa (GreenCape, 2024).

Electricity demand has gradually outweighed its supply. The country’s traditional electricity generation equipment is ageing resulting in frequent failures and is usually non-functional for maintenance repairs. Electricity supply shortage is arguably South Africa’s pressing challenge. Eskom has resorted to supply interruptions as a reaction to the supply-demand imbalance. The phenomenon is termed as “load-shedding”. Despite prior notification in time, some of the interruptions are sudden resulting in customer inconvenience. The energy availability factor for the utility’s generation architecture has been gradually decreasing over the years as shown in Figure 1.2. This implies power supply unpredictability leaving consumers vulnerable to electricity supply interruptions.

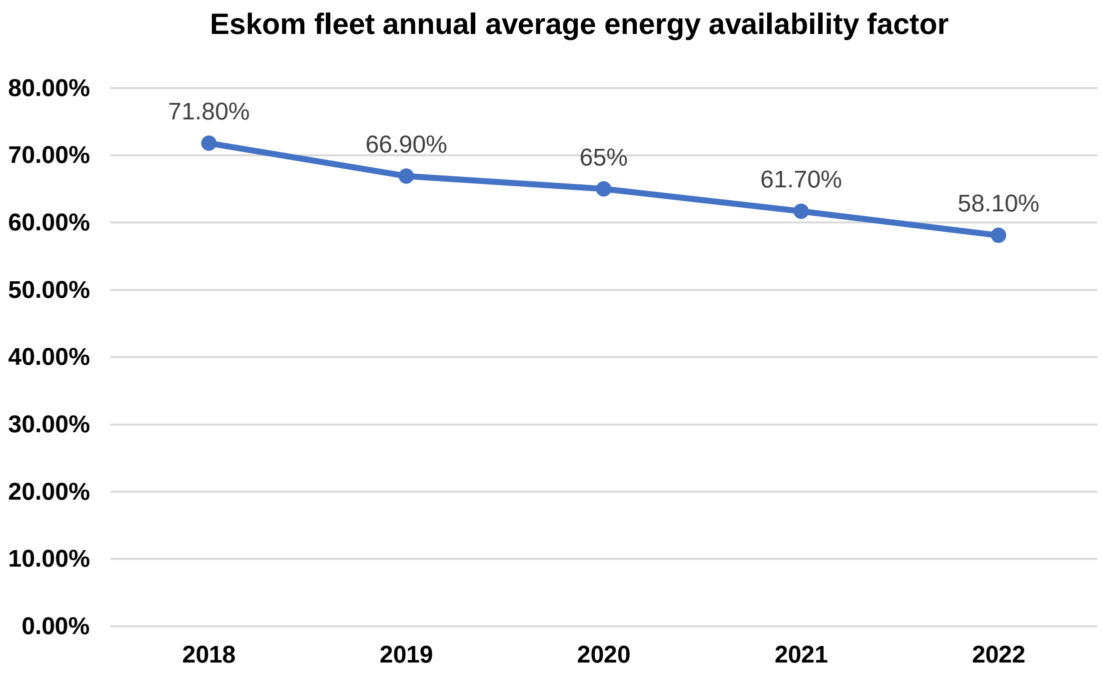

Figure 1.2 Eskom generation annual average energy availability factor (CSIR, 2023).

The Frequent load-shedding incidents of varying durations have adversely impacted the economy. The load-shedding events have spelt a power supply crisis for the country. In Figure 1.3, the historical annual outage hours from 2014 to 2022 are shown. For instance, the comparison between the total annual outage periods experienced in 2021 and 2022 shows that the outage time has more than quadrupled.

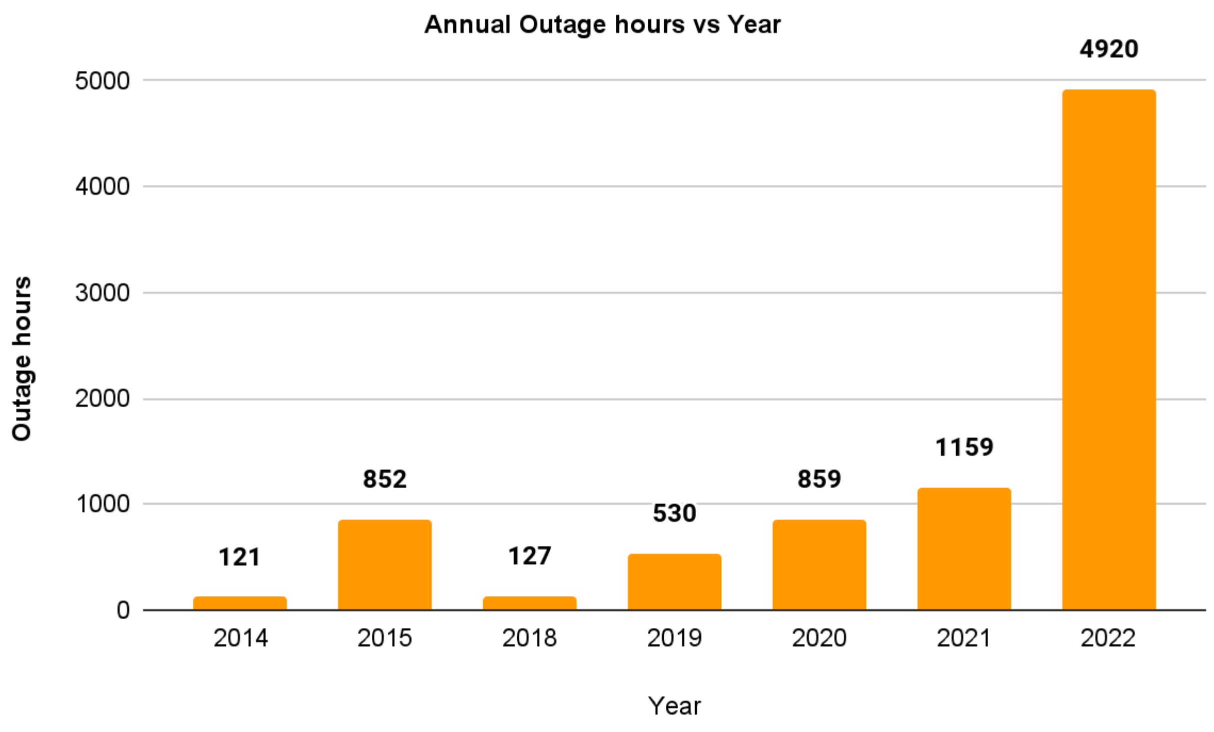

Figure 1.3 Historical annual outage hours for South Africa (Africa Energy Chamber, 2023).

The African Development Bank Group (ADBG) (2023) suggested that prior to the COVID-19 pandemic, the estimated economic losses attributed to load-shedding ranged between R59 Billion to R128 billion. This corresponded to 1 – 2.2% of the country's gross domestic product (ADBG, 2023). The electricity tariff in South Africa has been increasing over the years in consultation with the National Energy Regulator of South Africa (NERSA). A few months ago, the electricity price per kWh increased by 9.61% (Eskom, 2022). Figure 1.4 shows the historical average electricity tariff. Cloete *et al.* (2011) noted that the electricity tariff increases and the need for sustainable electricity supply are key drivers for companies opting for self-generation energy technologies.

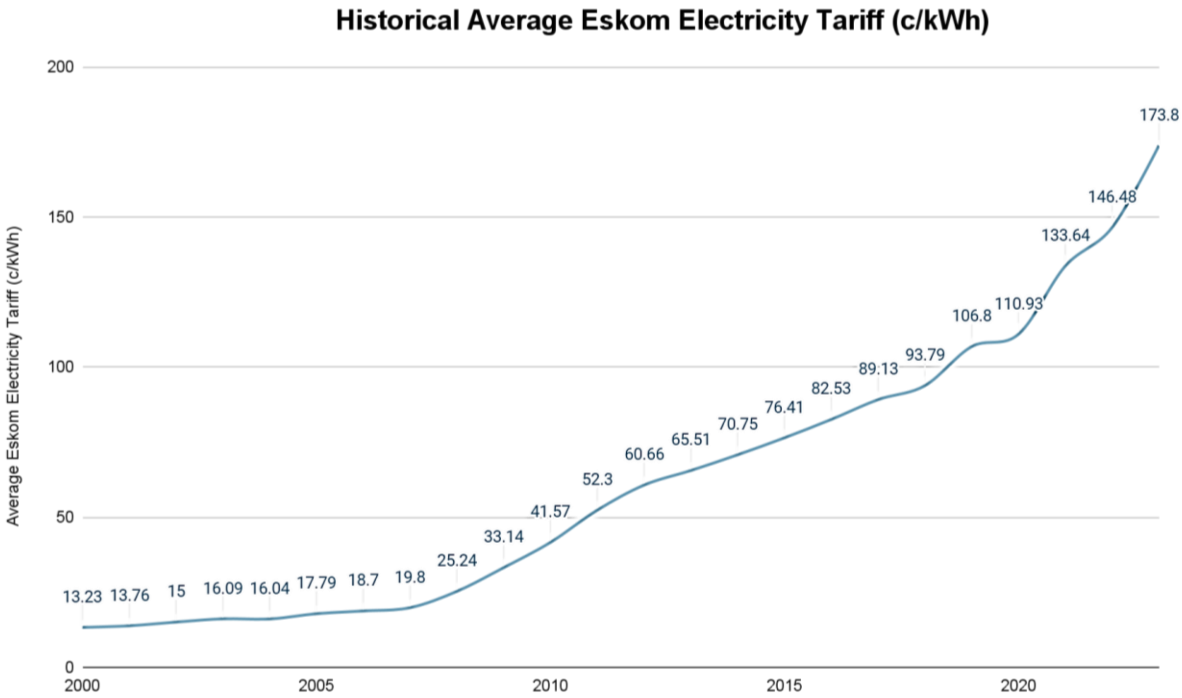

Figure 1.4 Historical average Eskom electricity tariff (c/kWh) (African Energy Chamber, 2023).

The global market influences the price of goods and services in the local market. The global fuel price volatility leads consumers to pay more for goods and services. In the past few months, fuel price hikes have been influenced partly by the ongoing Ukraine-Russia impasse (South African Reserve Bank, 2022). Diesel fuel is usually the fuel of choice to run backup generators during periods of interrupted power supply. Figure 1.5 shows the diesel fuel pricing volatility. These diesel pricing fluctuations affect the energy costs and ultimately an organisation's bottom line.

Umar and Kunda-Wamuwi (2019) noted that load-shedding has negative socioeconomic effects on consumers including businesses. IRENA (2022) suggests that consumers' use of renewable energy lessens their vulnerability to global hikes. Over the past decade, renewables have developed from niche technology to a global industry. The World Bank (2018) suggested that economic development and general social welfare can be hampered by the lack of a dependable, sustainable, and affordable power supply. Green Cape (2020) noted that the government of

South Africa has introduced a tax incentive of 28% of the total cost of a new commercial or industrial solar photovoltaic PV plant.

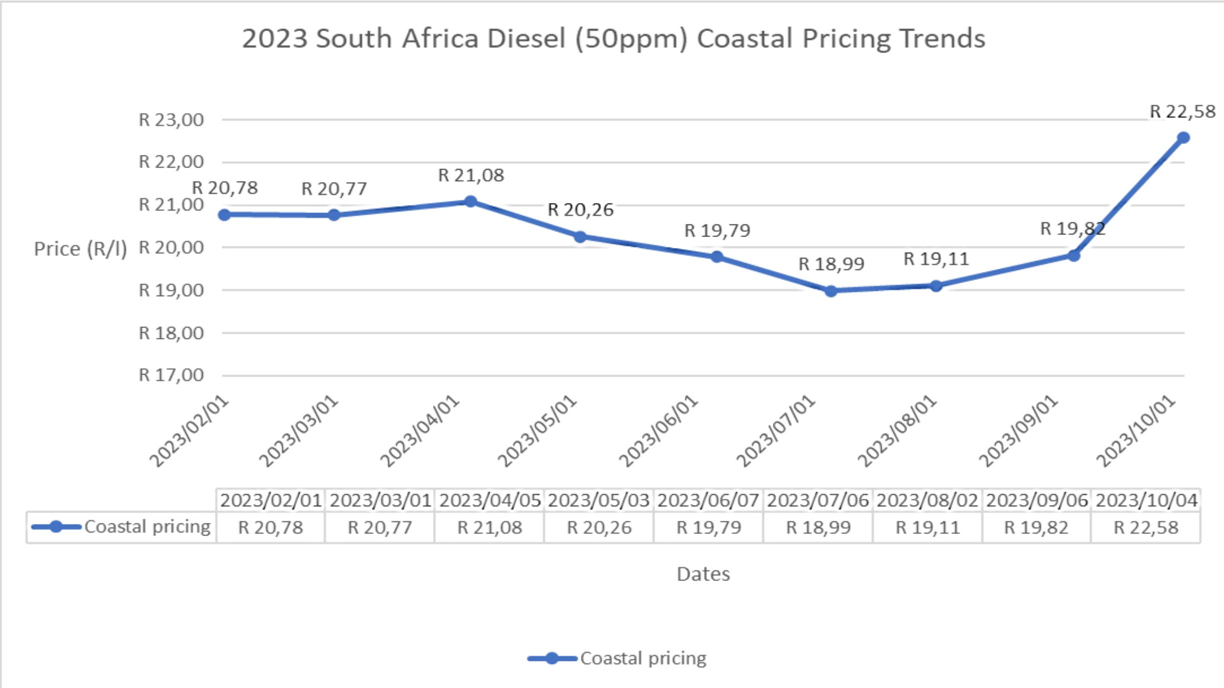

Figure 1.5 South Africa diesel coastal pricing (AASA, 2023).

Eskom has implemented load-shedding stages up to stage 8, with each stage representing shedding in 1000MW increments, indicating higher severity with a higher amount of electricity curtailment during power shortages (African Energy Chamber, 2023). Figure 1.6 shows the estimated portion of offline users during different load-shedding stages.

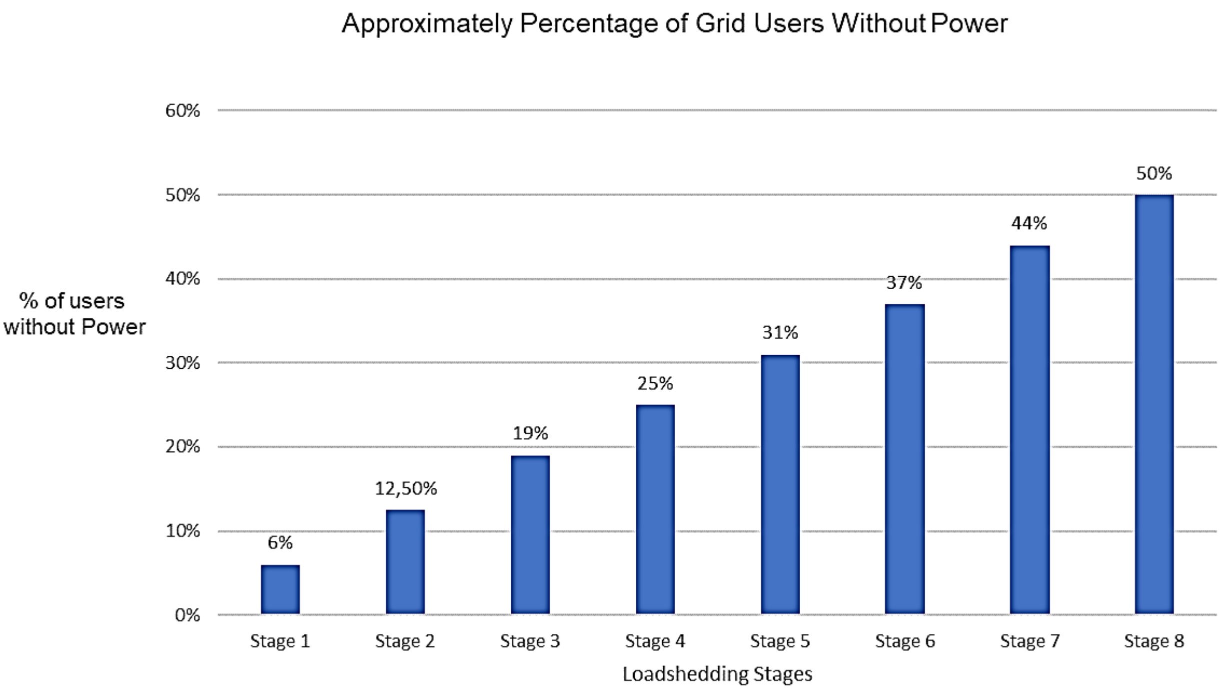

Figure 1.6 Approximate percentage of grid users without power during load-shedding stages (African Energy Chamber, 2023).

To combat the effects of load-shedding, there is a need for reliable alternative sources of energy which can sufficiently supply all year-round energy demand requirements. A total energy load assessment is important to determine the required system size with enough battery storage to last throughout load-shedding schedules. This necessitates the determination of the seasonal total energy load profiles. There is a need for a solution that best suits the dynamic load profile. The needs for the solar PV system include:

- Uninterrupted power supply
- Affordable power supply
- Elimination of potential downtime
- Sustainable energy source

Electricity supply is fundamentally essential for the financial performance and smooth running of any company's operations. The company relies on electricity for overall company productivity. An increase in the electricity tariff adversely affects the company's bottom line hence it is most likely to be passed onto the customer. This makes the company lose its competitive edge amid the existence of various players and the customers' low switching costs. The designed solar energy system helps lock the price by price-hedging thereby offsetting the risk of frequent tariff increases and taking advantage of the pro-renewable business environment.

1.1 Background to the research problem

A year-on-year slight increase of 2.1% in manufacturer's production capacity use was observed between in February 2022 (Statistics South Africa, 2022). IRENA (2022) noted that renewable energies enable sustainable socio-economic development. The Fraunhofer Institute for Solar Energy (FISE) (2015) projected that solar PV energy will become the cheapest electricity source globally. Over the years, the costs of associated products have declined owing to the industry's continuous development and breakthrough innovations. Ouedraogo and Yamegueu (2019) suggested that renewable energies are now widely accepted to provide energy security as an environmentally friendly alternative. Azeem *et al.* (2018) recommended solar energy PV systems due to their ease of installation, maintenance and subsequent control. Zabihi *et al.* (2012) noted that the modularity of solar PV systems enables custom sizing for different energy needs per site.

Thango and Bokoro (2022) acknowledged an enhanced business case for customers to switch to renewable energy supply for their daily power requirements. However, despite solar photovoltaic (PV) energy technologies being more common, there are challenges due to power supply intermittency and production losses (Hirth, 2015). Solar energy production fluctuations require prior forecasting adjustment (Hirth, 2015). Ouedraogo and Yamegueu (2019) postulated that grid-tied solar photovoltaic systems only produce energy subject to grid power supply availability. The solar PV hybrid systems include energy storage components to store excess energy during times of low energy demand for later use during load-shedding events. Installing

PV systems with energy storage components increases the overall economic benefits of solar systems. Kristiawan *et al.* (2018) recommended the use of batteries as energy storage devices in a hybrid solar PV system for enhanced system performance. The batteries are discharged to ensure sufficient power supply to the load in times of reduced solar PV energy generation and at nighttime (Thango and Bokoro, 2022). There is, however a need for appropriate solar PV system sizing to ensure improved power supply reliability.

The solar PV systems require high upfront costs, which are usually prohibitive. GreenCape (2020) studies show that solar PV systems below 500 kWp approximately have a capital cost of between R10 000 - R14 000 per kilowatt (kW). Mhundwa *et al.* (2020) conducted a case study for a 75 kWp fixed-tilt ground-mounted grid-tie system in the Eastern Cape, South Africa. The capital investment for the said system was approximately R26 667 per kW. This is way out of the range in contrast to what GreenCape (2020) reported. Mukisa *et al.* (2021) in a study recommended an energy business model they termed 'store-on grid' (SOG) as a win-win between the consumer and the utility. Under this model, also known in the South African context as 'net-metering', the consumer exports excess power produced from the solar PV system to the grid at the utility's discretion. The consumer is credited for the power exported which is offset against their usage thereby reducing their monthly electricity bill. GreenCape (2020) mentioned that this programme is available in more than half of the municipalities in the Western Cape including Cape Town's municipality. The feed-in tariff mechanism is one of the measures set to promote the use of solar PV technology (GreenCape, 2020). The scheme enables the utility to pay for the consumer-generated energy resulting in sustainable power supply through resource pooling.

Hirth (2015) argues cost-effectiveness of a technology doesn't imply its efficiency. Saleheen *et al.* (2021) stated that most prior studies premised on the performance evaluation of solar PV systems installed and usually operational for a maximum of two years. Furthermore, they argue that most technical and economic performance evaluation are usually conducted for large solar PV systems and hardly for small and medium ones. Edalati (2016) acknowledged the use of simulation software programs during feasibility studies of grid-connected PV systems. These PV simulation tools are used in the design and project planning of PV systems. Harder (2011) in a similar study used RETScreen simulation software to estimate energy yield projections and to determine the economic feasibility of a system. Kristiawan *et al.* (2018) used HOMER in preparing an optimal system design. Husain *et al.* (2021) used PVSyst for the analysis and design of a similarly sized solar PV system. In that study, PVSyst was used to estimate energy yield which was subsequently the basis for a financial analysis to determine the profitability evaluation for the system. Husain *et al.* (2021) conducted the study under a net-metering policy and concluded that the payback period was 8.4 years. Mhundwa et al. (2020) determined the simple payback period for their 75 kWp grid-tied system case study to be 6.44 years.

The researcher used PVSyst as the simulation software tool in this study.

Most solar PV systems installed in the commercial and industrial environment are rooftop-mounted. There have been other systems that have been installed with different configurations such as carports or ground mounted. Ghaleb and Asif (2021) explored the usability of rooftops for commercial solar PV systems based on satellite imagery data from Google Earth and the roof area. The researcher explored the different scenarios and determined the best solar PV system configuration.

1.2 Research study area context

The city of Cape Town's geographical coordinates is -33.88565671003413°, 18.52876621967593° and its city's map is shown in Figure 1.7. Cape Town experiences a typical Mediterranean climate characterised by cold rainy winters and dry (World Bank Group, 2021). The coastal city is Western Cape provincial capital, and a major economic hub ranked second in South Africa's economic contribution (Cooperative Governance and Traditional Affairs, 2020).

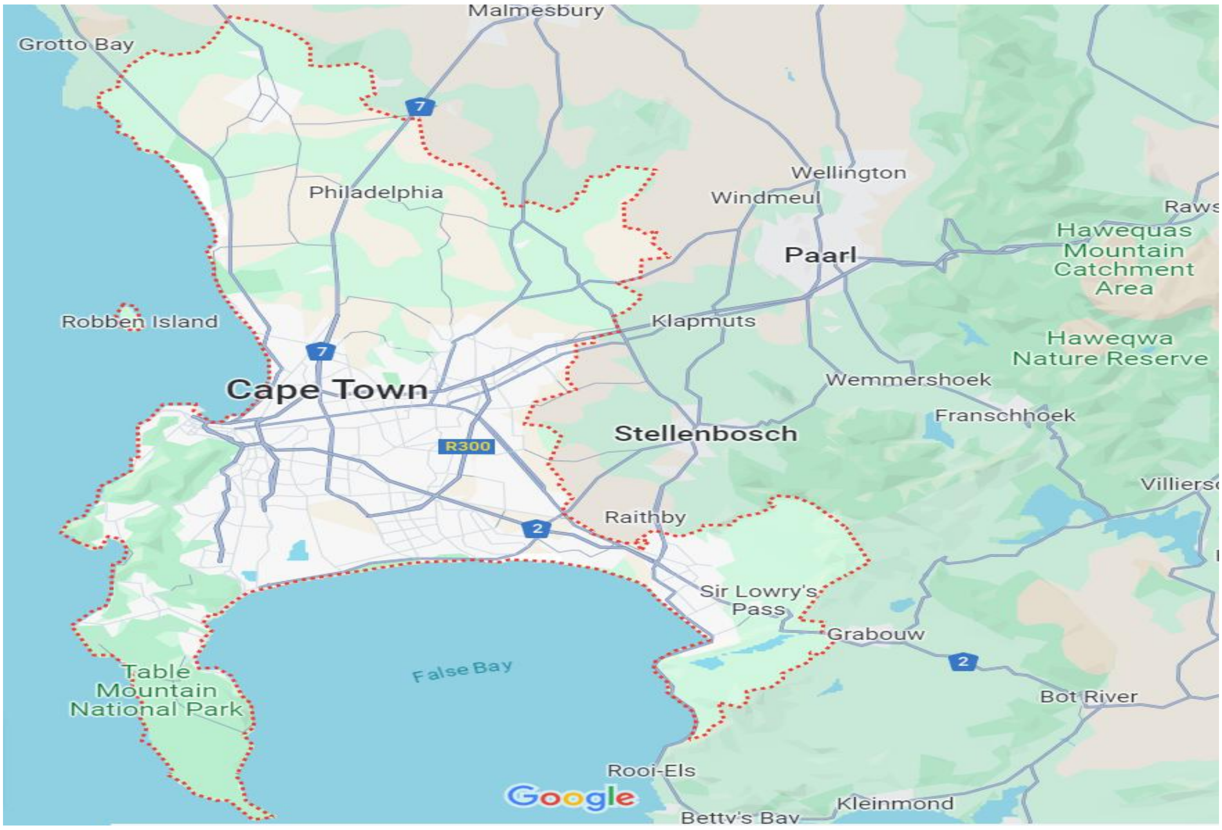

Figure 1.7 City of Cape Town map (Google, 2024).

Rapid urbanisation is ongoing in the Cape Town area resulting in population increases (COGTA, 2020). This implies there is an increased demand for services in the local economy. The historical and future projected population numbers are shown in Figure 1.8. Approximately seventy-three percent of the province's annual gross domestic product is attributed to the City of Cape Town (City of Cape Town, 2023). The city has various industrial zones which are crucial for the strategic development of the city's economy.

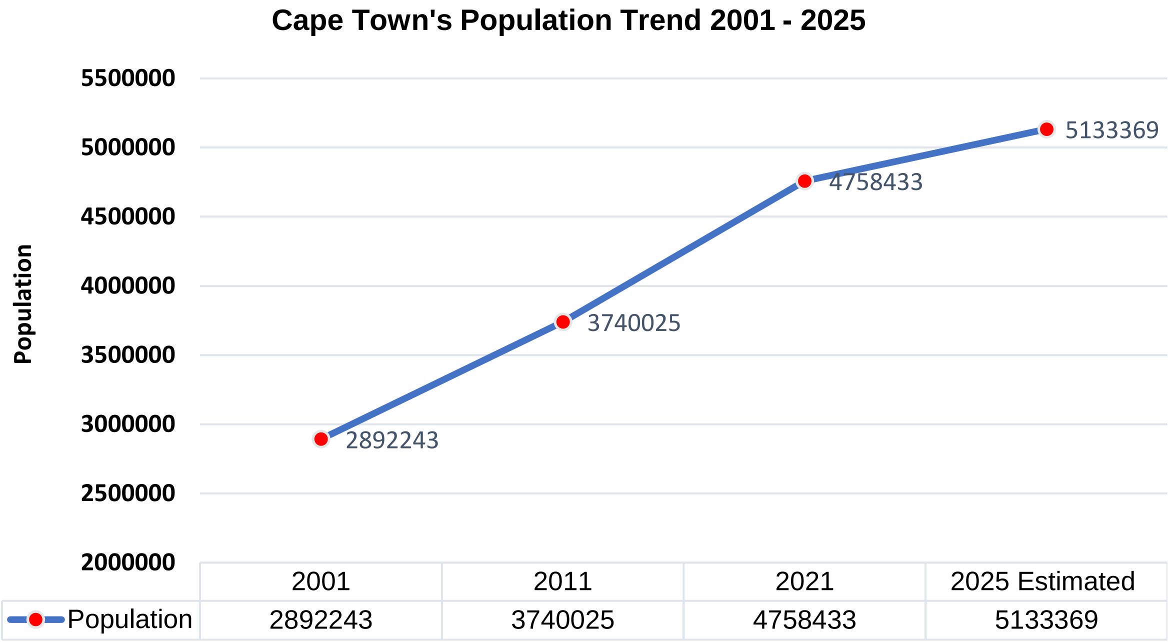

Figure 1.8 City of Cape Town population trends (COGTA, 2020; Western Cape Government, 2021).

One such industrial area is Blackheath situated on the outskirts of the City of Cape Town. The Blackheath industrial area has been touted as one of Cape Town metropolitan's most thriving industrial zones (City of Cape Town, 2017). Figure 1.9 shows the sectoral split of Blackheath's economic activity.

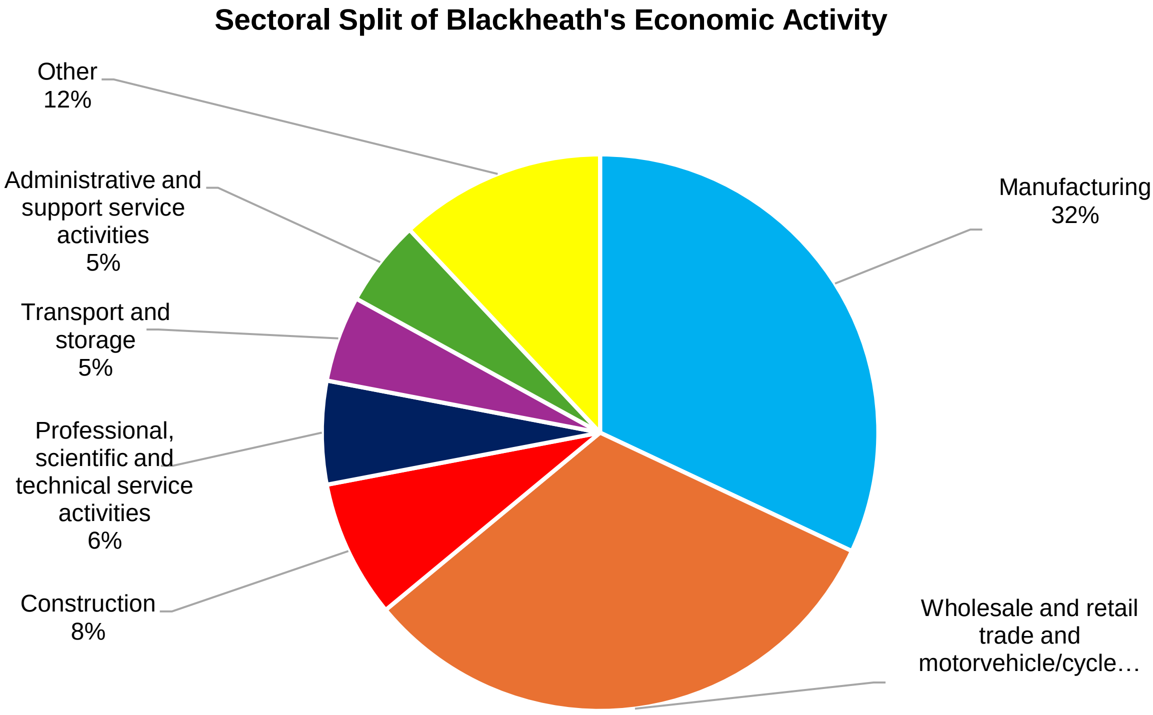

Figure 1.9 Sectoral split of Blackheath's economic activity (City of Cape Town, 2017).

1.3 Research problem statement

Frequent load-shedding has resulted in downtime and loss of revenue revealing a critical need for reliable and cost-effective energy solutions. During load shedding, diesel generators are unsustainable as a backup power source due to the increasing diesel and maintenance costs.

1.4 Associated research questions

1.4.1 Research question

Is it technically and economically viable to implement a solar photovoltaic system with battery backup for commercial applications?

1.4.2 Research investigative sub-questions

- What is the total energy consumed per month throughout the year and daily load profile for the site?
- How much is the energy generated by the PV system?
- What is the optimum size for the solar photovoltaic system and battery size?
- What is the payback period of the project?

1.5 Research aim

To assess the techno-economic feasibility of integrating solar PV hybrid systems with energy storage for commercial application.

1.5.1 Primary research objectives

The objectives of this research are to:

a. determine the total energy consumed in the selected study area;
b. audit the electricity generated by the PV system; and.
c. evaluate the economic viability of the solar PV system.

1.5.2 Assumptions

There are some assumptions identified for the research study to guide the analysis.

- The researcher assumes that the solar PV market conditions will maintain relative stability throughout the study period, allowing for accurate cost estimations.
- The energy consumption profile and patterns of the reference commercial site under study are assumed to remain consistent over the analysis period.

- The researcher further assumes that the performance of the designed solar PV system components is in conformance with the manufacturer's specifications and ratings.
- The researcher assumes that there will be no significant technological failures and/or ground-breaking discoveries during the project's operational period.
- The researcher assumes that there will be no significant changes to the regulatory and economic environment in South Africa which could affect the feasibility analysis during the study period.

1.5.3 Delimitations

The research study's delimitations are stated below.

- The research study is limited to a reference in Cape Town, South Africa which may not be representative of other regions with different solar irradiation levels or regulatory frameworks.
- The research focuses specifically on a solar PV system with battery backup for a commercial site.
- The analysis is conducted over a specific time frame of 20 years.
- The study relies on data sources for energy consumption, prevalent solar PV component market prices, and performance metrics from the PVSyst simulation tool.

1.5.4 Hypothesis

The research's primary hypothesis suggests that the installation of a solar PV system with battery backup for commercial applications results in significant cost savings for the end-user. In addition, the secondary hypothesis suggests that the financial viability of the designed solar PV system project with an internal rate of return (IRR) exceeding the prevalent interest rate.

1.6 The Research Process

The research work was conducted by following distinct steps which are all critical to the overall output. The tasks include:

- Problem Identification.
- Literature review.
- Research question and objectives formulation.
- Research design.
- Data collection.
- Data analysis.
- Summary of findings and drawing of conclusions.
- Peer review and final report compilation.

The research methodology diagram is shown in Figure 1.10 illustrating the structured approach in executing this study. The structured methodology aimed to ensure a systematic evaluation of the solar PV system's techno-economic viability.

1.7 Dissertation Breakdown

The dissertation's chapters form the building blocks with each section contributing to achieving the research aim. The dissertation breakdown is as follows: -

Chapter 1: Introduction

The research topic is introduced in the chapter. South Africa's energy challenges and prevalent electricity supply scenario are outlined, unpacking the load-shedding and energy insecurity threat. In Chapter 1, the need for reliable energy solutions is established. The research problem, hypothesis, objectives and the research process are presented.

Chapter 2: Literature review

Chapter 2 focuses on the review of the solar PV systems existing literature and their economic feasibility. In addition, current literature gaps focusing on the techno-economic assessment of solar PV systems in commercial applications, which the research seeks to address are identified. The different system components, performance metrics and economic analysis methods are explored in this chapter.

Chapter 3: Research design and methodology

This chapter focuses on the study's research design and methodology. The overall approach, data collection methods, and tools used for simulations and analyses are described. Each of the research objectives is unpacked and the methods taken to achieve them are detailed. The chapter forms the research study's framework.

Chapter 4: Simulation

The outcomes of the conducted simulations and analyses are outlined in Chapter 4. Further analysis of energy consumption patterns at the reference commercial site is conducted. The PVSyst simulation results and economic evaluations are also included. Key economic performance metrics such as net present value (NPV) and internal rate of return (IRR) are calculated. Subsequently, the sensitivity analyses on the results are conducted. The research findings are interpreted and discussed in relation to the research questions and objectives. It analyses how the results align with existing literature, highlighting the study's contributions to the field.

Chapter 5: Conclusion and Recommendations

The research's key findings and their significance are summarised. Recommendations for future study are included.

Chapter 1 provided a comprehensive contextual background for the study. The current energy scenario characterised by supply challenges and the need for sustainable power supply has been established. The research problem, objectives, and significance of the study were established. The next chapter explores the review of existing literature on solar PV systems and battery technologies. Current research gaps are identified preparing the framework for the study's methodology and analysis. The following chapter will explore the review of existing literature identifying the research gaps as well and establish a theoretical framework for the study.

Research methodology structure diagram

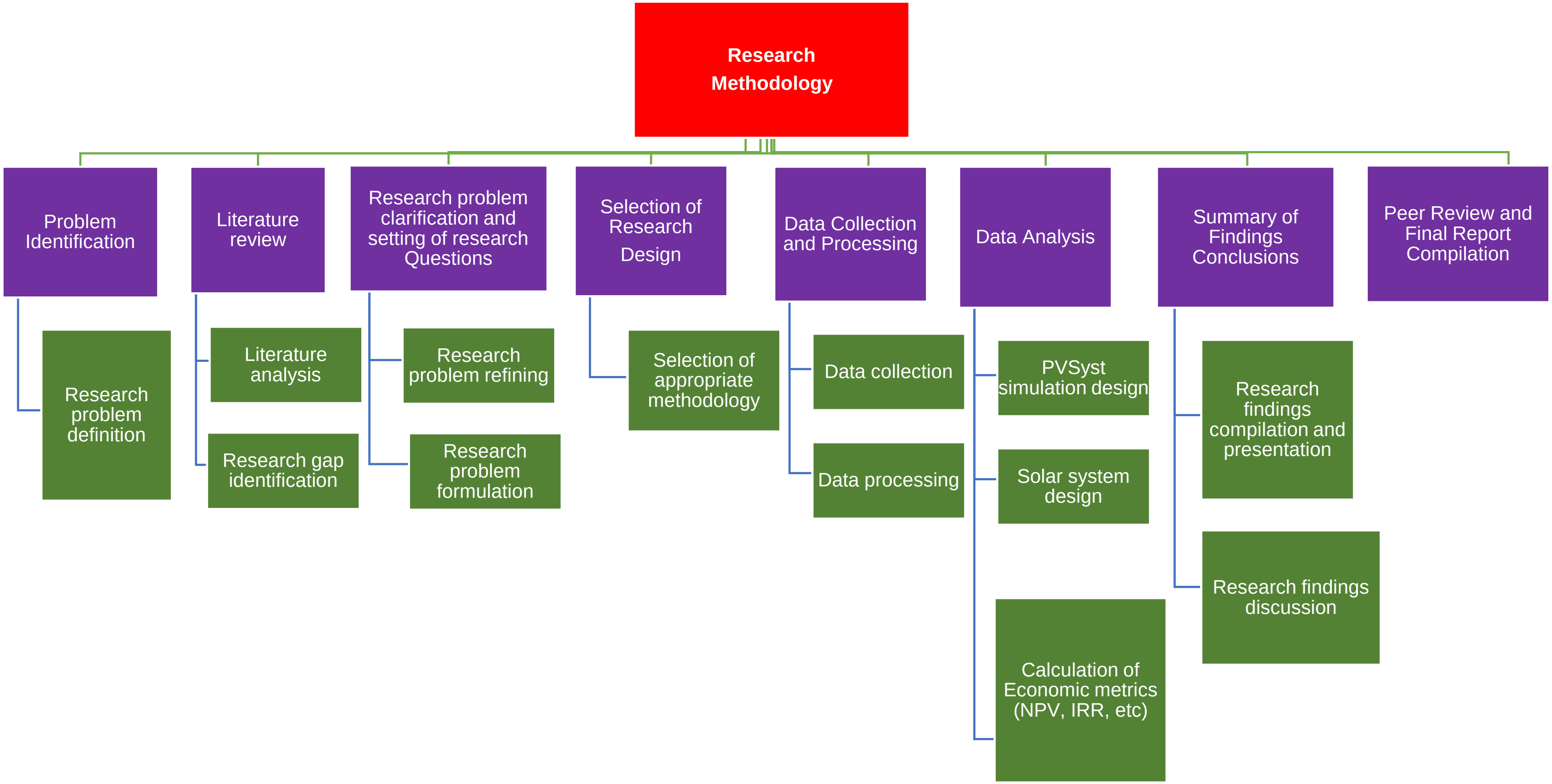

Figure 1.10 Research methodology structure diagram.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter focuses on a comprehensive literature review focused on solar photovoltaic (PV) systems and battery technologies essential for commercial applications. Figure 2.1 shows the research study's literature review diagram.

An overview of solar PV technology, discussing the fundamental principles of solar energy conversion, the various types of solar panels available, and their operational mechanisms. The chapter also explores the different applicable battery technologies used in solar PV hybrid systems unpacking their characteristics, advantages, and limitations.

Key system performance factors affect the reliability and efficiency of solar PV systems, such as system design, environmental conditions, and maintenance practices. Economic considerations are also evaluated, focusing on the financial implications of implementing solar PV systems, including cost analysis, return on investment, and available financial incentives.

The chapter identifies gaps in the existing research focusing on techno-economic assessments for solar PV systems with battery backup. This chapter provides a framework for the study's subsequent research methodology and analysis.

Literature review structure diagram

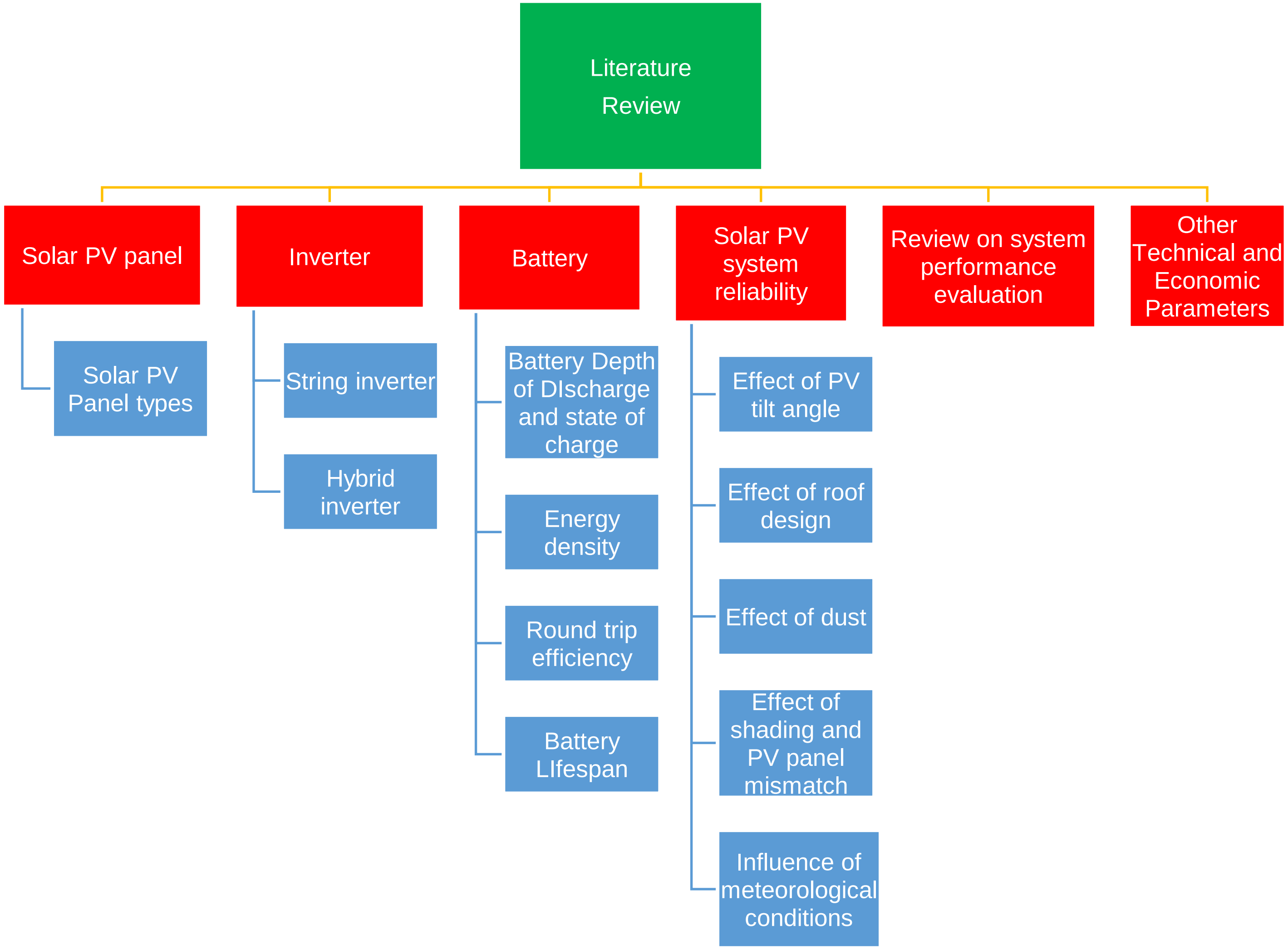

Figure 2.1 Literature review structure diagram.

A typical solar PV hybrid system or microgrid system comprises various energy sources that are interconnected to provide power to an off-taker or consumer. The various energy sources include: -

¶ Solar PV panels

¶ Inverter

¶ Batteries (Energy Storage).

The main components are discussed in detail in the following segments.

2.1 Solar panel

Adekanmbi *et al.* (2024) highlighted the solar panel as an integral part of a solar photovoltaic system. Venkateswari and Sreejith (2019) suggested that solar PV modules convert incident solar irradiation to direct current through the photovoltaic effect.

A solar photovoltaic (PV) panel is composed of individual PV cells typically connected in series and parallel (Ghosh and Yadav, 2021). In addition, Ghosh and Yadav (2021) noted that a PV array is formed when individual PV modules are connected in various configurations such as series and/or parallel. A string is formed when solar panels are in serial connection (Ghosh and Yadav, 2021). Each solar panel has various rating parameters such as open circuit voltage (V_{OC}), short circuit current (I_{SC}), voltage at maximum power point (V_{MPP}), and current at maximum power point (I_{MPP}). The length of a PV module string, dependent on the solar PV ratings, indicates the number of modules that are interconnected in series. The PV array is formed by connecting the separate solar PV strings in parallel as per the required design and ratings of other components to which they are connected.

There are various solar panel technologies on the market. Figure 2.2 shows the split of the different solar cell technology revealing the clear dominance of polycrystalline solar cells. Allouhi *et al.* (2022) and Venkateswari and Sreejith (2019) concurred that silicon-based (monocrystalline and polycrystalline) cells constitute approximately 90% of today's market share as shown in Figure 2.3. Allouhi *et al.* (2022) further noted that the monocrystalline cells are made of single crystalline wafers whilst the polycrystalline are made of multiple crystalline wafers.

Ghosh and Yadav (2021) concluded that improved solar PV cell efficiency increases the PV array output. Venkateswari and Sreejith (2019) added that monocrystalline solar panels are more efficient than polycrystalline solar panels emanating from the difference in their design and construction. Allouhi *et al.* (2022) concurred but however, mentioned that monocrystalline solar panels were more expensive than both polycrystalline and thin film solar panels.

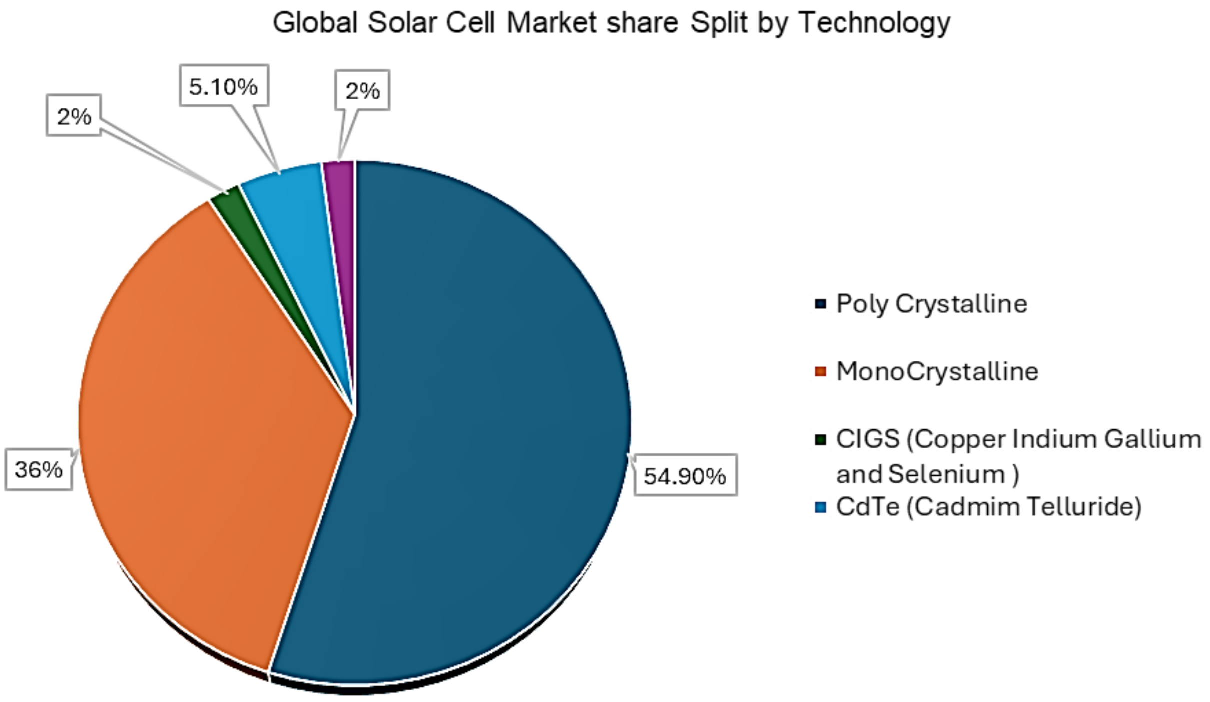

Figure 2.2 Breakdown of the global solar cell market share (Venkateswari and Sreejith, 2019).

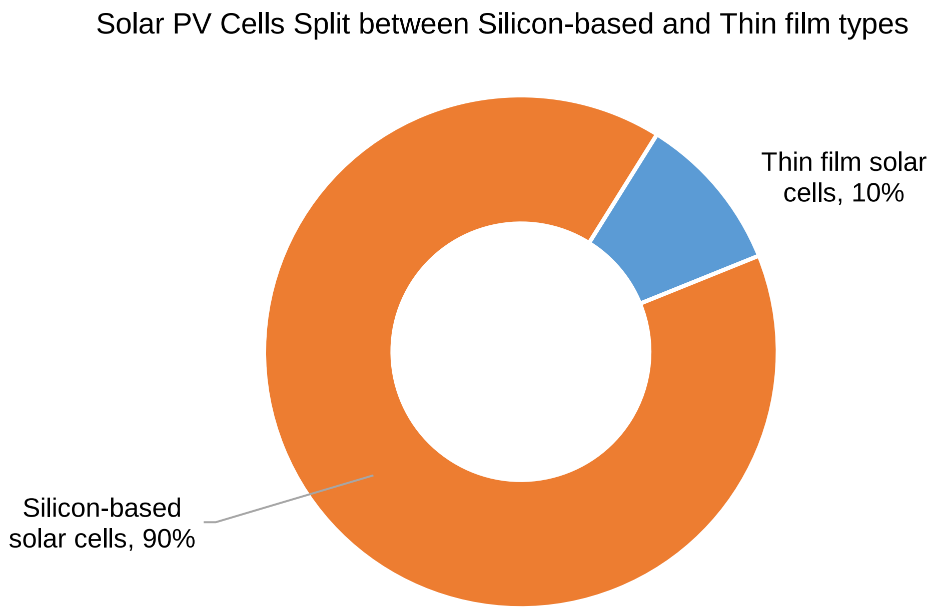

Figure 2.3 Solar PV cells split between silicon-based and thin film types (Venkateswari and Sreejith, 2019).

2.1.1 Monocrystalline vs polycrystalline solar panels

Solar panels are durable with an expected lifespan of between twenty to thirty years (Abdi, 2020). Edalati *et al.* (2015) compared the power output and efficiencies of monocrystalline and polycrystalline solar photovoltaic panels. This lifespan is used in the economic evaluation of solar PV systems. Most manufacturers provide a linear power warranty of a minimum of twenty-five years.

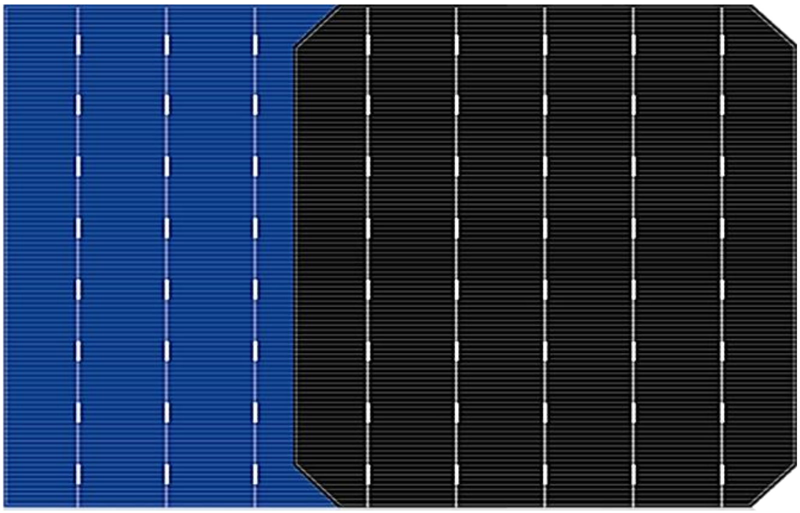

Figure 2.4 Solar PV cells (polycrystalline on the left and monocrystalline on the right) (Seraphim, 2024).

The polycrystalline solar panels typically have a bluish appearance whilst the monocrystalline solar panels variants have a blackish appearance as shown in Figure 2.4. Edalati *et al.* (2015) compared the power output and efficiencies of monocrystalline and polycrystalline solar photovoltaic panels. Reputable solar PV panel manufacturers are now focusing on mainly monocrystalline panels with various variants on the market. The table below shows the efficiencies of five solar PV models from reputable suppliers on the market currently.

Table 2.1 Latest solar PV panel ratings of five models from five reputable suppliers.

Manufacturer	**Model**	**Power (W)**	**Efficiency (%)**	**Power Warranty (years)**
Longi	Hi-MO 6 LR5-72HTH	585W	22.60%	25
Jinko	Tiger Neo 72HL4-(V)	585W	22.65%	30
JA Solar	JAM78S30 585/MR	585W	20.90%	25
Trina Solar	Vertex TSM-DE19R	585W	21.60%	25
Canadian Solar	HiKu7 Mono CS7L-585MS	585W	20.70%	25

Table 2.2 Solar panel efficiencies recorded from previous studies.

	Efficiency	
Author	**Poly Crystalline**	**Monocrystalline**
Park *et al.* (2014)		15 -20%
Yoo *et al.* (2011)	16.79%	
Jayakumar (2009)	12-14%	
Bertolli (2008)		17-18%

2.2 Inverter

An inverter is a device that converts direct current to alternating current output. Tariq *et al.* (2018) postulated that inverters are critical components of solar photovoltaic systems that greatly affect the overall system reliability. Schettino *et al.* (2020) noted that various studies had concluded that the inverter is the system component which is most susceptible to malfunction. Tariq *et al.* (2018) pointed out that inverter malfunction causes system downtime affecting the return on investment. There are different types of inverters which are most common for commercial and industrial applications in South Africa. These are: -

- String PV inverters.
- Hybrid Inverters.

2.2.1 String PV Inverters

These are inverters to which PV panels are connected in addition to an AC input to produce sine wave alternating current (AC) output. Most models have multiple MPPTs built in. By design, even when the sun is shining, these inverters will switch off when there is a power outage. This is because the grid-tie solar PV inverters use the grid input as a reference voltage. Kolantla *et al.* (2020) noted that string inverters have higher efficiency by reducing mismatch losses. Figure 2.5 shows a typical efficiency curve for a grid-tie string inverter. It shows that the inverter is more efficient when there is a higher DC input voltage from the solar PV. During system design, this information guides the system design on the string length.

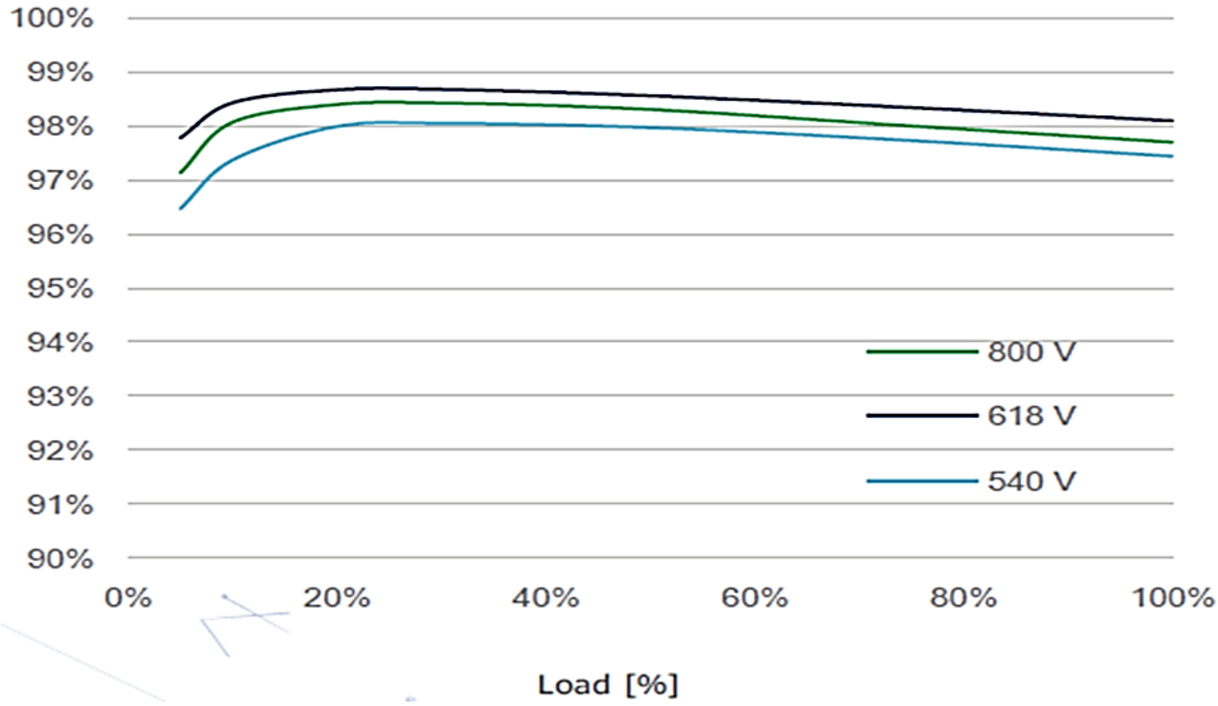

Figure 2.5 Typical efficiency curve for a grid tie inverter (Huawei, 2020).

2.2.2 Hybrid grid-interactive inverters

These are inverters that accept input from two or more energy sources e.g. battery energy storage as well as solar PV input in addition to input from an alternating current (AC) source which is usually the grid. Figure 2.6 illustrates the schematic of a generic hybrid inverter configuration. The hybrid inverters are connected to batteries to store excess power when the solar PV array output exceeds the instantaneous load. Some models have more than one AC source with the secondary source usually being the standby generator. Nowadays, most common hybrid grid-inverters now have a built-in charge controller with a split between variants with PWM (pulse width modulation) and MPPT charge controllers with bigger units having more than one MPPT. The units with built-in MPPT charge controllers are usually more expensive than the PWM variants for the same power output. These models allow for the configuration of settings to choose source output priority which determines the power sources' sequence of supplying the loads. Some models on the market such as Quattro 15 kVA, manufactured by Victron Energy, have two outputs i.e. one dedicated for critical loads and the other one for normal loads.

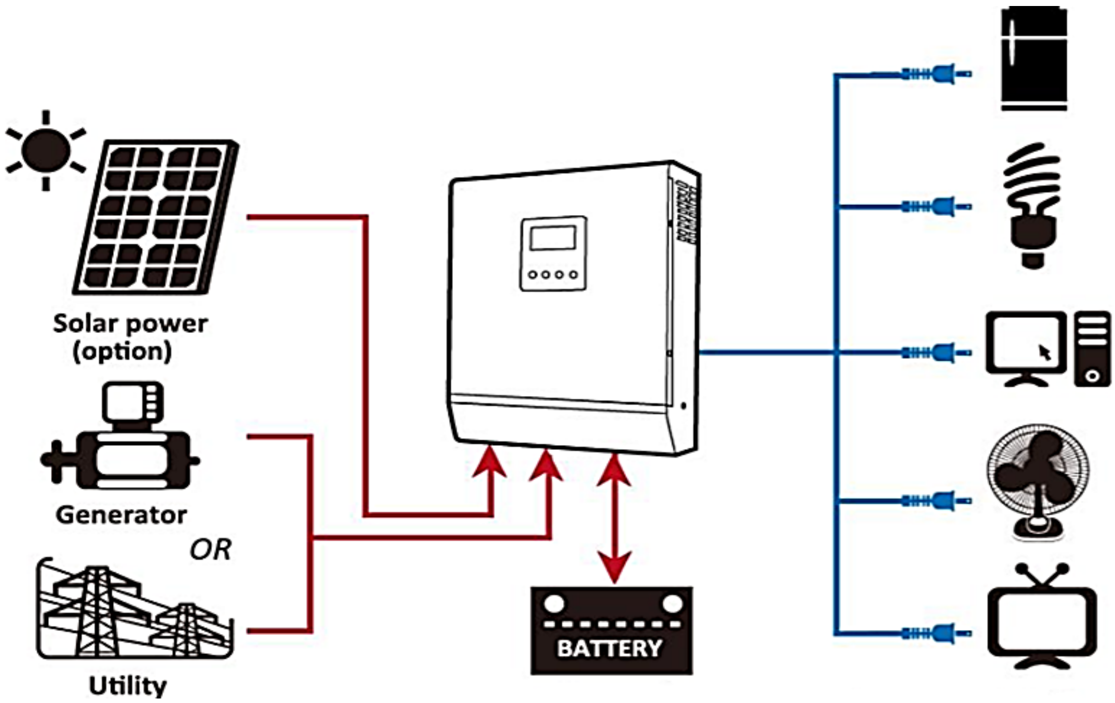

Figure 2.6 Schematic for a generic Axpert hybrid inverter variant (Full Circle Solar, 2018).

Hybrid inverters bring flexibility to system design as some units can be paralleled together to achieve a higher power output or to achieve a 3-phase supply in the case of single-phase inverters. These inverters are designed to handle a variety of battery types whose charge and discharge parameters are configurable. Some hybrid inverters allow the integration of backup generators allowing them to switch on when required.

2.3 Battery

The battery is the most expensive system component of a solar PV hybrid system (Sobamowo *et al.*, 2024). The intermittency of solar energy necessitates the use of batteries hence their continuous research and development (Dwipayana *et al.*, 2021). Dwipayana *et al.* (2021) proposed that battery stores excess solar PV generated energy for later use thereby improving the system's efficiency as energy wastage is averted. The excess stored energy is derived when the load demand is smaller than the solar PV energy generation. The integration of batteries in solar PV systems enhances efficiency and power quality resulting in lower operational costs

(Yoomak and Ngaopitakkul, 2019). There are various battery energy storage options available in the market which are suitable for solar PV Hybrid systems. These include:

¶ Lead-acid batteries
¶ Lithium-Ion batteries.

Dwipayana *et al.* (2021) suggested various parameters which they deemed critical in the selection of batteries for solar PV hybrid system deployment. Figure 2.7 shows the critical characteristics useful for battery selection for a solar PV system, apart from cost.

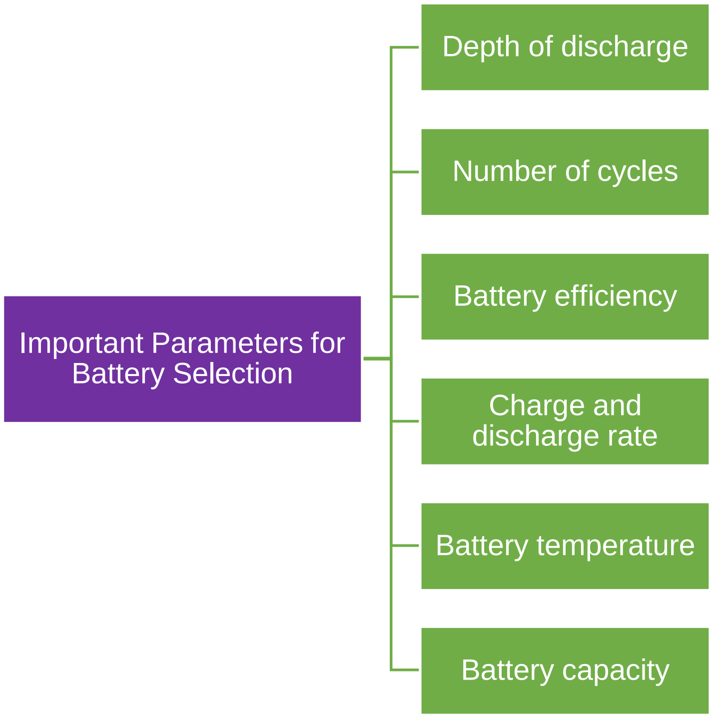

Figure 2.7 Critical parameters for solar PV hybrid battery selection (Dwipayana *et al.*, 2021).

2.3.1 Battery depth of discharge and state of charge

The performance, longevity, and efficiency of batteries in solar PV applications are significantly influenced by the battery's depth of discharge and state of charge. A battery's depth of discharge indicates the amount of energy released when it discharges from its full capacity. For example, a 55% depth of discharge indicates that the battery capacity left is 45% since the battery has discharged 55% of its capacity. In this example, the remaining capacity of the battery is its remaining charge and is termed the "state of charge". The battery state of charge is 100% when full and 0% when empty. Zhongming *et al.* (2018) suggest that batteries with a bigger depth of discharge typically exceeding 80% have a shorter lifespan. There is a correlation between the battery lifespan and its depth of discharge. A shallow depth of discharge prolongs the battery's lifespan i.e. more cycles and vice versa. Figure 2.8 illustrates the battery state of charge and depth of discharge. The figure shows that the state of charge decreases from as the battery discharges. Conversely, the depth of discharge increases as the battery is used.

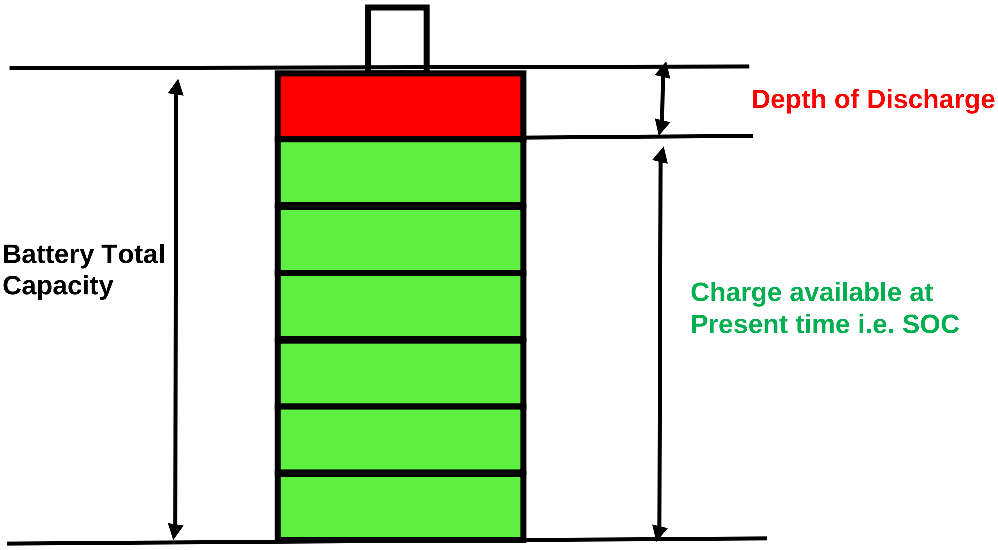

Figure 2.8 Battery's state of charge and depth of discharge (Priya *et al.*, 2023).

Batteries can also be compared by considering the different metrics. These include:

¶ Energy density
¶ Round trip efficiency
¶ Lifespan / cycle number

2.3.2 Energy density (Wh/kg)

The energy density is a critical metric useful for evaluation and comparison of battery technologies. In addition, it indicates the battery stored energy per unit weight. This metric is expressed in watt-hours per kilogram (Wh/kg). Various authors have compared different batteries and their characteristics. For instance, Yudhistira *et al.* (2022) and Sobamowo *e t a l .* (2024) suggest that lithium-ion batteries typically have a superior energy density. Kebede *et al.* (2021) concur with Yudhistira *et al.* (2022) proposed that the energy density of lithium-ion batteries is at least four times that of lead-acid batteries.

2.3.3 Round-trip efficiency

A battery's round-trip efficiency considers its charging and subsequent discharge. A battery's round-trip efficiency shows how much stored energy is successfully discharged as useful energy throughput in comparison with the stored energy. Santos Pereira *et al.* (2021) suggested that lithium-ion batteries have superior round-trip efficiency resulting in their integration in solar PV systems. Zhongming *et al.* (2018) noted that typical lithium-ion batteries have an approximately 90 - 95% round-trip efficiency whereas, for lead acid batteries, it is 60-70%. Selection of a battery with a higher round trip efficiency ensures maximum usage of solar energy leading to enhanced energy security. Karthigeyan *et al.* (2017) proposed that lithium ion batteries outperform lead-acid batteries at high temperature.

2.3.4 Battery lifespan

The battery lifespan is a critical factor in the overall performance and economic viability of a solar PV hybrid system. Lifespan denotes the number of cycles that a battery can provide before it substantially degrades and becomes unusable. A cycle equates to the discharge of a battery from full charge to and then charges the battery from that state of charge to full capacity. Santos Pereira *et al.* (2021) proposed that lithium-ion batteries are suitable for solar PV microgrid systems as they accommodate higher cycling. Lithium-ion batteries have a superior design life in comparison to lead-acid batteries (Kebede *et al.*, 2021) highlighting their suitability for solar PV investment projects. Figure 2.9 shows the relationship of a lithium-ion battery's cycle life and depth of discharge at 25°C. There is an inverse relationship between the depth of discharge and cycle life. As the cycle depth increases, the number of cycles decreases sharply.

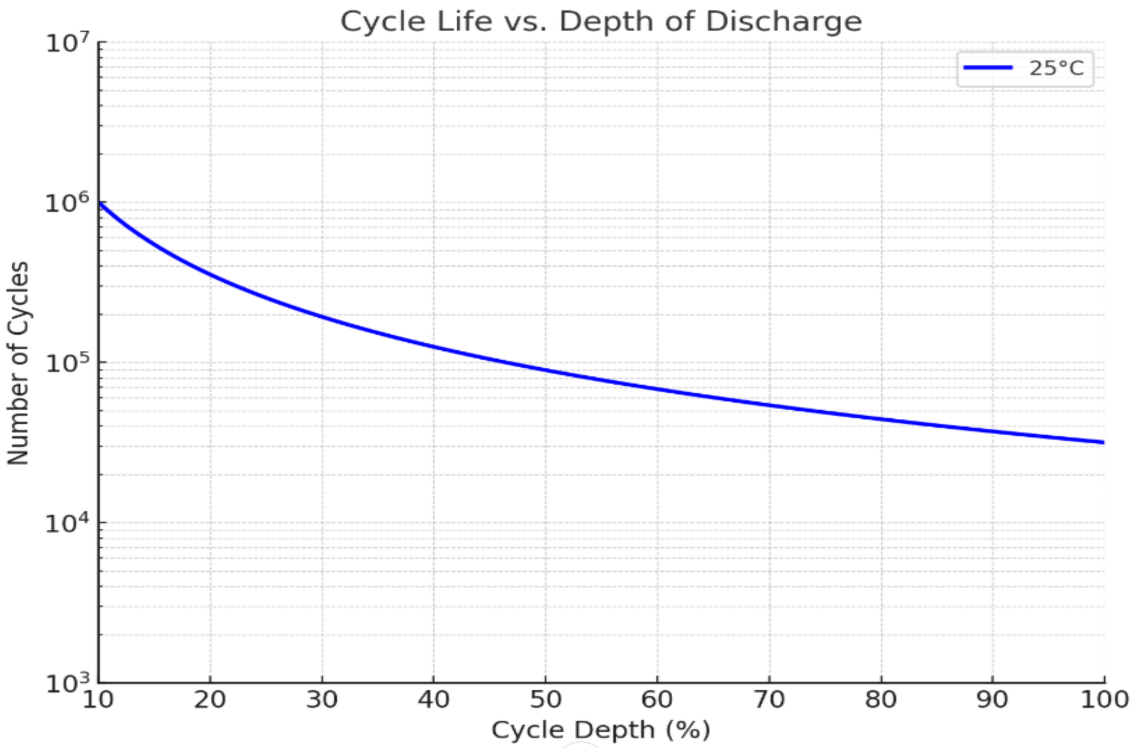

Figure 2.9 Curve showing cycle number and depth of discharge (Zhongming *et al.*, 2018).

Zhongming *et al.* (2018) suggests that the lithium-ion battery lifespan of up to 15 years as compared to 3 – 6 years for lead-acid is a major advantage. According to Zhongming *et al.* (2018) shows that a smaller depth of discharge results in a bigger cycle number whilst an increase in depth of discharge results in smaller cycle number. Table 2.3 summarises the comparison of lithium-ion and lead acid battery characteristics as suggested by Zhongming *et al.* (2018).

Table 2.3 Summary of lithium-ion vs lead-acid battery characteristics (Zhongming *et al*., 2018).

	Energy Density(kW/kg)	Round Trip Efficiency (%)	Lifespan (years)	Eco-friendliness	Capital Cost ($/kWh)
Lithium ion	150-250	95%	10 -15	Yes	High
Lead acid	30-50	60-70%	3-6	No	Low

Karthigeyan *et al.* (2017) suggested that lithium-ion batteries are eco-friendly whilst lead-acid batteries are not as they contain lead which is harmful to the environment. The values contained therein differ from one place to another. Overall, lithium-ion batteries have several advantages over lead-acid batteries, including higher energy density, higher efficiency, longer lifespan, and better environmental impact. The lithium-ion batteries are now very popular due to their performance and characteristics. The lithium-ion battery pricing has been a deterrent in the past. The introduction of many industry players coupled with increased mass production, has helped reduce its market prices. The global Lithium-ion battery price downward trend from 2013 to 2023 is shown in Figure 2.10. In general, the price generally decreased over this period, with some slight fluctuations. In this period, the 2018 recorded the highest price whilst the lowest price was observed in 2023.

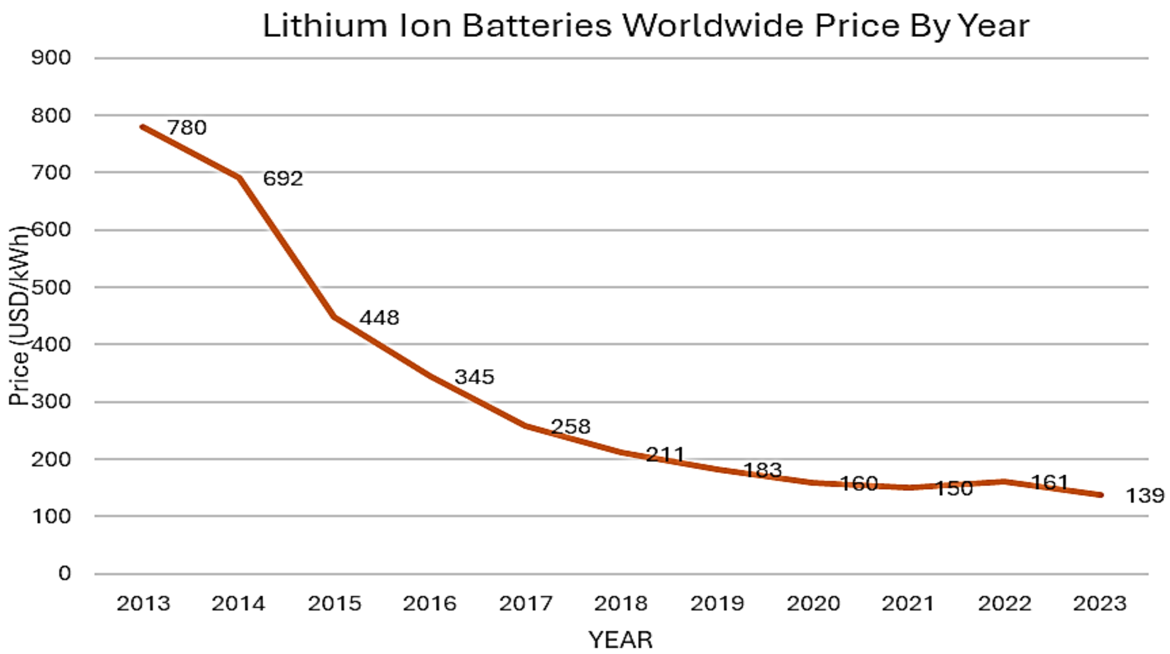

Figure 2.10 Global lithium-ion battery price trend (Statista, 2023).

Considering the huge capital investment, Ashtiani *et al.* (2020) postulated that accurate sizing of a solar PV-Battery hybrid and not oversizing is critical in optimizing the system output and achieving optimum energy costs.

2.4 Solar PV system reliability

Desai *et al.* (2021) pointed out that solar PV system performance is dependent on meteorological conditions and other factors such as accumulated dust/dirt and hotspots. The energy production of solar panels is decreased by dust and dirt build-up on their surface

(Mahmood and Majeed, 2022). The meteorological conditions which differ from one location to the other, include temperature and humidity fluctuations, wind velocity, and solar irradiance. Saxena and Gidwani (2018) concluded that the solar panel's surface temperature is the proportionate solar radiation it receives. They noted the power output and efficiency of a solar panel is inversely proportional to the surface temperature.

2.4.1 Effect of PV system tilt angle

Chowdhury *et al.* (2010) suggested that solar panel tilting helps to generate energy efficiently. The authors added that the optimum tilting angle is site-dependent and noted that this is usually equal to the latitude of the site location. Desai *et al.* (2021) pointed out that the tilt angle is measured relative to the horizontal plane. However, Chowdhury *et al.* (2010) noted that for site locations in the southern hemisphere, the panels are tilted towards the north and for the northern hemisphere the panels must face south.

Tarigan (2022) concluded that the output from solar PV panels is dependent on the angle at which they are tilted. For their site of assessment in Indonesia, they concluded that the optimum angle was 0˚ meaning the solar panels are in North-facing orientation. There is a slight variance in energy generation for a solar PV panel provided they are within a 5˚ tolerance to the optimum tilt angle for that side (Saxena and Gidwani, 2018).

2.4.2 Effect of roof design on system performance

Proper system design, including the selection of appropriate tilt angles and orientations enhances energy yield from the solar overall system reliability Tarigan (2022) pointed out that sufficient area with access to solar radiation is critical for the overall solar PV system performance. On the other hand, they noted the economic infeasibility of solar panel ground-mounting. Saxena and Gidwani (2018) concluded that roof inclination determines the roof-mounted solar panels' energy yield. The authors added that the solar panels should be away from shading which greatly reduces the energy generated despite how little it is. Abdi (2020) concluded that a 20% shading of a solar panel surface corresponds to up to a 50% energy generation reduction from it.

2.4.3 Effects of dust on solar PV output

Dajuma *et al.* (2016) noted that particulate dust typically smaller than 500 micrometres is present in the atmosphere. Salamah *et al.* (2022) and Dajuma *et al.* (2016) concurred that dust deposit and accumulation has an adverse effect on Solar PV efficiency. Dajuma *et al.* (2016) concurred with Salamah *et al.* (2022) that the degree of dust accumulation is dependent on the dust properties as well as the site's prevalent environmental conditions. Mani and Pillai (2010) suggested various factors affecting the degree of dust settlement shown in the Figure 2.11.

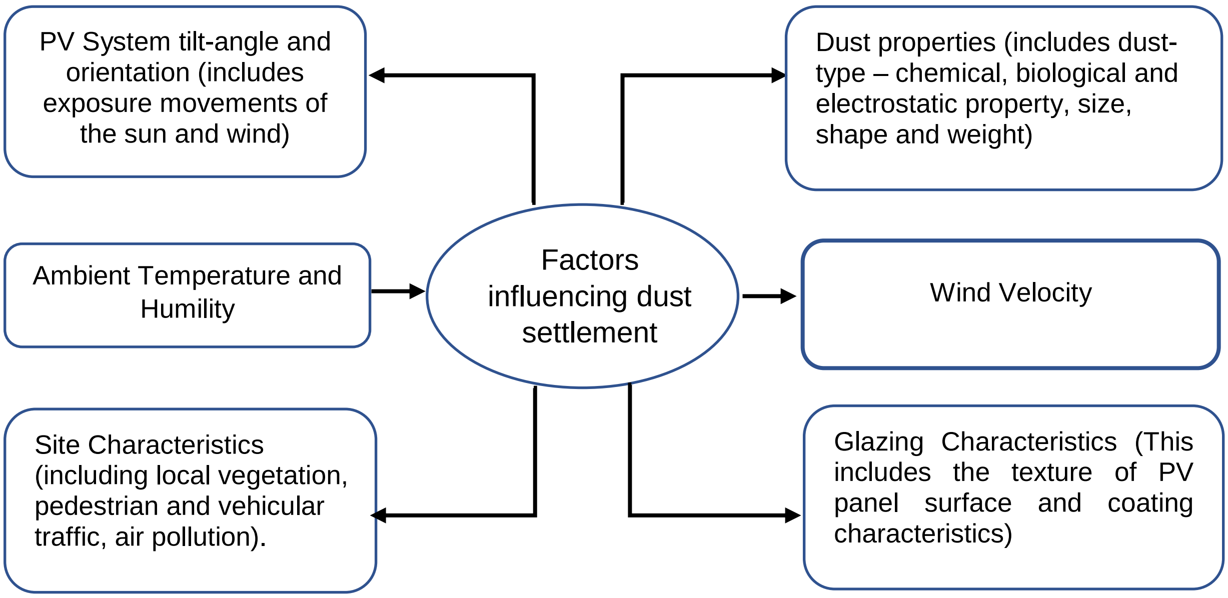

Figure 2.11 Dust settlement factors (Mani and Pillai, 2010).

Kazem and Chaichan (2019) also noted that wind speed and direction influence dust accumulation as it displaces dust particles from the surroundings. Mani and Pillai (2010) considering the gravity effect concluded that tilted solar PV panels have less dust accumulation in comparison to horizontally mounted panels. Ghazi *et al.* (2014) considered the global dust intensity indicating that South Africa generally has moderate dusting levels which are lesser as compared to North Africa and the Middle East. Kazem and Chaichan (2019) also noted that wind speed and direction influence dust accumulation as it displaces dust particles from the surroundings. Mani and Pillai (2010) considering the gravity effect concluded that tilted solar PV panels have less dust accumulation in comparison to horizontally mounted panels.

Alghamdi and Almutairi (2019) suggested that dust accumulation on a solar PV panel or array reduces the solar panel's power output. They attributed the reduction in energy generation to reduced light penetration. Maghami *et al.* (2016) noted that continuous dust accumulation increases solar PV soiling losses. Ghazi *et al.* (2014) carried out a study in Egypt where they compared the power output of a dusty and clean solar PV panel in an experimental setup. They observed a 25% power output reduction on a dusty solar PV panel over three months and 35% over twelve months. Kazem *et al.* (2014) carried out a similar study in which they didn't clean solar PV cells for forty-five days. They observed that the PV cell electrical efficiency halved from 16% to 8% during the test period. Salamah *et al.* (2022) concluded that soiling losses reduce the overall system outputs and negatively affect the system's techno-economic feasibility. Olorunfemi *et al.* (2022) agreed and further noted a slight decrease in solar PV system performance affects its economics.

Benghanem *et al.* (2023), under low solar radiation conditions, observed a higher power output drop on polycrystalline panels than on monocrystalline panels. Conversely, the dust effect was higher for monocrystalline panels under high solar radiation conditions than for polycrystalline panels. Various interventions can reduce solar PV system losses due to dust accumulation. Mani and Pillai (2010), as shown in Figure 2.12, noted that some factors can be changed whilst others cannot and those need to be considered and their effect mitigated.

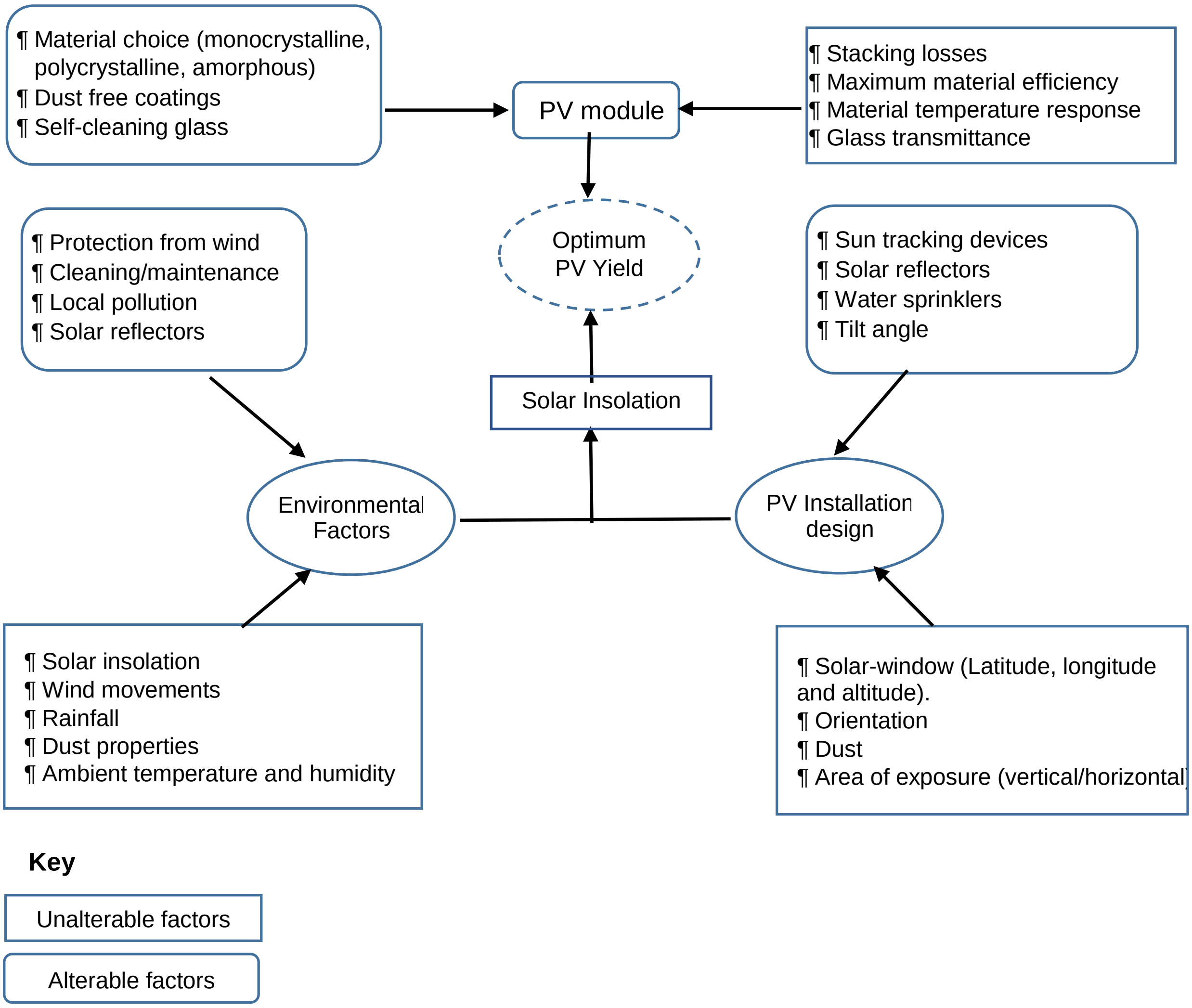

Figure 2.12 Factors affecting photovoltaic system output (Mani and Pillai, 2010).

The design phase is thus critical in the overall performance of a designed system layout. For instance, the selection of optimum tilt is possible whilst one cannot control the environmental factors prevalent at the selected site. Kalam *et al.* (2020) recommended regular solar panel cleaning to ensure improved and more reliable energy generation.

2.4.4 Effect of shading and module mismatch

Maghami *e t* (2016) noted that despite being manufactured by the same manufacturer and having the same ratings, solar panels will have different electrical characteristics. They further added that when the panels are connected in arrays, the power output of the solar panels is less than their calculated output summation. This phenomenon is known as "module mismatch" and according to Maghami *e t* (2016) results in power losses. These typically affect the solar photovoltaic system's efficiency, and the losses must be considered during the design phase.

Maghami *et al.* (2016) concluded that shading occurs when there is a partial or complete obstruction of incident light from reaching the solar panel surface. They added that the shading losses are dependent on the degree of shading. When a panel is shaded in an array, it introduces reverse bias and when in a serial connection, pulls down all the panels' current to its output current leading to significantly reduced power output (James *et al.*, 2006; Alghamdi and Almutairi, 2019). There are innovations current on the market such as power optimisers which are connected on the rear of each panel in an array to achieve maximum power output efficiency. A picture of the Solar Edge S1400 power optimiser shown in Figure 2.13.

Figure 2.13 Power optimiser (SolarEdge, 2024).

2.4.5 Influence of meteorological conditions on solar panel output

Roy *et al.* (2021) noted ambient temperature as a key determinant of the solar PV system's energy output. Habib *et al.* (2023) pointed out a correlation between ambient temperature, solar PV module surface, and cell temperature. They suggested that an increase in ambient temperature corresponded to a solar PV cell and surface temperature increase.

Kazem and Chaichan (2019) noted that if the ambient temperature is high, there is reduced heat transfer from the PV cells to the environment. Habib (2023) suggested that the increase in temperature resulted in reduced voltage and PV panel power output. This concurred with Kazem and Chaichan (2019) who mentioned that cell efficiency is reduced. Any ambient temperature deviation whether positive or negative from the standard temperature conditions of 25°C results in a corresponding PV cell temperature. A metric called temperature coefficient, quantified in %/°C indicates the solar PV power output reduction because of the temperature change. The temperature coefficient can be used to compare between two products as it shows the performance at various temperatures.

PV cell temperature is usually 20 - 30°C warmer than the surrounding environment reaching up to 85°C on a hot, windless day on a black unshaded solar PV array (Clean Energy Reviews, 2024). Figure 2.14 shows that polycrystalline solar PV has higher power output loss versus monocrystalline solar PV panels at different temperatures above standard temperature conditions (STC) i.e. 25°C. However, a marginal difference in the power output is observed at temperatures below 25°C.

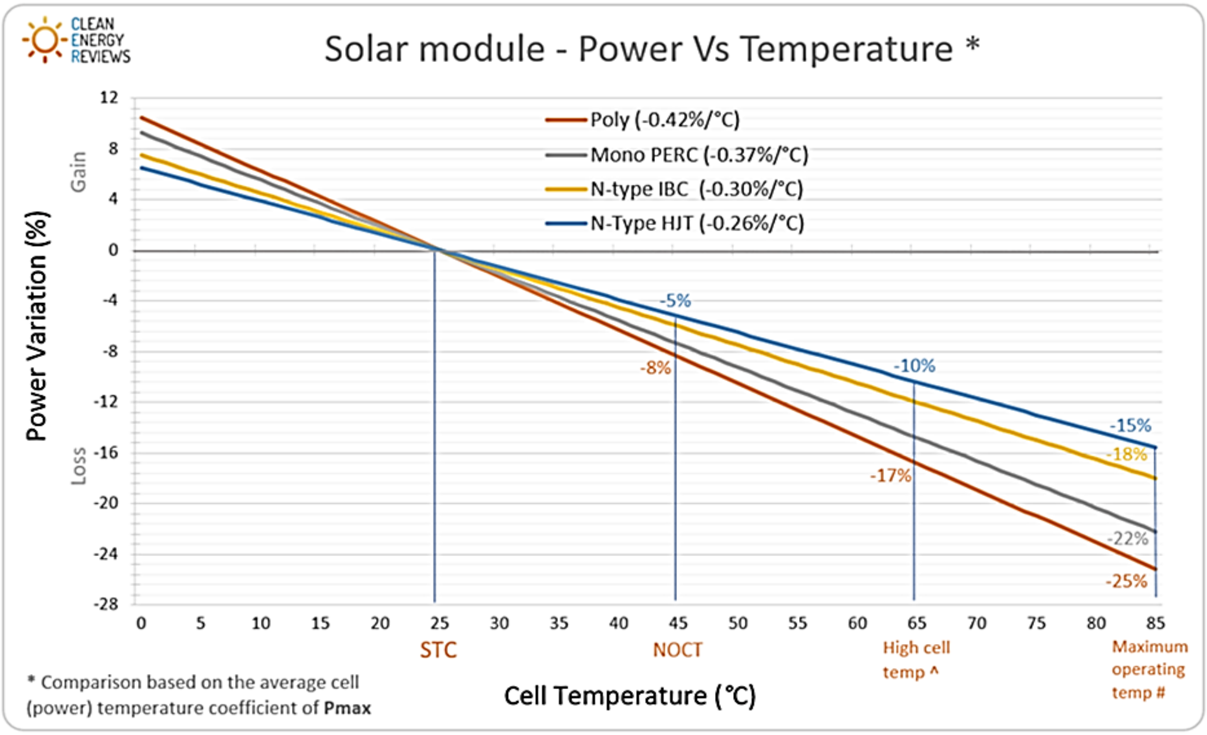

Figure 2.14 Power variation with cell temperature change (Clean Energy Reviews, 2024).

2.5 Review on system performance evaluation

To simplify the design process and assess the economic potential, several simulation software tools have been developed. Chowdhury *et al.* (2010) and Rallabandi *et al.* (2021) designed grid-connected solar PV systems manually without the use of simulation tools. For instance, they used aerial images to calculate the usable roof space and divide it by the surface area of an individual solar panel to deduce the quantity of solar panels. The deduced solar panel quantity and their maximum output were then used to determine inverter size and quantity. Dondariya *et al.* (2018) however acknowledged the use of simulation software programs for site-specific solar PV potential performance evaluation and system design and planning. Various metrics such as performance ratio, estimated energy yield, and solar fraction can be determined. The authors considered various simulation tools namely, PVSOL, PVGIS (Photovoltaic Geographical Information System), SolarGIS, and SISIFO. In this study, they recommended PVSOL as a more suitable tool for its perceived flexibility, ease of use, and quick result processing. Adesina *et al.* (2021) also carried out a study to develop a solar PV system web-based software simulation tool.

The software tool is used for sizing different components for a reliable system. Sawyer and Shukla (2021) used PVsyst, another simulation tool, for a study of a 100 kWp rooftop solar PV grid-tied system in India. Vidur and Jagwani (2022) recommended PVSyst is designed to best suit autonomous use by professionals and researchers alike. In that study, the performance ratio, efficiency, and the associated losses were determined. Tarigan (2022) used PVGIS as the simulation tool for system planning and potential evaluation in which they considered a 10-year dataset. Tarigan(2023) conducted a financial analysis of a rooftop solar PV system and used SolarGIS simulation software. Soysal and Soysal (2014) used Solmetric-SunEye to evaluate the cost-effectiveness and techno-economic performance of a solar PV system. Table 2.4 shows examples of previous studies and the different simulation software tools used. The commonly used software programmes include PVSyst, Helioscope, and HomerPro. The researcher benchmarked the software tools and considered PVSyst for the simulation of the project as shown in Table 2.5.

Table 2.4 Software tools recommended from previous similar studies.

Authors of previous similar study	**Simulation software recommended**
Soysala and Soysal (2014)	Solmetric-SunEye
Dondariya *et al.* (2018)	PVSOL
Tarigan (2022)	PVGIS
Tarigan (2023)	SolarGIS
Vidur and Jagwani (2022)	PVSyst

Table 2.5 Benchmarking of software tools PVSyst, Helioscope and HomerPro.

Benchmark	PVSyst	Helioscope	HomerPro
Type of Analysis	Useful for comprehensive modelling of PV systems including performance and shading analysis. It offers a financial analysis applicable to a variety of systems e.g. grid tie, stand-alone, etc.	Provides a technical analysis with 3D modelling and shading analysis. It provides energy yield estimates which are mostly used in creating proposals.	Simplifies microgrid system design, optimisation, sensitivity analyses, and technical and financial analysis incorporating various energy sources.
Costs	It is a commercial software that offers various licensing access options.	It is subscription-based offering various plans to system designers.	It is subscription-based with different usable-based pricing.
Reliability	The software offers accurate simulations considering different variables such as irradiance, temperature, shading, and losses.	Reliable performance helps estimates based on shading analysis, other meteorological factors, and modelling.	The software has advanced algorithms that provide accurate microgrid designs.
Advantages	Comprehensive database and support plug-ins are available helping users in navigating the software and to understand difficult modelling concepts. The results include several simulation tools with high accuracy in the prediction of production levels of PV systems as it includes factors like irradiance, temperature, shading, and system losses. It has extensive modelling capabilities since it includes shading analysis, performance estimation, and financial analysis.	User friendly which makes it easy to quickly design and analyse solar projects. It is a web-based tool with subscription-based pricing plans offering flexibility and scalability in usage. It allows 3D model design rendering and provides a detailed wiring diagram with shading analysis and production estimates.	Very user-friendly with drag-and-drop functionality. Task-based tutorials and examples simplify the design process. Various possible system configurations can be evaluated by applying advanced optimisation algorithms for the design and analysis of microgrid systems. It accounts for factors like availability, load profiles, and economic parameters.
Disadvantages	The software can be expensive for some users. There are no single-line diagrams, and steep learning curves because of the software's complexity and extensive feature set. Software requires quality data and system parameters which can be challenging to obtain.	Its scope is limited with a focus on solar projects and not extensive PV system design and modelling. Helioscope may not be suitable for complex simulations since it does not support advanced scientific calculation.	Relatively time-consuming as it requires careful input parameter selection and an understanding of design principles. It is not exactly suitable for solar project design or standalone PV systems as it focuses on microgrid design and optimization. The software comes at a premium and deterrent for occasional small-scale project users.

2.6 Other technical and economic performance parameters

Vasita *et al.* (2017) selected estimated yields, performance ratio (PR), capacity factor, and energy losses as key performance indicators for a
152 kWp solar PV system. The net usable energy exported to the distribution network is referred to as the 'final yield'. On the other hand, 'reference yield' is the system's possible energy output at standard test conditions. The performance ratio is thus the ratio of the final yield to the reference yield (Vasita *et al.*, 2017). According to the authors, the performance ratio can be used

to compare system performances regardless of their location. A higher performance ratio is desirable as it implies that the solar PV system is performing efficiently.

Mhundwa *et al.* (2020) reported an average performance ratio of 80% from their analysis of a 75 kWp system in the Eastern Cape, South Africa. Other studies in South Africa noted were for smaller systems, which were 3.2 kWp in Port Elizabeth and 8 kWp in Durban. These studies yielded an average performance ratio of 84.30% (Okello *et al.*, 2015) and 87.10% (Adebiyi *et al.*, 2019), respectively. Dondariya *et al.* (2018) showed a performance ratio of 75.01% and as an energy yield of 1528.125 kWh/kWp. Mhundwa *et al.* (2020) reported a final yield of 1864.29 kWh/kWp for their case study, whilst Tarigan (2022) determined a final yield of 1462 kWh/kWp. The researcher sought to determine such technical parameters, considering the meteorological conditions prevalent in Cape Town.

In conclusion, Chapter 2 provides a comprehensive review of solar photovoltaic (PV) systems and battery technologies. The principles of solar energy conversion and the various types of solar panels. The battery technologies are explored focusing on the characteristics and limitations of different battery types. The section explored the system components and the factors affecting energy generation. The various simulation tools used by previous researchers have been acknowledged. The researcher also benchmarked the various simulation software to determine which one to use in this study. The different techno-economic parameters from similar studies are discussed. Research gaps in existing literature are identified. The next chapter focuses on the study’s research design and methodology, outlining the systematic approach used to achieve the research’s aim. This chapter describes the research’s objectives and the methods employed to achieve them. Data collection techniques and the use of PVSyst simulation software for system performance analysis. Chapter 3 provides the research framework for the subsequent analysis and results by connecting the theoretical insights shown in Chapter 2.

CHAPTER THREE

RESEARCH DESIGN AND METHODOLOGY

3.0 Introduction

This section explores the research methodology employed by the researcher. The section also aims to detail the different objectives and how they have been accomplished.

This chapter is an important component of this research study, building on the theoretical framework established in the literature review presented in Chapter 2. The research methodology is structured to ensure all the research objectives are achieved. Data collection methods are described in this section as a basis for the designed system design process. Furthermore, the chapter highlights the use of PVSyst simulation software in determining the optimal solar PV system design. Chapter 3 highlights the economic analysis framework by outlining the key evaluated financial metrics such as net present value (NPV), internal rate of return (IRR), and payback period. These metrics are crucial for understanding the financial implications of the designed solar PV system and for comparing its viability against other energy solutions. The validity and reliability of the research findings are established through a clear and systematic methodology shown in Chapter 3. In summary, this chapter not only provides a detailed account of the research design and methodology but also connects the theoretical insights from Chapter 2 to the practical application of the study.

Quantitative data collection and analysis methods are employed in this research study. Quantitative research provides objective data collection analysis reducing the influence of personal biases. The use of quantitative methods allowed the researcher to objectively measure the designed system technical performance metrics, such as energy yield and performance ratio. These metrics are critical for the determination of the designed solar PV system’s technical feasibility. In addition, the quantitative methods enabled the researcher to conduct statistical analysis essential to assess financial metrics such as net present value (NPV), internal rate of return (IRR), and payback period. This approach presents a strong framework for evaluating the economic viability of the solar PV system further allowing comparisons with similar studies and industry benchmarks. The quantitative methods chosen for the research rely on systematic data collection and analysis ensuring consistency and reliability in the study’s findings. Data-driven decisions and policy-making processes are enabled by the numerical data provided through the quantitative research approach.

3.1 Research methodology

The researcher conducted the research study in significant steps to address the set objectives as elaborated below.

Objective 1: To determine the total monthly energy consumption throughout the year and analyse the load profile at various times of the day.

The research objective was completed in section 4.1 of this dissertation. The researcher collected and compiled the historical monthly electricity consumption data for the selected site. The individual monthly consumption data provided was processed and the average daily electricity demand was calculated. The data provided the basis for the system design process.

Objective 2: To determine the electricity generated by the solar PV system.

This objective was achieved in section 4.2. Using simulation tools such as PVSyst that use embedded meteorological databases and considering the geographical coordinates of the reference site, the researcher determined the optimum configuration of the system. The estimated energy yield/generation of the designed solar system and the performance metrics were also determined by leveraging the distinctive features of the software enabling the researcher to get accurate values. The researcher subsequently determined the designed system's annual technical performance.

Objective 3: To conduct a technical assessment of the optimal sizing for the solar photovoltaic system and battery storage capacity, considering the energy consumption patterns and location-specific factors to ensure efficient system performance.

This research objective was achieved in section 4.2 and section 4.3 of this dissertation. The various system components were considered by leveraging the features of PVSyst, an internationally acclaimed design simulation tool. Various system configurations were considered to ensure optimum system performance. The technical design output from PVSyst included the total size of the designed system’s solar PV array, specifications, and its projected energy yields throughout the year. Analysis of the PVSyst simulation report also helped to extract insights on key metrics such as losses, and performance ratios thereby enabling the determination of technical feasibility. Technical performance metrics such as performance ratio were benchmarked against similar systems that have been deployed and recorded in other studies. The inverter selection was based on the system application inclusive of the batteries. The battery sizing was conducted by considering the hourly electricity consumption values for the different months of the year. Using the formulae and considering the specifications of batteries available in the South African market, the researcher calculated the optimum battery sizing.

Objective 4: To evaluate the economic viability of the solar PV system

This objective is achieved in section 4.4 of this dissertation. The researcher compiled a cost analysis for the system including calculating the costs of the system components, and installation-related costs, to determine the initial capital investment for the system. The cost data was extracted from websites of local reputable suppliers of solar PV and electrical component suppliers. The researcher also attended various solar exhibitions to understand the various products available on the market. The determination of the total system upfront cost was done by creating a bill of quantities. An economic analysis followed considering the replacement costs of the components according to their rated lifespans. Insurance costs were also included. The economic analysis factored in the current interest rate from which a discount factor was calculated for each year. The discount factor enabled the researcher to calculate the annual discounted cash flows and subsequently the cumulative cash flow. The annual electricity tariff hikes were also analysed. The average of the electricity tariff escalations over the past 10 years was considered as the base case. Using a customised Excel sheet and considering the annual cash flows, the project's NPV and IRR were determined. Sensitivity analyses were conducted to determine the effects of the changes in variables such as battery pricing, interest rate and electricity tariff escalations.

3.2 Data collection design and methodology

The researcher obtained monthly electricity consumption data from the reference site that was provided. Analysis of the electricity consumption data helped identify the site's load profile including peak demand, daily and seasonal variations and average consumption. As part of the data analysis, the average hourly and daily electricity consumption were calculated. Solar irradiance data was analysed to determine the site's solar resource potential. PVSyst was used for the solar PV system's performance simulation analysis. The simulation software enabled the system design. The simulation provided insights into key performance metrics such as energy yield, performance ratio, and system losses. The analysis was crucial for evaluating the designed solar PV system's technical viability and fine-tuning its design to align with the site's energy requirements. PVSyst simulation report analysis helped to extract insights on key system performance metrics thereby enabling the determination of technical feasibility. The technical performance metrics were compared with similar systems recorded in previous studies enabling the validation of the designed system's expected performance.

A comprehensive economic analysis was conducted using a customised Excel spreadsheet. This analysis involved calculating the total upfront capital costs, operational costs, and potential energy savings from the solar PV system. To understand the financial viability of the designed solar PV system, the economic metrics calculated included NPV and IRR. Sensitivity analysis also formed part of the data analysis. The researcher approached industry players such as suppliers to understand the applicable products and technologies available on the market, together with their technical performance data and costs to factor it into the system design process. The comprehensive data analysis provided a robust foundation for the techno-economic assessment of the designed solar PV hybrid system.

The comprehensive data analysis was conducted using the simulation tools and quantitative techniques to derive meaningful insights. Combining PVSyst for technical performance evaluation and Microsoft Excel for economic analysis allowed for a thorough assessment of the solar PV system's techno-economic feasibility. This approach enhanced the reliability of the findings providing stakeholders with a solid foundation for up-to-date solar energy adoption decision-making. Figure 3.1 summarises the research methodology used.

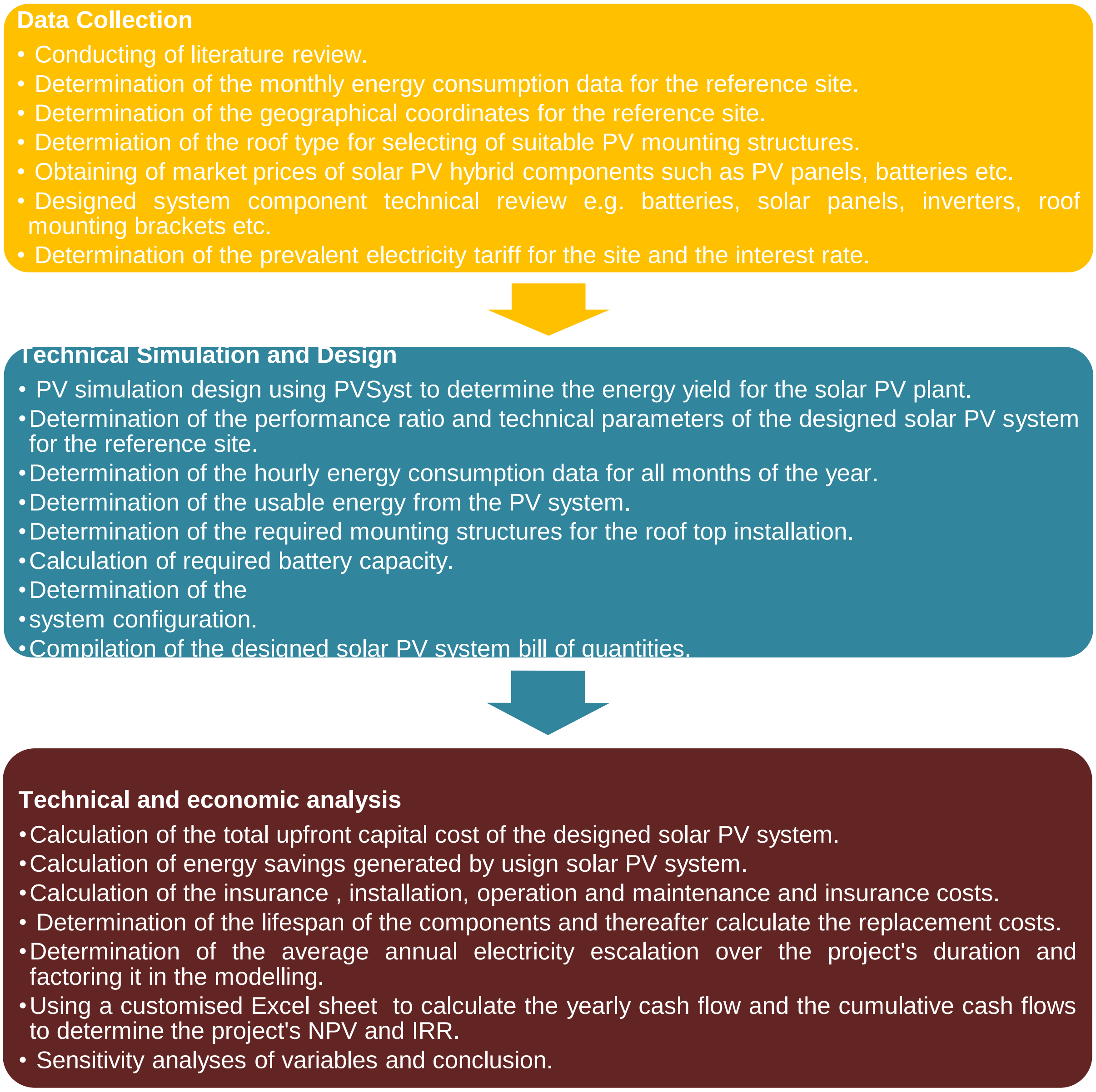

Figure 3.1 Summary of research methodology used.

In conclusion, Chapter 3 outlines the adopted research design establishing robust framework for data collection and analysis. The research objectives are unpacked and methods to achieve them were described. The methodological framework established in Chapter 3 paves way for Chapter 4 which explores the simulation and research results derived from the implemented methodology. Chapter 4 presents the energy consumption analysis for the selected commercial site leading to the system's design.

CHAPTER FOUR

SIMULATION AND RESEARCH RESULTS

4.0 Introduction

Chapter 4 outlines the empirical outcomes emanating from the adopted methodology outlined in Chapter 3. The chapter provides a comprehensive understanding of the projected system's performance and financial viability.

A crucial detailed energy consumption analysis for the study's commercial site is presented establishes the energy requirements. By examining monthly and annual consumption patterns, the chapter highlights peak demand periods, seasonal variations, and overall energy usage trends, which are essential for informing the system design and configuration.

Following the energy consumption analysis, the chapter delves into the technical performance metrics obtained from the PVSyst simulations. The solar array size, battery storage capacity, and expected energy yields are determined revealing the optimal configuration for the designed solar PV system. Key performance indicators such as performance ratios, system losses, and efficiency metrics are presented providing insights into the technical feasibility of the designed system. The designed solar system's PV simulation results are analysed comprehensively.

In addition to the technical analysis, Chapter 4 presents the economic evaluation of the designed solar PV system. A comprehensive evaluation of the financial metrics such as net present value (NPV), internal rate of return (IRR), and payback period is also conducted. The findings will reveal the economic viability of the designed system thereby offering valuable insights for stakeholders considering investment in renewable energy solutions.

This chapter aims to bridge the gap between theoretical concepts and practical applications, providing a detailed account of the findings that will inform the conclusions and recommendations in Chapter 5.

4.1 Simulation and research results

This section is critical for the outcome of the research study. The energy consumption, simulation output, system design and subsequent economic evaluation are contained herein.

4.1.1 Energy consumption for the site

The monthly electricity consumption for the business operation is shown in Figure 4.1. The month of May has the lowest electricity consumption value whilst November, in contrast, has the highest electricity consumption. The total annual electricity consumption amounted to 133 081 kWh.

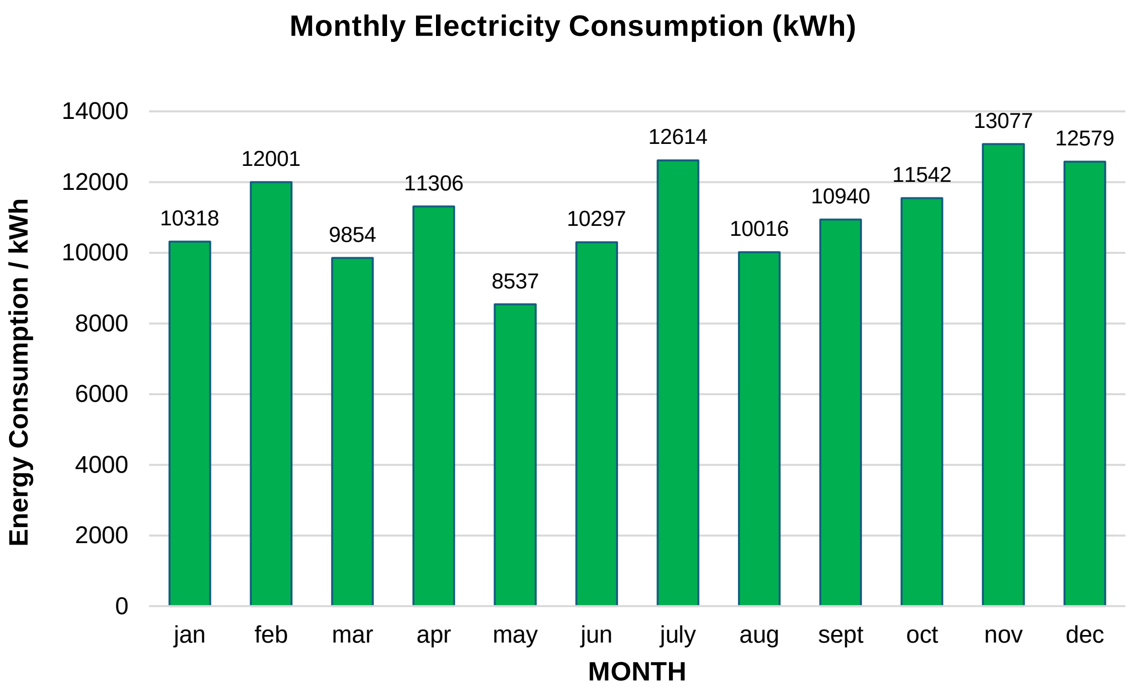

Figure 4.1 Monthly electricity consumption in kWh.

Figure 4.2 and Table 4.1 shows the average hourly electricity consumption for the different months of the year. The daily and seasonal variations are reflected in the data. Electricity demand is lower during after-hours and early morning hours whilst most of the energy is used during the working hours of the day.

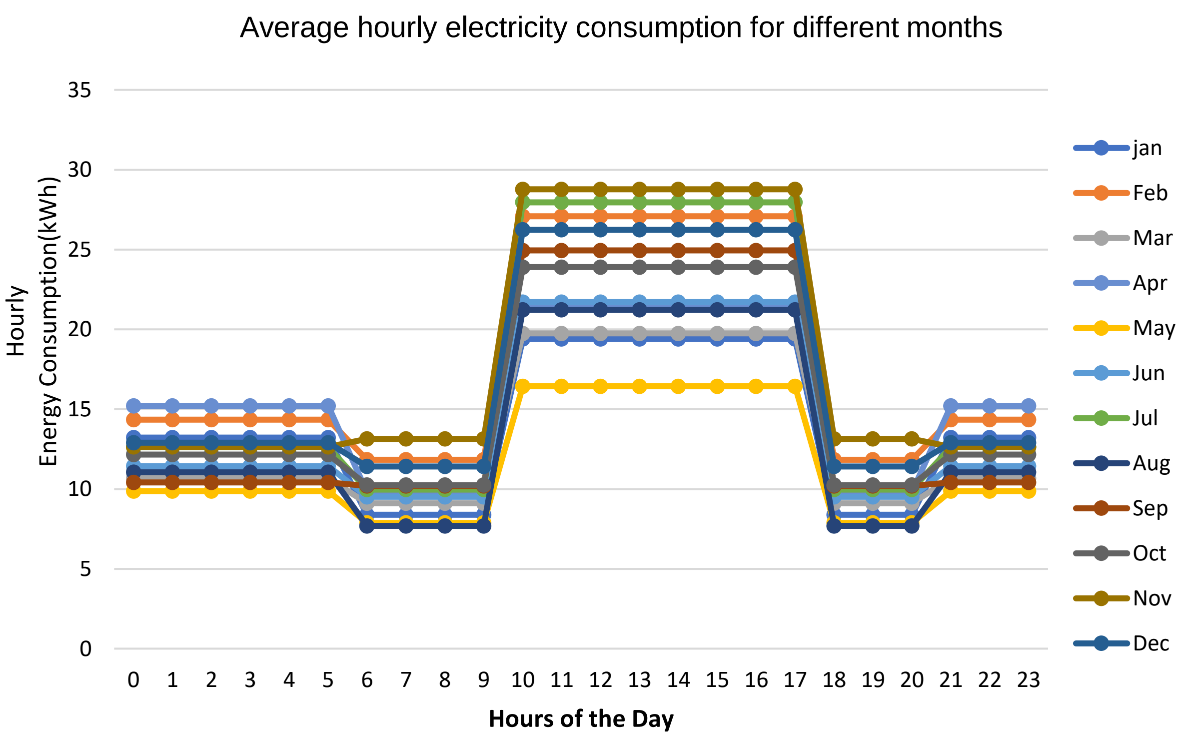

Figure 4.2 Average hourly energy consumption by month.

Table 4.1 Hourly energy consumption by month.

	Hours of the day																							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Jan	13.2	13.2	13.2	13.2	13.2	13.2	8.4	8.4	8.4	8.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	8.4	8.4	8.4	13.2	13.2	13.2
Feb	14.3	14.3	14.3	14.3	14.3	14.3	11.8	11.8	11.8	11.8	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	11.8	11.8	11.8	14.3	14.3	14.3
Mar	10.7	10.7	10.7	10.7	10.7	10.7	9.1	9.1	9.1	9.1	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	9.1	9.1	9.1	10.7	10.7	10.7
Apr	15.2	15.2	15.2	15.2	15.2	15.2	9.8	9.8	9.8	9.8	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	9.8	9.8	9.8	15.2	15.2	15.2
May	9.9	9.9	9.9	9.9	9.9	9.9	7.9	7.9	7.9	7.9	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	7.9	7.9	7.9	9.9	9.9	9.9
Jun	11.4	11.4	11.4	11.4	11.4	11.4	9.5	9.5	9.5	9.5	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	9.5	9.5	9.5	11.4	11.4	11.4
Jul	12.6	12.6	12.6	12.6	12.6	12.6	10.0	10.0	10.0	10.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	10.0	10.0	10.0	12.6	12.6	12.6
Aug	11.1	11.1	11.1	11.1	11.1	11.1	7.7	7.7	7.7	7.7	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	7.7	7.7	7.7	11.1	11.1	11.1
Sep	10.4	10.4	10.4	10.4	10.4	10.4	10.2	10.2	10.2	10.2	24.9	24.9	24.9	24.9	24.9	24.9	24.9	24.9	10.2	10.2	10.2	10.4	10.4	10.4
Oct	12.2	12.2	12.2	12.2	12.2	12.2	10.2	10.2	10.2	10.2	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	10.2	10.2	10.2	12.2	12.2	12.2
Nov	12.6	12.6	12.6	12.6	12.6	12.6	13.1	13.1	13.1	13.1	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	13.1	13.1	13.1	12.6	12.6	12.6
Dec	12.9	12.9	12.9	12.9	12.9	12.9	11.4	11.4	11.4	11.4	26.2	26.2	26.2	26.2	26.2	26.2	26.2	26.2	11.4	11.4	11.4	12.9	12.9	12.9

4.2 Technical simulation

The designed system's output is sufficient for the user's energy requirements. The PVSyst simulation provided the basis of the system design. The site's geographical coordinates were input into the program to determine the site-specific energy yields and other technical parameters. The solar PV layout uses the existing roof tilt thereby eliminating the need for extra solar PV panel mounting tilting. Figure 4.3 shows the solar PV layout. The complete PVSyst simulation report is included in the appendix section.

Figure 4.3 Solar PV roof layout.

The solar panels are installed at a 2.9° tilt on the IBR (inverted box rib) roof and due north. The PVSyst results showed that 175 solar panels of 585 Wp nominal power each. The total PV installed capacity is 102.375 kWp. The site is free from shading hence there are no shading effects noted in the design output. Figure 4.4 shows the PV installation's aerial perspective.

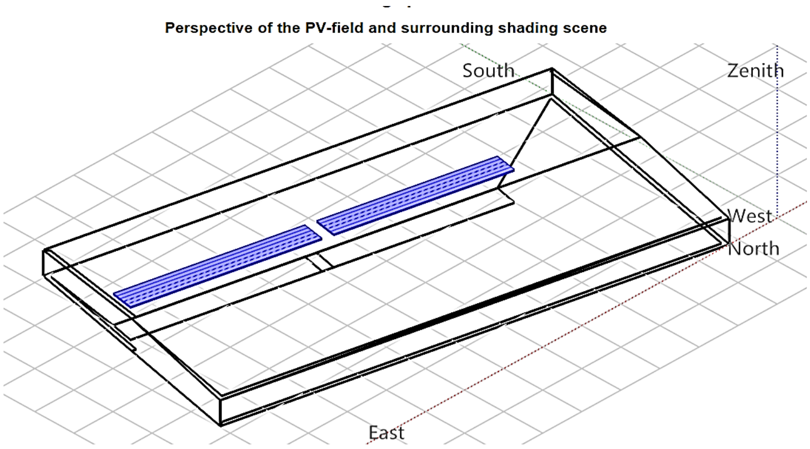

Figure 4.4 The perspective of the PV field and surrounding shading scene.

4.2.1 System losses

The system losses are quantified in the PV system's design simulation. For instance, most losses are due to temperature deviations amounting to 6.67%, whilst 3% of losses were attributed to soiling. There are no expected losses due to shading as the site is free from distractions. The system losses are shown in Figure 4.5.

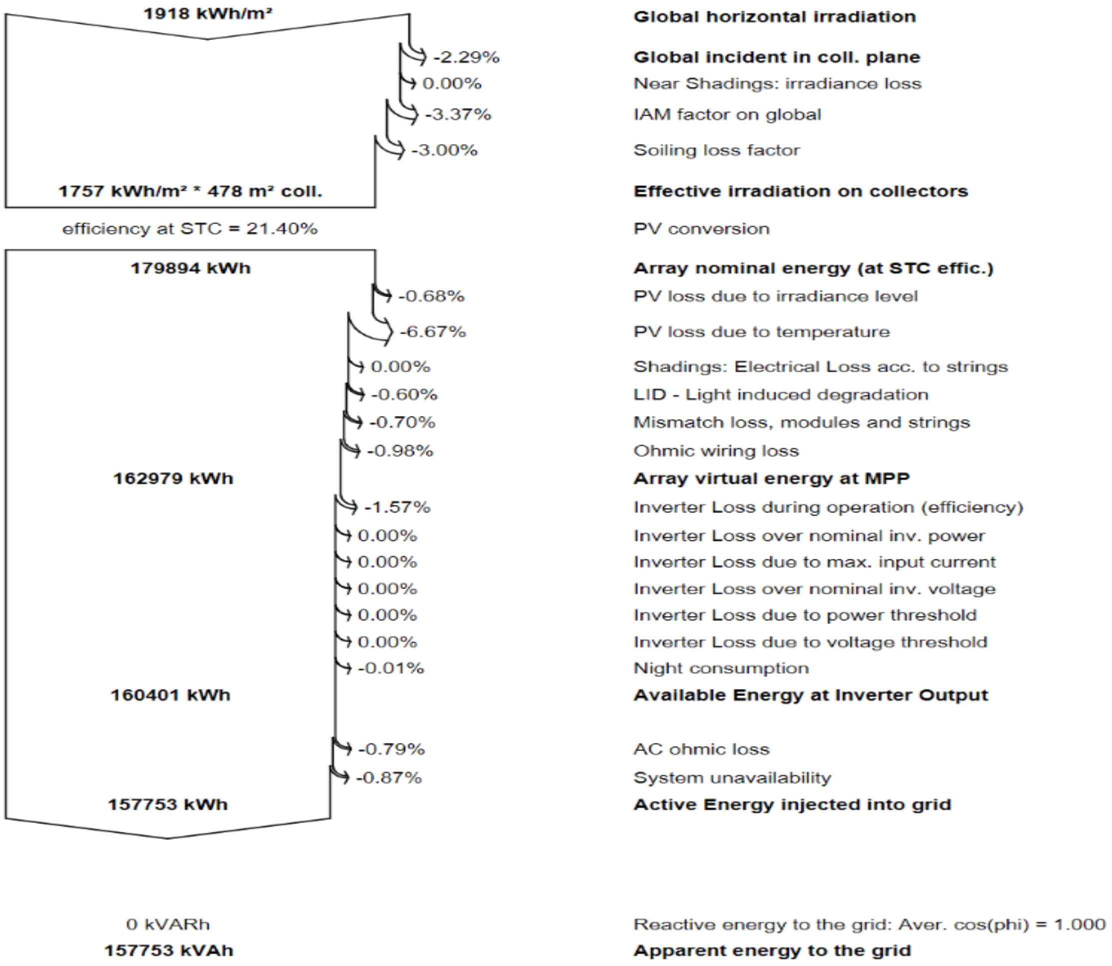

Figure 4.5 System losses diagram.

4.2.2 Performance ratio

PVSyst was used to determine the system's monthly performance ratio. The system's performance ratio was much lower in January, May and June as compared to other months in the year. The annual average system's performance ratio was recorded as 0.822, i.e. 82.2%. The system's performance ratio is a very important technical metric for the designed system, which enables easier comparison of different projects from various similar studies.

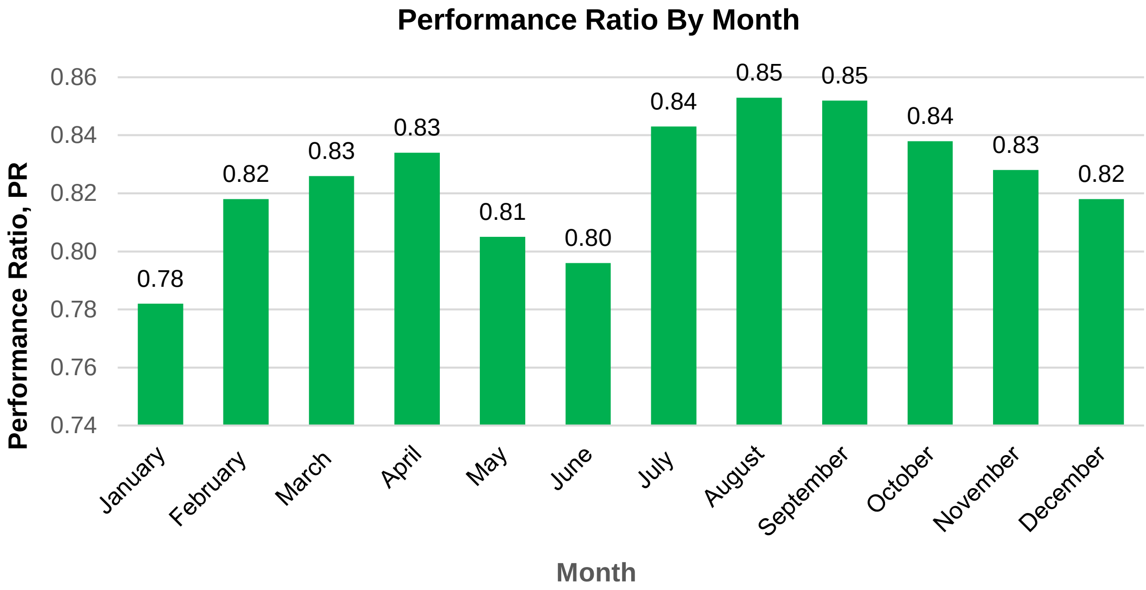

Figure 4.6 Monthly PV system's performance ratio.

4.2.3 Total usable energy generated

The monthly energy generation is quantified by using the simulation tool as shown in Figure 4.7. The month of December has the highest usable energy produced value of 20810kWh whilst June recorded the lowest usable energy produced value of 6 066kWh. The designed system's estimated energy yield is 157 753kWh of clean usable energy in the first year of operation. There is an annual degradation in the solar PV energy yield of 2% in the first year and then 0.55% thereafter as mentioned on the solar panel data sheets.

The designed system layout is shown in Figure 4.8. The simulation results show the configuration of the specifications of the system components. An estimated length of 380.2 metres of solar DC cable has been considered in the system layout.

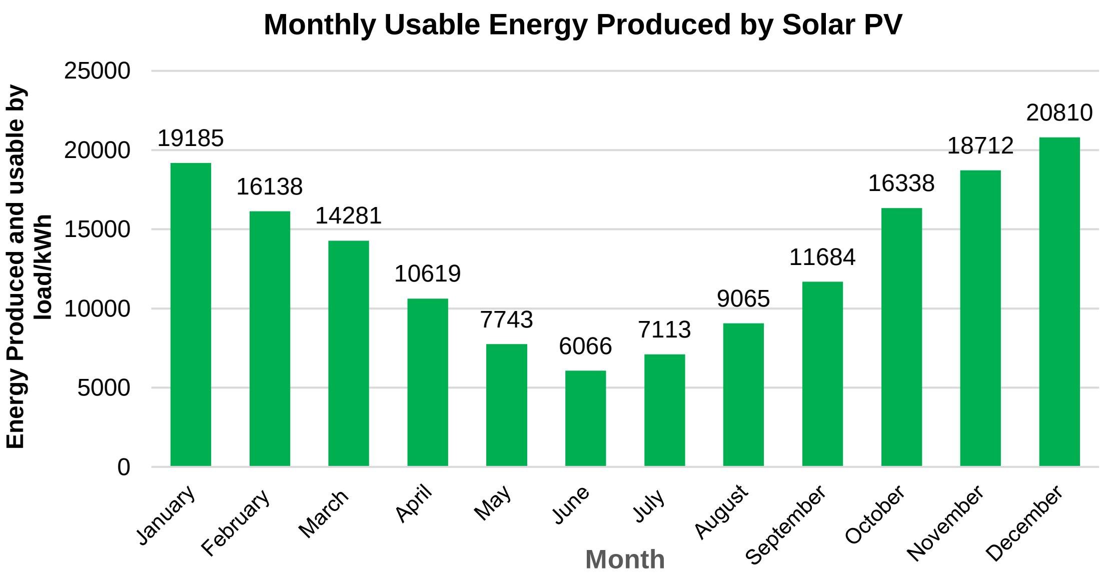

Figure 4.7 Monthly usable energy produced by solar PV.

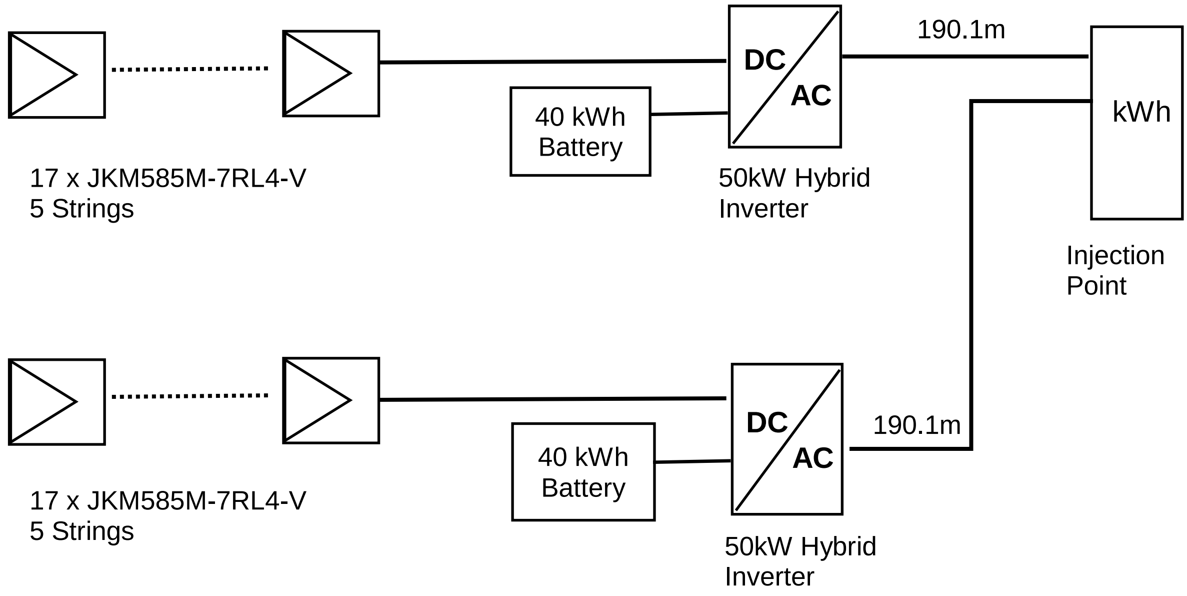

Figure 4.8 Solar system connection layout.

4.2.4 Solar panel specifications

There are various solar panels on the market. Table 4.2 shows the solar panel specifications used in this study.

Table 4.2 Solar panel specifications (JinkoSolar, 2020)

Technical Parameter	**Value**
Maximum Power Output at STC	585W
Maximum Power Voltage (V_{mp}) at STC	44.42V
Maximum Power Current (I_{mp}) at STC	13.17A
Power Output Degradation	2% first-year degradation and 0.55% thereafter.
Power Warranty	25 years
Module Efficiency	21.40%

4.2.5 Inverter selection

The inverter selection was done on the PVSyst platform subject to the type, and availability of the product in the South African market amongst many considerations. The inverter should be a hybrid inverter allowing for multiple energy sources to be connected to it. The inverter has an inbuilt MPPT charge controller to ensure proper charging.

To minimise the technical risk of system failure, two units of nominal output of 50kVA were selected as opposed to one 100kVA inverter unit. The Inverter specifications are summarised in Table 4.3. This document's appendix section contains the complete inverter datasheet.

Table 4.3 Inverter specifications (Ningbo Deye Inverter Technology Ltd, 2024).

Technical Parameter	Value
Battery Type	Lithium-Ion
Battery Input Voltage Range (V)	160 – 800 V
Max DC Input Power (W)	65 000W
Maximum DC Input Voltage (Solar PV)	1000V
MPPT Efficiency	99.6%
Rated AC Output	50 000W
Protection (anti-islanding protection, PV input lightning protection, PV string input reverse polarity protection, insulation resistor detection, output over-voltage protection, battery over current protection, output shorted protection, residual current monitoring unit, output over current protection)	Integrated

4.2.6 Battery Sizing

The hourly consumption data shown in Table 4.1 was used in the design of the battery system. The most active time of the day for this commercial operation is between 0900hrs and 1800hrs. Data analysis showed that the highest and average hourly energy consumption recorded over the annual period are 28,775kWh and 15,22kWh respectively. Assuming a four-hour backup time, equivalent to Stage 3 load-shedding and 1 day of autonomy (self-support), the battery sizing is calculated using equation [4.1].

$$\text{Battery Capacity} = \frac{\text{(Energy Required for the 4hr period * Days of Autonomy)}}{\text{(Depth of Discharge * Efficiency * Nominal Battery Voltage)}} \quad [4.1]$$

The energy required during the backup time was calculated by multiplying the average hourly energy consumption by 4 as shown in equation [4.2]

$$= 15\ 220\text{Wh} * 4 = \underline{60\ 880\text{Wh}} \quad [4.2]$$

The battery was selected from a local manufacturer. The recommended battery depth of discharge to achieve the rated 4000 cycles was stipulated as 80% though the maximum is 90%. The battery's nominal voltage is 410V whilst the efficiency is 96%.

Battery Capacity = (15 220Wh *4 * 1) / (0.8 * 0.96 * 410V)

= <u>193,35Ah</u>

The battery energy capacity in kWh can be calculated using equation [4.3]

$$= (410\text{V} * 193.35\text{Ah})/1000 \quad [4.3]$$

= <u>79,27kWh</u>

The energy capacity of the selected battery is 80kWh which will be sufficient for the project's requirements. Table 4.4 summarises the battery's specifications. The complete battery specifications sheet is provided in this document's appendix section.

Table 4.4 Battery specifications (FreedomWon, 2024).

Technical Parameter	Value
Total Energy Capacity	80kWh
Recommended Depth of Discharge	80%
Nominal Voltage	410V
Energy available at 80% DOD	64kWh

4.3 Economic analysis

The economic analysis is conducted by considering various variables. These include: -

- Prevalent electricity tariff and average electricity tariff increment
- Annual solar PV energy yield (kWh)
- System's capital cost
- Operation and maintenance costs
- Replacement costs
- Insurance costs
- Prevalent interest rate

This section focuses on the above-mentioned to derive the key project metrics using a customised Excel worksheet.

4.3.1 The system's total capital cost, C_{cap}

The total system cost, C_{cap} is determined by adding all the system component's prices as indicated in the system's bill of quantities. The bill of material showing the cost breakdowns is shown in Table 4.5.

Table 4.5 Designed system cost breakdown.

Qty	Description	Unit Cost	Total Cost
2	6mm2 single-core DC cable 100m - black	R1,899.33	R3,798.66
2	6mm2 single-core DC cable 100m - red	R1,899.33	R3,798.66
2	Deye 50kva hybrid inverter	R86,125.80	R172,251.60
175	JINKOSolar 585W Mono Perc Half-Cell MBB LR MC4	R1,374.75	R240,581.25
438	Solar Roof Universal Mid/End Clamp 30-45mm	R17.19	R7,529.22
2	Solar Roof Pro Rail 3500mm	R409.31	R818.62
86	Solar Roof Pro Rail 4600mm	R548.50	R47,171.00
2	Freedom Won Lite Commercial 40/32 HV battery	R190,087.99	R380,175.98
10	MC4 connector (twin pack)	R99.76	R997.60
2	10-way 1000Vdc 125A PV stringbox with surge protection	R14,260.00	R28,520.00
Total before VAT			R885,642.59
VAT at 15%			R132,846.39
Total Cost Payable			**R1,018,488.98**

4.3.2 System installation costs

The installation costs, **C**$_{inst}$ are assumed as a percentage of the total system costs as proposed by various researchers. Hasan *et al.* (2019) and Karmiathi *et al.* (2018) proposed that the system installation costs are approximately 3% and 5% respectively of the system upfront investment/capital cost. The researcher however assumes that the designed system's installation costs amount to 7.5% of the system's total capital cost as the highest of the aforementioned studies and a reasonable estimate. The installation costs are calculated using equation [4.4].

$$C_{installation} = 0.075 \times C_{cap} \quad [4.4]$$

= 0.075 * R1 018 488.98

= R76 386.67

4.3.3 Annual operation and maintenance costs

Previous studies have proposed various estimates of the operation and maintenance costs. Table 4.6 shows the values proposed for operation and maintenance cost estimation in some of the previous similar studies. The researcher assumed an average of the values included in the table for estimation purposes.

Table 4.6 Operation and maintenance cost estimation from previous studies.

Study Authors	**Operation and maintenance costs as a percentage of the total system costs**
Katyara *et al.* (2018)	2%
Karmiathi *et al.* (2018)	1%
Hasan *et al.* (2019)	3%
Mardikaningsih *et al.* (2016)	1-2 %

The researcher assumes that operation and maintenance costs amount to 2% of the total system costs. The operation and maintenance costs are calculated using equation [4.5].

$$C_{O\&M} = 0.02 \times C_{cap} \quad [4.5]$$

= 0.02 * R1 018 488.98

= R20 369.78

4.3.4 System replacement costs

The replacement costs are dependent on the frequency of system component replacement due to reaching the end of usable life. The period of assessment for this study is 20 years. The solar panels and cable have a typical lifespan of 25 years meaning that they will not be replaced during the assessment period. The lithium-ion batteries are more suitable for this project owing to their outstanding technical performance in addition to their being readily available in the market. The Lithium-ion batteries are rated at 4000 cycles. The lifespan of the batteries can be converted to years assuming a single daily cycle. The lifespan is calculated using equation [4.6].

The lifespan of batteries = 4 000 / 365 cycles per year [4.6]

= <u>10.96 years</u>

The above calculation indicates that the batteries will only be replaced once during the 20-year assessment period i.e. in the fourteenth year. Chowdhury et al (2021) suggested in a similar study that the estimated lifespan of an inverter is fifteen (15) years. The inverter replacement will therefore occur once during the assessment period.

The total replacement costs are the sum of the inverter replacement costs in year 16 (**C**$_{inv}$) and the battery replacement cost in year 11 (**C**$_{batt}$). Equation [4.7] shows their calculation.

[illegible] [4.7]

= R198 089.34 + R437 202.38

= <u>R635 291.72</u>

4.3.5 Annual system’s insurance cost

The solar system must be insured against damages and other accidental occurrences. In recent months, with the increased adoption of rooftop solar systems, there have been unfortunate incidents which resulted in buildings being damaged. For instance, the Vodacom building in Century City had a fire incident which though the solar system’s role in causing the fire was exonerated, has increased the need to have insurance coverage for on-site solar hybrid systems. The researcher assumes that the annual insurance costs amounted to 0.40% of the system's upfront capital cost. Equation [4.8] shows the calculation of these insurance costs.

[illegible] [4.8]

= 0.40% * R1 018 488.98

= <u>R4 073.96</u>

4.3.6 Interest Rate

The prevalent interest rate of 8.25% as per the country’s central bank, SARB, is assumed for this study. Using this interest rate, the discount factor for each year is calculated leading to the calculation of the annual and cumulative cash flows.

4.3.7 Annual Electricity Tariff increments

The electricity tariffs in South Africa have been ever-increasing over the last number of years. However, the percentage annual increase has been varying. For this study, the researcher considered the tariff increments over the last 10 years to establish an average percentage increase to use in the economic modelling. The average value of the electricity tariff percentage increments since the 2014/2015 cycle is 10.56%. The researcher assumed a fixed annual escalation of the electricity tariff from year to year. The monetary value of the solar PV system's generated energy is calculated by multiplying the energy amount by the prevalent electricity tariff. The site energy consumption falls in Cape Town's Small Power Users 1 electricity tariff. The electricity tariff percentage increase in 2023/2024 was 18.65% whilst it was 12.72% for the 2024/2025 financial year (Eskom, 2024). The electricity tariff at the start of the project is estimated by applying the tariff percentage escalations to the 2022/2023 gazetted tariff of R1.65/kWh. Accordingly, at the start of the project, the electricity tariff is R2.20/kWh.

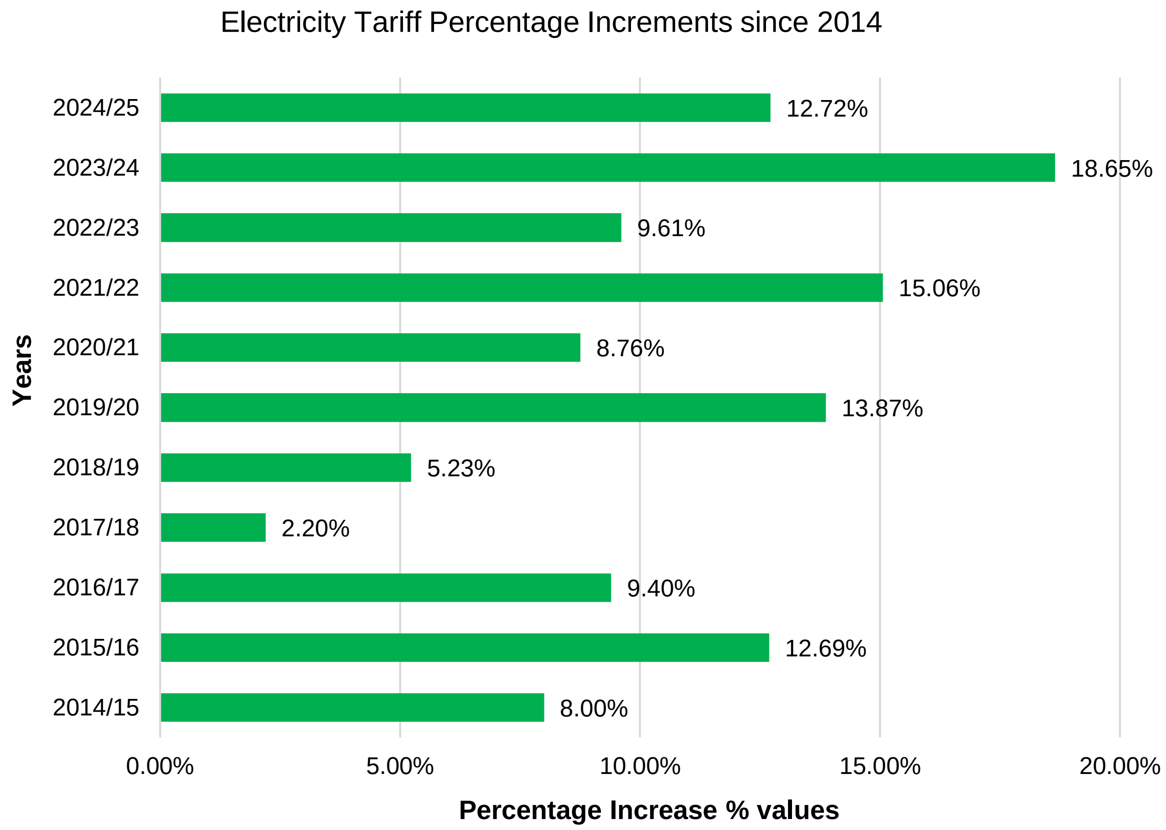

Figure 4.9 Electricity tariff percentage increments since 2014 (Eskom, 2024).

Table 4.7 and Figure 4.10 ensuing show the project's economic analysis. All the costs and cash flows are shown. A detailed summary on the economic analysis follows in section 4.6.

Table 4.7 Economic analysis showing costs and cash flows.

Yea	Cash Investm	Instal Cost /	Replac Costs	Annual Op & Mainte Cost / R (2% of C	Insura Cost / (0.40 Capex	Elect tari (R/k	Energ Genera from S PV (kWh)	Value of Energ Saved by Solar PV Ene to Gri	Undisco Annual Flow / R	Disc fact	Discour cash flo	Cumulat Cash Fl
0	-R1,018,488.98	-76,386.67							-R1,094,875.65	1.000	-R1,094,875.65	-R1,094,875.65
1				-R20,369.78	-R4,073.96	R2.20	157,753	R347,340.42	R322,896.69	0.924	R298,287.93	-R796,587.72
2				-R20,369.78	-R4,073.96	R2.43	154,598	R376,348.46	R351,904.73	0.853	R300,309.65	-R496,278.07
3				-R20,369.78	-R4,073.96	R2.69	153,748	R413,812.57	R389,368.83	0.788	R306,956.95	-R189,321.12
4				-R20,369.78	-R4,073.96	R2.98	152,902	R455,006.09	R430,562.35	0.728	R313,562.73	R124,241.61
5				-R20,369.78	-R4,073.96	R3.29	152,061	R500,300.27	R475,856.54	0.673	R320,137.47	R444,379.08
6				-R20,369.78	-R4,073.96	R3.64	151,225	R550,103.32	R525,659.59	0.621	R326,690.99	R771,070.07
7				-R20,369.78	-R4,073.96	R4.02	150,393	R604,864.09	R580,420.35	0.574	R333,232.46	R1,104,302.53
8				-R20,369.78	-R4,073.96	R4.45	149,566	R665,076.08	R640,632.35	0.530	R339,770.46	R1,444,073.00
9				-R20,369.78	-R4,073.96	R4.92	148,743	R731,281.96	R706,838.22	0.490	R346,313.07	R1,790,386.07
10				-R20,369.78	-R4,073.96	R5.44	147,925	R804,078.39	R779,634.65	0.453	R352,867.84	R2,143,253.91
11			-R437,202.38	-R20,369.78	-R4,073.96	R6.01	147,112	R884,121.44	R422,475.32	0.418	R176,642.17	R2,319,896.08
12				-R20,369.78	-R4,073.96	R6.64	146,302	R972,132.47	R947,688.74	0.386	R366,041.95	R2,685,938.03
13				-R20,369.78	-R4,073.96	R7.35	145,498	R1,068,904.69	R1,044,460.95	0.357	R372,674.30	R3,058,612.33
14				-R20,369.78	-R4,073.96	R8.12	144,698	R1,175,310.22	R1,150,866.48	0.330	R379,344.92	R3,437,957.25
15			-R198,089.34	-R20,369.78	-R4,073.96	R8.98	143,902	R1,292,308.03	R1,069,774.95	0.304	R325,742.07	R3,763,699.32
16				-R20,369.78	-R4,073.96	R9.93	143,110	R1,420,952.54	R1,396,508.81	0.281	R392,823.26	R4,156,522.58
17				-R20,369.78	-R4,073.96	R10.98	142,323	R1,562,403.14	R1,537,959.41	0.260	R399,641.41	R4,556,163.99
18				-R20,369.78	-R4,073.96	R12.14	141,540	R1,717,934.63	R1,693,490.89	0.240	R406,518.74	R4,962,682.74
19				-R20,369.78	-R4,073.96	R13.42	140,762	R1,888,948.70	R1,864,504.97	0.222	R413,459.86	R5,376,142.59
20				-R20,369.78	-R4,073.96	R14.84	139,988	R2,076,986.60	R2,052,542.86	0.205	R420,469.15	R5,796,611.74
												R45,358

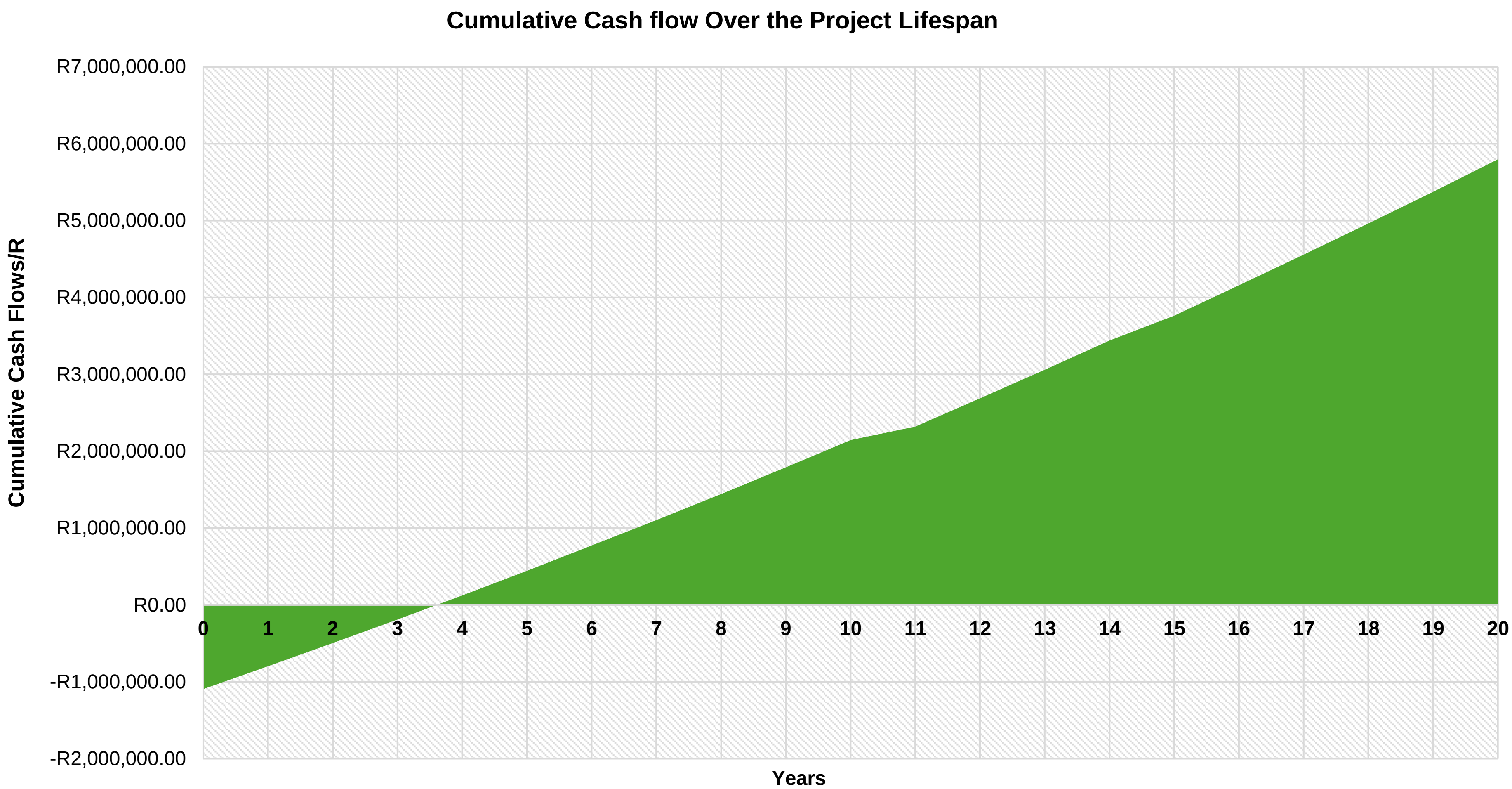

Figure 4.10 Graph showing cumulative cash flows over the project lifespan.

4.4 Economic metrics evaluation

The economic metrics evaluated in the study include: -

¶ NPV
¶ IRR

Project Feasibility evaluation was determined by assessing the economic metric values calculated from the Excel model. With regards to NPV,

¶ The project will be accepted and considered feasible provided the NPV is greater than zero.
¶ The project will be rejected i.e. considered unfeasible provided the NPV is lesser than zero.

With regards to IRR,

¶ The project will be accepted i.e. deemed feasible provided the project's IRR exceeds than the prevalent interest rate.
¶ The project will be rejected i.e. deemed unfeasible provided the project's IRR is lower than the prevalent interest rate.

The NPV and IRR for the project were calculated using the Excel worksheet. The NPV value is R45 358 870.35 whilst the IRR is 27.55%. Since the project's calculated IRR of 27.55% is greater than the interest rate of 8.25%, the project is deemed to be feasible. In the same vein, the project's NPV value is R45 358 870.35 is greater than 0, the project is considered feasible.

Table 4.8 Summary of project economic metrics.

Economic metric	Value
NPV	R45 358 870.35
IRR	27.55%

4.5 Sensitivity analysis

The sensitivity analysis considered changes in some variables such as battery pricing, electricity tariff and interest rate. Determining the effects of the changes in these variables provides insight into the project's feasibility over the project's lifespan. Each of the variables was investigated and the outcomes were determined.

4.5.1 Battery pricing

The battery pricing has declined over time. The sensitivity analysis considered changes to the battery pricing. The results in Table 4.9 show that there are marginal changes in the IRR and NPV of the different scenarios as compared to the base case. The project will still be considered feasible despite the changes in the battery pricing during the 20-year term.

Table 4.9 Sensitivity analysis on battery pricing.

Battery pricing scenario	NPV	IRR
10% decrease	R45 541 670.09	27.58%
5% decrease	R45 450 270.02	27.57%
0% decrease/increase i.e. No change (Base Case)	R45 358 870.35	27.55%
5% increase	R45 267 470.49	27.53%
10% increase	R45 176 070.62	27.52%

4.5.2 Annual electricity tariff escalation

Over the past 15 years, the electricity tariff has been increasing serving as a driver to adopt cheaper energy sources by consumers. The sensitivity analysis considered changes in the annual electricity tariff. As shown in Table 4.10, there is a slight deviation from the NPV and IRR values of the base case in comparison to that of the scenarios modelled. The project will be more financially sound with a huge electricity tariff increase. The project is considered feasible as the NPV and IRR values of each scenario are shown in Table 4.10.

Table 4.10 Sensitivity analysis on annual electricity tariff changes.

Electricity tariff changes	NPV	IRR
0% decrease/increase i.e. No change	R45 541 670.09	15.97%
5% increase	R45 450 270.02	21.70%
10% increase	R42 908 867.25	26.98%
10.56% increase (Base Case)	R45 358 870.35	27.55%
15% increase	R69 410 111.97	32.00%
20% increase	R110 496 093.97	36.87%

4.5.3 Interest rate changes

Over the past year, the interest rate has changed more than three times. The interest rate has a huge bearing on the total cost of capital. In this regard. The sensitivity analysis considered changes in the prevalent interest rate. Table 4.11 shows a marginal change in the project's NPV and IRR for the various interest rate change scenarios compared to the base case.

Table 4.11 Sensitivity analysis on interest rate changes.

Changes to the current interest rate	NPV	IRR
0.25% increase	R44 154 646.53	27.24%
0.50% increase	R42 994 568.61	26.93%
0.75% increase	R41 865 416.82	26.62%
1% increase	R40 766 167.64	26.31%
0% change (Base Case)	R45 346 714.77	27.55%
0.25% decrease	R46 571 879.96	27.86%
0.50% decrease	R47 831 293.12	28.17%
0.75% decrease	R49 126 151.59	28.49%
1% decrease	R50 457 701.13	28.81%

According to the criteria described in earlier sections of this subsection, it was observed that the project remains feasible thus the project can be executed accordingly.

This section showed a comprehensive economic analysis in which parameters such as NPV and IRR are calculated. A sensitivity analysis for the various variables was conducted to determine the impact of any deviation to the project's feasibility. In conclusion, the project's feasibility has been demonstrated. It was observed that changes in the variables stated above have a marginal effect on the financial viability of the project.

4.6 Summary of economic analysis

The economic analysis of the designed solar photovoltaic (PV) system with battery backup is comprehensively illustrated in Table 4.7 and further visualised in Figure 4.10. Figure 4.10 illustrates the trajectory of cumulative cash flow over the project term, providing a clear visual representation of the financial performance of the solar PV system. In Figure 4.10, the x-axis represents time in years, and the y-axis represents the cumulative cash flow in Rands (R).

Table 4.7 presents a structured breakdown of the various costs and cash flows over the project's term. An initial capital investment of R1 018 488.98 at the start of the project comprised the cost of system components and the installation costs. This upfront investment is shown as a negative entry in both Table 4.7 and Figure 4.10. The table also outlines the annual operation and maintenance costs, amounting to R76 386.67 translating to 2% of the initial capital expenditure. In addition to operational costs, Table 4.7 shows an annual insurance cost of R4 073.96 which is 0.40% of upfront investment. The electricity tariff at project inception is R2.20 per kWh, with future projected tariff increments over the project's duration. This highlights the economic benefit of generating energy through the designed solar PV system. In Year 1, the designed solar PV system's expected energy yield is 157 753 kWh, resulting in energy savings amounting to R347 340.42. However, there is a degradation of the system's energy yield as the project lapses with the maximum being recorded in year 1. The electricity tariff increases gradually as the project lapses. The generated energy savings increase over the project's term from R347 340.42 in Year 1 to R2 076 986.60 in the 20th year which is the end of the project.

For Year 1, the cash flow analysis shows that the undiscounted annual cash flow of R322 896.69 indicates a significant inflow after accounting for operational costs and energy savings. However, the discounted cash flow in Year 1 is R298 287.93 indicating immediate and long-term investment returns. By the end of Year 1, the cumulative cash flow is still negative (- R796 587.72), showcasing a positive progression from -R1 018 488.98 at project inception. Figure 4.10 shows a positive cumulative annual cash flow between 3rd and 4th year indicating the payback period which is grown graphically when the curve crosses the x-axis. This highlights the project's financial viability. The payback period for the study is 3.4 years.

In summary, the combination of Table 4.7 and Figure 4.10 offers a comprehensive view of the economic analysis of the solar PV system. Figure 4.10 complements the data shown in Table

4.7 through a visual representation of the cash flow dynamics over the project term. The detailed breakdown of costs, cash flows, and visual representation of financial performance highlights the project's financial viability.

4.7 Comparison of research findings with prior studies.

The researcher compared the findings from the study to that of other relevant studies. Table 4.12 presents the solar PV system performance ratios across diverse global locations, offering valuable insights into the influence of geographical and environmental factors on system efficiency.

de Lima *et al.* (2016) conducted an in-depth analysis of a 2.2 kWp system in Brazil observing a performance ratio of 82.90%. This data points to a moderately efficient system, reflecting Brazil's unique climatic conditions. In Graaff-Reinet, South Africa, Mhundwa *et al.* (2020) analysed the performance of a 75 kWp solar PV plant which recorded a performance ratio of 80%. In a study conducted in Durban, South Africa, Adebiyi *et al.* (2019) evaluated an 8 kWp solar PV system, observing an average performance ratio of 87.10% which is quite high. This suggests that the system's optimal operation and provides an indication of the favourable weather conditions. Goel and Sharma (2020) recorded a performance ratio of 81% when they evaluated an 11.2 kWp system in India. Dondariya *et al.* (2018) showed a performance ratio of 75.01%. Jbilou *et al.* (2024) in their study in Algeria, observed a performance ratio of 80.7% for a 12 MWp solar PV plant.

Table 4.12 Summary of different results from various studies

Study Location	System Array size	Performance Ratio	References
Graaff-Reinet, South Africa	75 kWp	80%	Mhundwa *et al.* (2020)
Brazil	2.2 kWp	82.90%	de Lima *et al.* (2016)
Durban, South Africa	8 kWp	87.10%	Adebiyi *et al.* (2019)
Bhubaneswar, India.	11.2 kWp	81%	Goel and Sharma (2020)
Port Elizabeth, South Africa	3.2 kWp	84.3%	Okello *et al.* (2015)
Nouakchott, Mauritania	15 MWp (15 000 MWp)	67.96%	Sidi *et al.* (2016)
Ujjain, India	6.4 kWp	75.01	Dondariya *et al.* (2018)
Dhaya, Algeria	12 MWp (12 000 kWp)	80.7%	Jbilou *et al.* (2024)
Cape Town, South Africa	102.375 kWp	82.2%	Current study

Okello *et al.* (2015) evaluated a 3.2 kWp solar PV system in Port Elizabeth, South Africa, observing an average performance ratio of 84.3%. This highlights an efficient system considering the region's solar potential. Sidi *et al.* (2016) conducted a study for a 15MWp (15 000kWp) solar PV plant in Mauritania where they observed a performance ratio of 67.96%. Finally, the current study in Cape Town, South Africa, evaluated the performance of a much larger solar PV system in comparison to the smaller systems mentioned earlier. The study of the designed 102.375 kWp solar PV system revealed a performance ratio of 82.2%, which is consistent with other studies in similar climates, thereby indicating a reliable and efficient system operation.

In summary, the findings from other studies across various locations provide understanding of solar PV system performances. The performance ratios of the aforementioned studies range from 67.96% to 87.10%, highlighting the importance of location-specific factors in maximising the efficiency and effectiveness of solar energy systems. The recorded performance ratio for this study of 82.2% is a good indicator of the system's technical performance.

CHAPTER FIVE

CONCLUSION

5.0 Introduction

The research study focused on determining the techno-economic feasibility of a solar PV system with battery backup for commercial applications. The research study's findings demonstrate the techno-economic feasibility of implementing the designed solar PV system at the identified site. The technical analysis mainly using PVSyst provided a comprehensive evaluation of the performance metrics of the designed solar PV system. It included the assessment of key technical indicators such as energy yield and performance ratio which are essential for understanding the system's expected performance. The technical analysis provided a foundation for the economic evaluation. The required capital investment amounted to R1 018 488.98. The designed system's economic evaluation metrics such as NPV and IRR were calculated. The net present value (NPV) is R45 358 870.35 whilst the calculated IRR (internal rate of return) is 27.55%. These findings present up-to-date standardised information to help the company, similar consumers and other stakeholders such as investors to make accurate decisions based on current and up-to-date insights. The study revealed the potential capital investments that are required to set up similar plants. In a time where solutions are being sought, the researcher believes the findings also add to the knowledge base in the academic field for future reference. The research helps provide insights on improving energy costs and its success may be replicated in other areas within the Western Cape, the rest of South Africa and the world at large.

5.1 Financial viability

The solar system project requires a capital investment of R1 018 488.98. The project's internal rate of return (IRR) is 27.55%, whilst the net present value (NPV) is R45 358 870.35. The research calculated the designed system's discounted payback period for the project is 3.40 years. The project's financial viability is further highlighted by the expected energy savings worth R18 624 092.67.

5.2 Technical feasibility

The 102.375 kWp solar PV system designed consists of many components mainly two units of 50 kVA hybrid inverters, 175 solar PV panels rated 585W mounted on an IBR roof and two 40 kWh batteries. The performance ratio of the designed system is 82.20%. This indicates the system's good performance.

5.3 Dissertation deliverables

5.3.1 Technical simulation results

The technical simulation results from the PVSyst simulation are a key deliverable of this study. The PVSyst simulation results include energy yield estimations for the designed system over the period of assessment. The designed system's performance ratio indicates the efficiency of the system, comparing the solar PV actual output to the expected output from the installed capacity. The technical simulation results also provide insight into the technical parameters such as the specifications of the solar PV system, including array size, inverter capacity etc. The technical simulation results form the basis for the economic evaluation.

5.3.2 Economic viability evaluation

A detailed economic evaluation of the designed solar PV system is also a key dissertation deliverable. The economic viability evaluation consists of the following key sub-sections:

- Net present value (NPV) calculation using the annual cash flows generated by the designed solar PV system over the project's term.
- Calculation of the project's internal rate of return (IRR) indicating the financial viability.
- Comprehensive analysis of the expected lifespan of components and subsequent calculation of associated replacement costs during the project's tenure.
- A comprehensive breakdown of all costs inclusive of the solar PV equipment, installation, insurance and operation and maintenance costs of the designed solar PV system.
- Calculation of the projected energy cost savings due to the solar PV system's energy generation.
- Sensitivity analysis summary of the impact of changes of key variables on the project's economic feasibility.

5.3.3 Possible application of the research study findings

The research study findings have several potential uses and/or applications. Some of the key applications are listed below.

a) Adoption of solar PV solutions in the commercial sector

The research findings are current and relevant to businesses interested in implementing solar PV systems for electricity cost management, improvement of power supply security of power and advance their sustainability goals.

b) Policy development

The research findings provide current insights on the economic viability of solar PV systems with battery backup for commercial applications. The insights are critical for development and implementation of promotive regulatory frameworks for renewable energy adoption. The research findings are relevant to the development of national and local energy security strategies, helping to mitigate the impacts of load shedding and energy shortages.

c) Potential investment decisions

The evaluation of key economic metrics (such as NPV and IRR) derived from the study provides a clear understanding of potential returns leading to investment promotion and attraction of renewable energy projects. Funding stakeholders such as banks can use the findings to formulate innovative financial products and solutions such as loans for customers to adopt solar PV solutions.

d) Academic and research contributions

The study's findings serve as the basis for future academic research on solar energy systems, advancing the knowledge base. Educational institutions can incorporate the study's findings into their curricula, thereby improving the understanding of renewable energy systems among students and staff.

e) Technological advancements

The insights gained from this study can lead to innovative solar PV system design and energy yield optimisation. Solar PV equipment manufacturers and distributors can use the research findings to develop and promote more efficient and cost-effective products which are tailored to the South African environment.

5.3.4 Contribution to knowledge

This research makes a significant contribution to the field of renewable energy, particularly in the domain of solar photovoltaic (PV) systems integrated with battery storage for commercial applications. The key contributions are summarised as follows:

a) Innovative techno-economic assessment framework

This study offers a robust and comprehensive framework for the techno-economic evaluation of solar PV systems. By integrating technical performance and economic metrics, this framework offers a systematic approach for stakeholders to assess the viability of solar energy solutions in commercial contexts. It sets a precedent for similar evaluations in varied geographic and regulatory environments, enhancing the research findings' applicability.

b) Substantial empirical data and simulation outcomes

Employing advanced simulation tools such as PVSyst, this research presents empirical data demonstrating the operational viability of solar PV systems under South African conditions. The simulated annual energy yield of approximately 157 753 kWh and a performance ratio of 82.20%, offer critical metrics that can guide future research and practical implementations.

c) Detailed financial viability metrics

The study presents key financial figures such as a net present value (NPV) of ZAR 45 358 870.35 and an internal rate of return (IRR) of 27.55%. Such metrically-based determinations are reference for investors, policymakers, and businesses contemplating investment in clean energies, hence promoting the use of clean technologies.

d) Policy and regulatory framework contributions

Insights derived from this research carry substantial implications for policymakers advocating for supportive regulatory measures and incentives promoting the adoption of solar energy solutions. By identifying the economic benefits highlighted in this study, policymakers can develop frameworks that facilitate market penetration of renewable energy technologies, thereby advancing national sustainability goals.

e) Advancement of future research pathways

The findings from this study open avenues for further academic inquiry, particularly in the optimisation of solar PV systems and the exploration of their applications in diverse environmental and regulatory contexts. Recommendations for subsequent studies include investigations into larger-scale systems, regional variations in solar resource availability, and the performance of evolving technologies under different climatic conditions—fostering a continuous cycle of innovation in the field.

f) Educational enhancement and knowledge dissemination

The research findings enhances academic discourse and curricula surrounding renewable energy technologies. By incorporating these findings into educational programs, institutions can better equip students and professionals with the knowledge needed to address the pressing challenges posed by the global energy transition.

In summary, this research enhances the theoretical understanding of solar PV systems providing practical insights that promote informed decision-making among various stakeholders. The implications of these findings extend beyond the immediate study, facilitating a broader transition toward sustainable energy solutions in South Africa and potentially setting a foundation for global applications.

5.4 Recommendations for further study

The researchers recommend future studies on technological devices to improve system output for solar PV panel cleaning considering the Cape Town weather. The study is based on simulations to determine the system outputs. Considering that, the researcher proposes future studies to be based on experimental data to collate and calculate system outputs. The researcher further recommends studies on much bigger systems to determine techno-economic feasibility in other regions such as KwaZulu-Natal. The researcher is aware of the net-metering programme which is ongoing in other metropolitan areas. The researcher proposes that there should be more studies to determine the techno-economic feasibility of systems under the net-metering programme in South Africa. There is a huge uptake of utility-scale Solar PV and battery energy storage systems (BESS). The researcher suggests that there should be studies on the techno-economic viability of such systems in areas of lower solar irradiation. In addition, since there are various business models, such as power purchase agreements and leasing options, the researcher suggests comparative studies between various business models to determine which one is more favourable for the different system sizes.

Since the hybrid inverter considered in this project converts DC power to AC power, it is essential to study the implications of directly injecting power into a DC grid. Further investigations could explore the performance benefits, potential cost savings, and efficiency improvements associated with DC grid systems compared to traditional AC grids. Research should also address the technical requirements and challenges of transitioning to a DC grid infrastructure in commercial applications.

In addition, future studies should investigate the feasibility of replacing traditional battery energy storage systems (BESS) with Hydrogen Fuel Cells (HAE-FC) or other alternative energy storage systems. This research could focus on evaluating the technical, economic, and environmental advantages and challenges associated with using HAE-FC technologies, particularly in regions where hydrogen production is feasible.

Incorporating real-time solar PV forecasting into the management of hybrid solar systems presents a significant opportunity for enhancing energy efficiency and reliability. Future research should assess how forecasting technologies can be integrated into existing systems to optimise energy production and consumption, improving financial performance and system reliability.

5.5 Anticipated publications

The researcher aims to contribute to the academic and professional discourse surrounding renewable energy applications. In this regard, the researcher expects to pursue various routes to publish the study’s findings. Such platforms include various reputable academic journals such as the International Journal of Energy Research, and also at energy and research conferences such as Solar Power Africa, and industry publications focusing on renewable energy, and related fields such as Energize.

5.6 Conclusion

The research aimed to evaluate the techno-economic feasibility of implementing solar photovoltaic (PV) hybrid systems with energy storage for commercial applications. The research aim was achieved through a detailed analysis that included both technical and economic assessments. The technical evaluation used simulation tools like PVSyst for system sizing and configuration of the solar PV system and battery storage, which provided insights into the system's performance metrics such as energy yield and performance ratio. Economically, a comprehensive cost analysis was performed, calculating the initial capital outlay and assessing financial metrics like the internal rate of return and payback period. The comparison of these metrics with similar studies offered valuable insights into the economic viability of the designed system.

The research study provided a comprehensive analysis of the techno-economic feasibility of solar photovoltaic systems with battery backup for commercial application in Cape Town. The research findings showed the viability of solar PV systems as alternative energy solutions to curb energy insecurity. Considering, the ever-increasing electricity utility tariffs, the solar PV systems yield significant economic benefits. The rigorous performance evaluations and cost analyses showed that adoption of renewable energy technologies yield long-term savings and contribute to a more sustainable energy future. The researcher will pursue the publication of the outcomes in contribution to the academic and professional discourse surrounding renewable energy applications, thereby fostering greater awareness and adoption of such technologies. The study findings demonstrate the advantage of adopting renewable energy solutions such as solar PV systems in commercial settings. There is also a good prospect to adopt the renewable energy solutions in different settings by the broader community to attain energy resilience and sustainability. The researcher presents the dissertation hoping it will serve as a call to action for stakeholders in the energy sector to embrace innovative solutions in alignment with global sustainability goals, ensuring a cleaner, more reliable energy landscape for future generations.

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APPENDIX A: PVSYST TECHNICAL SIMULATION REPORT

Version 7.4.6

PVsyst - Simulation report

Grid-Connected System

Project: Project 222625198

Variant: New simulation variant

System power: 102 kWp

Project summary

Geographical Site

South Africa

Situation

Latitude	-33.97 °S
Longitude	18.69 °E
Altitude	60 m
Time zone	UTC+2

Project settings

Albedo	0.20

Weather data

Meteonorm 8.1 (2000-2017), Sat=100% - Synthetic

System summary

Grid-Connected System

Tables on a building

PV Field Orientation

Fixed plane

Tilt/Azimuth 2.9 / 168 °

Near Shadings

According to strings : Fast (table)

Electrical effect 100 %

User's needs

Unlimited load (grid)

System information

PV Array

Nb. of modules	175 units
Pnom total	102 kWp

Inverters

Nb. of units	2 units
Pnom total	100 kWac
Pnom ratio	1.024

Results summary

Produced Energy	157753 kWh/year	Specific production	1541 kWh/kWp/year	Perf. Ratio PR	82.21 %
Apparent energy	157753 kVAh/year				

Table of contents

General parameters

Grid-Connected System — **Tables on a building**

PV Field Orientation

Orientation		**Sheds configuration**	**Models used**	
Fixed plane			Transposition	Perez
Tilt/Azimuth	2.9 / 168 °		Diffuse	Perez, Meteonorm
			Circumsolar	separate

Horizon	**Near Shadings**		**User's needs**
Free Horizon	According to strings : Fast (table)		Unlimited load (grid)
	Electrical effect	100 %	

Grid injection point

Power factor

Cos(phi) (lagging) 1.000

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	Jinkosolar	Manufacturer	Huawei Technologies
Model	JKM585M-7RL4-V	Model	SUN2000-50KTL-M0_400Vac
(Original PVsyst database)		(Custom parameters definition)	
Unit Nom. Power	585 Wp	Unit Nom. Power	50.0 kWac
Number of PV modules	175 units	Number of inverters	2 units
Nominal (STC)	102 kWp	Total power	100 kWac

Array #1 - PV Array			
Number of PV modules	85 units	Number of inverters	1 unit
Nominal (STC)	49.7 kWp	Total power	50.0 kWac
Modules	5 string x 17 In series		
At operating cond. (50°C)		Operating voltage	200-1000 V
Pmpp	45.4 kWp	Max. power (=>40°C)	55.0 kWac
U mpp	685 V	Pnom ratio (DC:AC)	0.99
I mpp	66 A	Power sharing within this inverter	

Array #2 - Sub-array #2			
Number of PV modules	90 units	Number of inverters	1 unit
Nominal (STC)	52.7 kWp	Total power	50.0 kWac
Modules	5 string x 18 In series		
At operating cond. (50°C)		Operating voltage	200-1000 V
Pmpp	48.0 kWp	Max. power (=>40°C)	55.0 kWac
U mpp	725 V	Pnom ratio (DC:AC)	1.05
I mpp	66 A	Power sharing within this inverter	

Total PV power		**Total inverter power**	
Nominal (STC)	102 kWp	Total power	100 kWac
Total	175 modules	Max. power	110 kWac
Module area	478 m²	Number of inverters	2 units
		Pnom ratio	1.02

Array losses

Array Soiling Losses
Loss Fraction 3.0 %

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 20.0 W/m²K
Uv (wind) 0.0 W/m²K/m/s

LID - Light Induced Degradation
Loss Fraction 0.6 %

Module Quality Loss
Loss Fraction 0.0 %

Module mismatch losses
Loss Fraction 0.6 % at MPP

Strings Mismatch loss
Loss Fraction 0.1 %

IAM loss factor
Incidence effect (IAM): Fresnel, AR coating, n(glass)=1.526, n(AR)=1.290

0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.999	0.987	0.962	0.892	0.816	0.681	0.440	0.000

DC wiring losses

Global wiring resistance 10 mΩ
Loss Fraction 1.5 % at STC

Array #1 - PV Array
Global array res. 171 mΩ
Loss Fraction 1.5 % at STC

Array #2 - Sub-array #2
Global array res. 181 mΩ
Loss Fraction 1.5 % at STC

System losses

Unavailability of the system
Time fraction 1.0 %
3.7 days,
3 periods

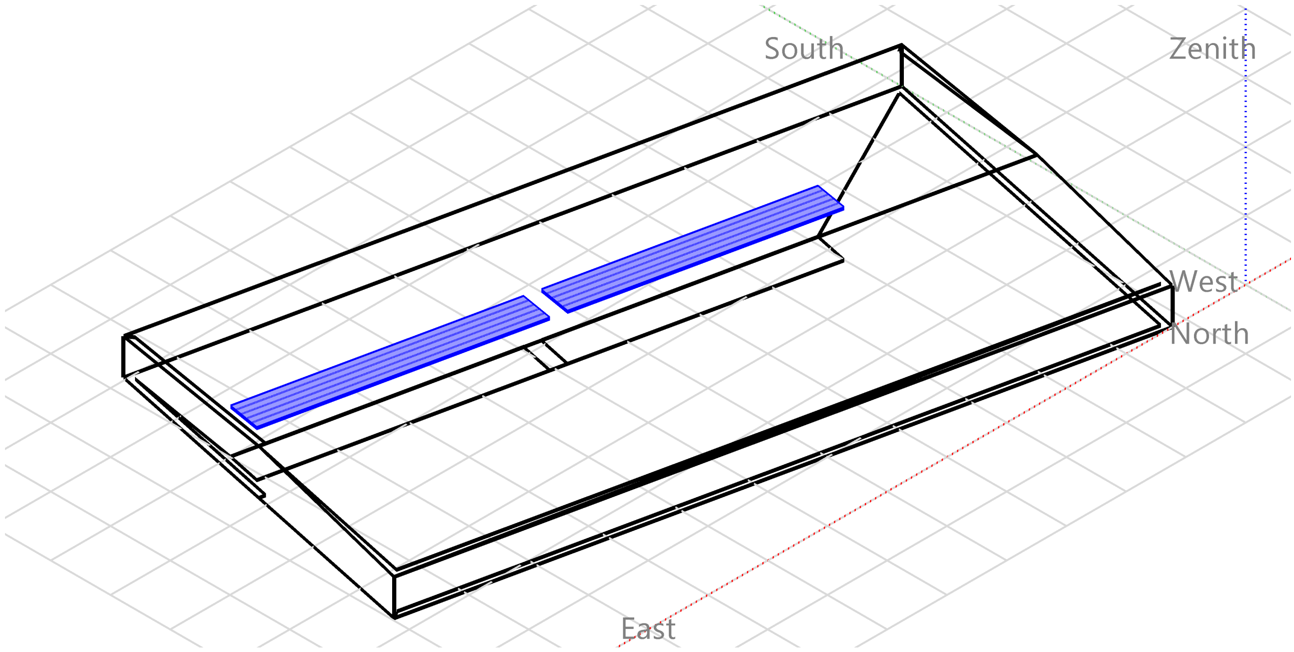
AC wiring losses

Inv. output line up to injection point
Inverter voltage 400 Vac tri
Loss Fraction 1.50 % at STC

Global System
Wire section Copper 3 x 150 mm²
Wires length 190 m

Near shadings parameter

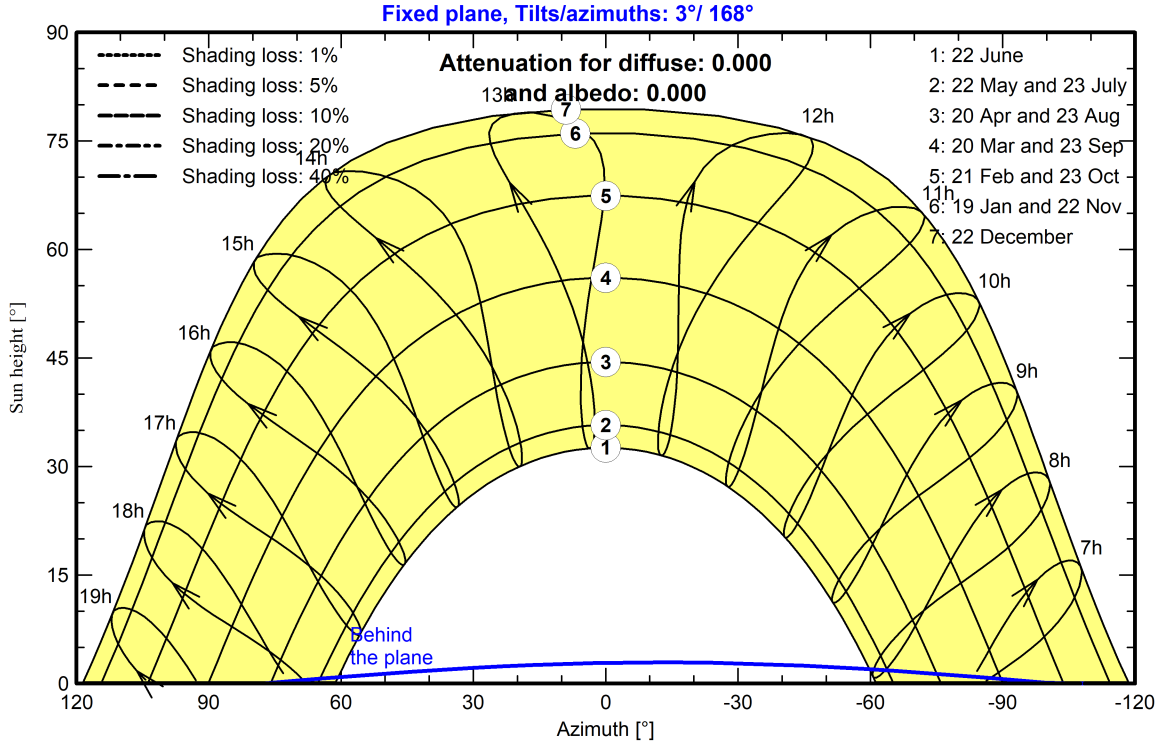
Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Orientation #1

Fixed plane, Tilts/azimuths: 3°/ 168°



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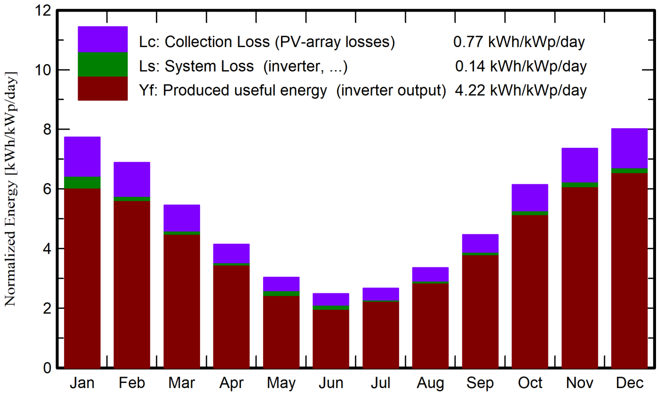
Main results

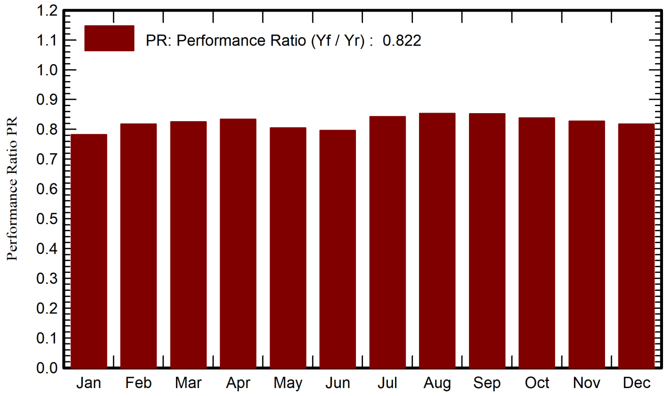
System Production

Produced Energy	157753 kWh/year	Specific production	1541 kWh/kWp/year
Apparent energy	157753 kVAh/year	Perf. Ratio PR	82.21 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	240.4	72.52	22.00	239.7	227.6	20451	19185	0.782
February	195.0	62.36	21.97	192.7	182.5	16538	16138	0.818
March	173.3	55.12	20.22	169.0	158.5	14622	14281	0.826
April	129.7	35.30	17.34	124.3	115.5	10864	10619	0.834
May	100.1	30.84	15.11	94.0	85.5	8236	7743	0.805
June	80.3	24.99	12.53	74.4	66.6	6502	6066	0.796
July	88.2	27.92	12.30	82.4	74.5	7269	7113	0.843
August	109.1	39.19	12.77	103.8	95.6	9265	9065	0.853
September	138.0	50.86	14.15	134.0	125.3	11956	11684	0.852
October	193.6	59.29	16.86	190.5	180.1	16746	16338	0.838
November	221.9	70.69	18.44	220.8	209.0	19185	18712	0.828
December	248.6	79.36	20.84	248.6	236.2	21346	20810	0.818
Year	1918.4	608.44	17.02	1874.4	1756.9	162979	157753	0.822

Legends

GlobHor	Global horizontal irradiation
DiffHor	Horizontal diffuse irradiation
T_Amb	Ambient Temperature
GlobInc	Global incident in coll. plane
GlobEff	Effective Global, corr. for IAM and shadings
EArray	Effective energy at the output of the array
E_Grid	Energy injected into grid
PR	Performance Ratio

Loss diagram

1918 kWh/m²	**Global horizontal irradiation**
-2.29%	**Global incident in coll. plane**
0.00%	Near Shadings: irradiance loss
-3.37%	IAM factor on global
-3.00%	Soiling loss factor
1757 kWh/m² * 478 m² coll.	**Effective irradiation on collectors**
efficiency at STC = 21.40%	PV conversion
179894 kWh	**Array nominal energy (at STC effic.)**
-0.68%	PV loss due to irradiance level
-6.67%	PV loss due to temperature
0.00%	Shadings: Electrical Loss acc. to strings
-0.60%	LID - Light induced degradation
-0.70%	Mismatch loss, modules and strings
-0.98%	Ohmic wiring loss
162979 kWh	**Array virtual energy at MPP**
-1.57%	Inverter Loss during operation (efficiency)
0.00%	Inverter Loss over nominal inv. power
0.00%	Inverter Loss due to max. input current
0.00%	Inverter Loss over nominal inv. voltage
0.00%	Inverter Loss due to power threshold
0.00%	Inverter Loss due to voltage threshold
-0.01%	Night consumption
160401 kWh	**Available Energy at Inverter Output**
-0.79%	AC ohmic loss
-0.87%	System unavailability
157753 kWh	**Active Energy injected into grid**
0 kVARh	Reactive energy to the grid: Aver. cos(phi) = 1.000
157753 kVAh	**Apparent energy to the grid**

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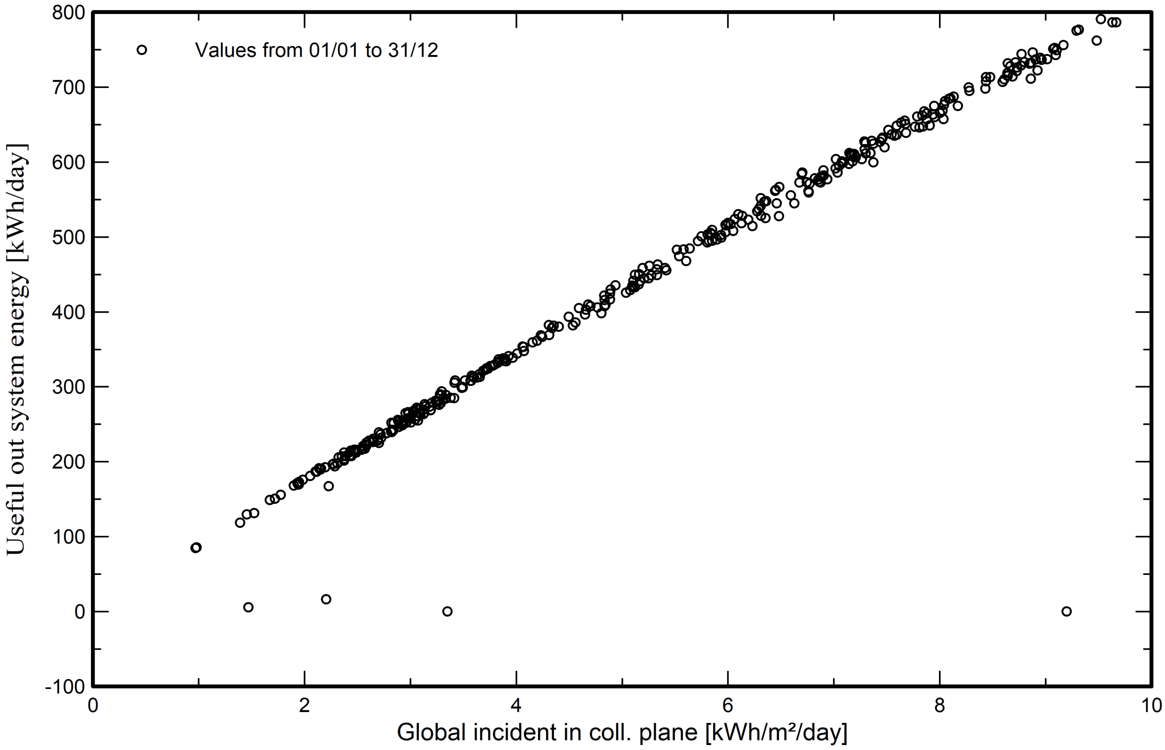
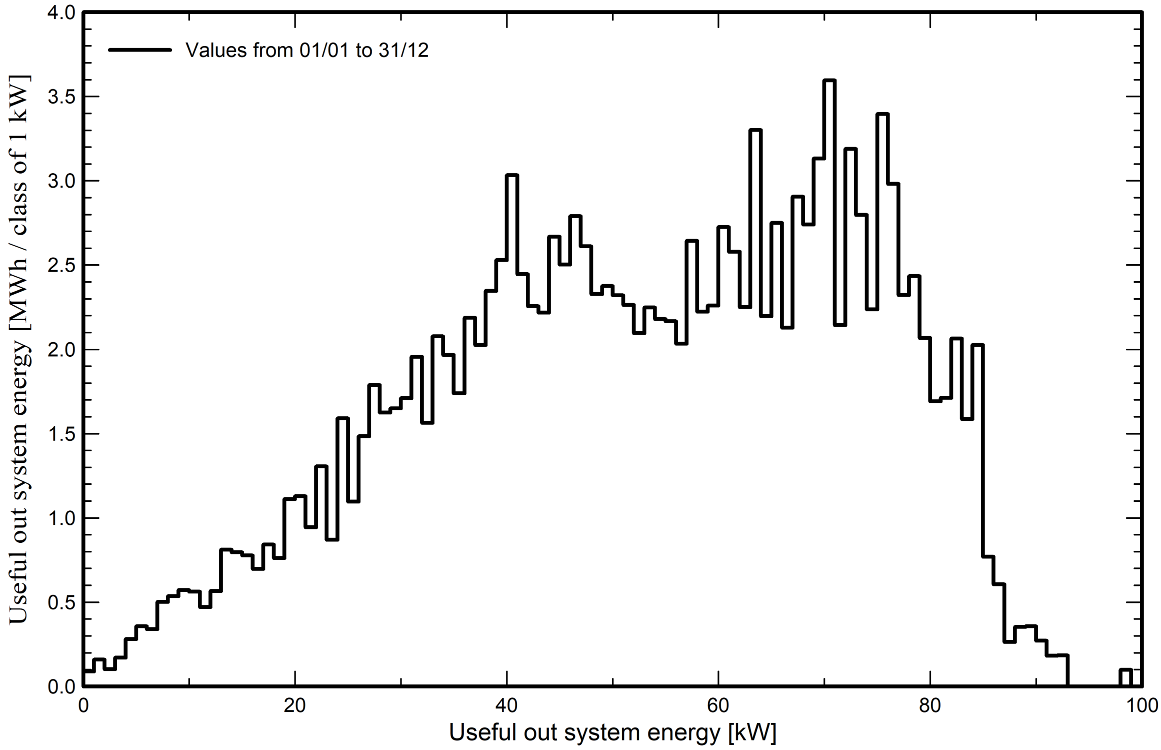
Predef. graphs

Daily Input/Output diagram



System Output Power Distribution



P50 - P90 evaluation

Weather data

Source	Meteonorm 8.1 (2000-2017), Sat=100%
Kind	TMY, multi-year
Year-to-year variability(Variance)	5.0 %
Specified Deviation	
Climate change	0.0 %

Global variability (weather data + system)

Variability (Quadratic sum)	5.3 %

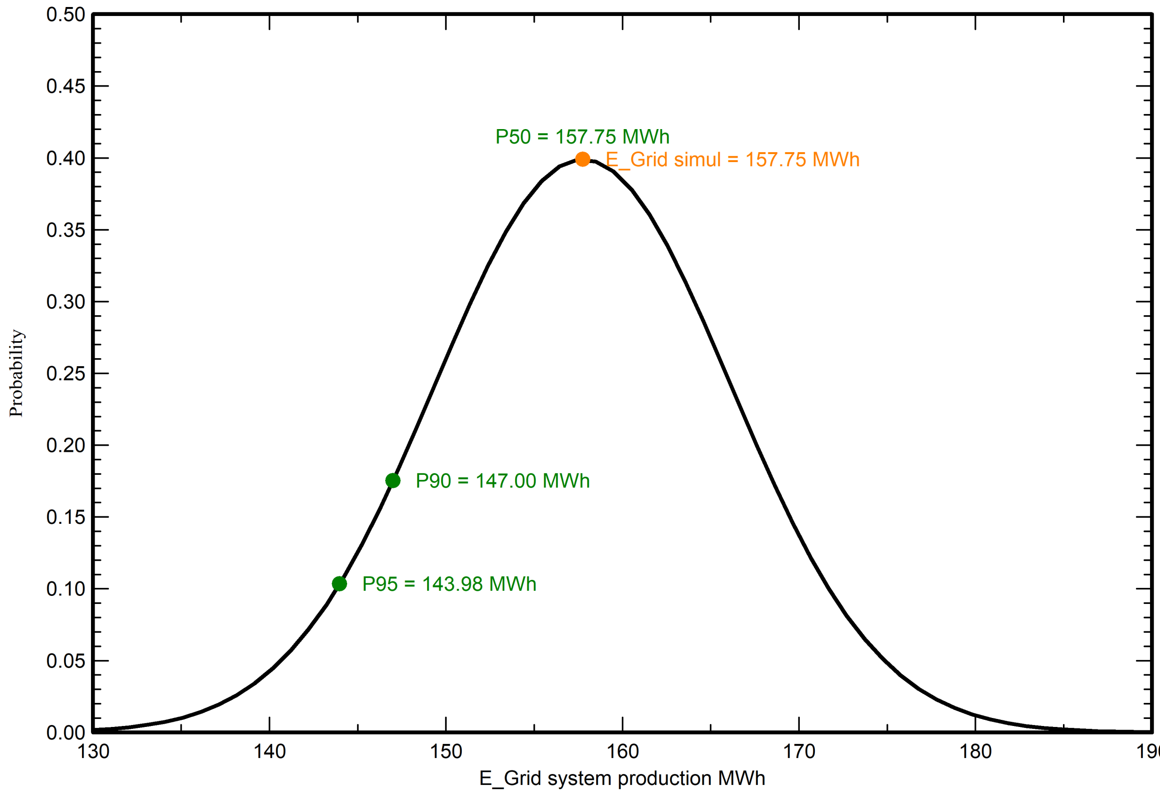
Simulation and parameters uncertainties

PV module modelling/parameters	1.0 %
Inverter efficiency uncertainty	0.5 %
Soiling and mismatch uncertainties	1.0 %
Degradation uncertainty	1.0 %

Annual production probability

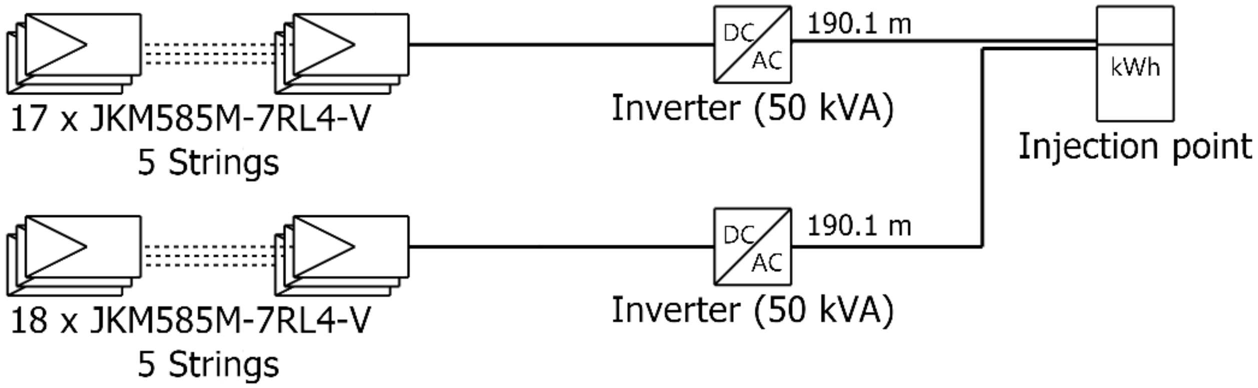
Variability	8.38 MWh
P50	157.75 MWh
P90	147.00 MWh
P95	143.98 MWh

Probability distribution



Single-line diagram

PVsyst V7.4.6
VC0, Simulation date:
09/05/24 16:51
with V7.4.6



PV module	JKM585M-7RL4-V
Inverter	SUN2000-50KTL-M0_400Vac
String 1	17 x JKM585M-7RL4-V
String 2	18 x JKM585M-7RL4-V

VC0 : New simulation variant

09/05/24

APPENDIX B : HYBRID INVERTER DATA SHEET

Three Phase Hybrid Inverter

SUN- 25 / 30 / 40 / 50 K-SG01HP3-EU-BM2/3/4

- 100% unbalanced output, each phase; Max. output up to **50%** rated power
- DC couple and AC couple to retrofit existing solar system
- Max. 10pcs parallel for on-grid and off-grid operation; Support multiple batteries parallel
- Max. charging/discharging current of 100A
- High voltage battery, higher efficiency
- 6 time periods for battery charging/discharging
- Support storing energy from diesel generator

Deye

Stock Code: 605117.SH

Technical Data

Model	SUN-25K-SG01HP3 -EU-BM2	SUN-30K-SG01HP3 -EU-BM3	SUN-40K-SG01HP3 -EU-BM4	SUN-50K-SG01HP3 -EU-BM4
Battery Input Data				
Battery Type	Li-Ion			
Battery Voltage Range (V)	160~800			
Max. Charging Current (A)	50+50			
Max. Discharging Current (A)	50+50			
Number of battery input	2			
Charging Strategy for Li-Ion Battery	Self-adaption to BMS			
PV String Input Data				
Max. DC Input Power (W)	32500	39000	52000	65000
Max. DC Input Voltage (V)	1000			
Start-up Voltage (V)	180			
MPPT Range (V)	150-850			
Full Load DC Voltage Range (V)	450-850	360-850	360-850	450-850
Rated DC Input Voltage (V)	600			
PV Input Current (A)	36+36	36+36+36	36+36+36+36	
Max. PV I_{SC} (A)	55+55	55+55+55	55+55+55+55	
No.of MPP Trackers	2	3	4	
No.of Strings per MPP Tracker	2			
AC Output Data				
Rated AC Output and UPS Power (W)	25000	30000	40000	50000
Max. AC Output Power (W)	27500	33000	44000	55000
AC Output Rated Current (A)	37.9/36.3	45.5/43.5	60.7/58	75.8/72.5
Max. AC Current (A)	50	60	70	83.3
Max. Continuous AC Passthrough (A)	150			
Peak Power (off grid)	1.5 time of rated power, 10 S			
Generator input/Smart load /AC couple current (A)	37.9 / 150 / 37.9	45.5 / 150 / 45.5	60.8 / 150 / 60.8	75.8 / 150 / 75.8
Power Factor	0.8 leading to 0.8 lagging			
Output Frequency and Voltage	50/60Hz; 3L/N/PE 220/380, 230/400Vac			
Grid Type	Three Phase			
DC injection current (mA)	<0.5%1n			
Efficiency				
Max. Efficiency	97.60%			
Euro Efficiency	97.00%			
MPPT Efficiency	99.90%			
Protection				
Integrated	PV Input Lightning Protection, Anti-islanding Protection, PV String Input Reverse Polarity Protection, Insulation Resistor Detection, Residual Current Monitoring Unit, Output Over Current Protection, Output Shorted Protection, Surge protection			
Output Over Voltage Protection	DC Type II/AC Type III			
Certifications and Standards				
Grid Regulation	EN50549, AS4777.2:2015, VDE0126-1-1, IEC61727, VDEN4105-2018, G99			
Safety EMC / Standard	IEC/EN 61000-6-1/2/3/4, IEC/EN 62109-1, IEC/EN 62109-2			
General Data				
Operating Temperature Range (℃)	-40~60°C, >45°C derating			
Cooling	Smart cooling			
Noise (dB)	<45 dB			
Communication with BMS	RS485; CAN			
Weight (kg)	75			
Size (mm)	527W×894H×294D			
Protection Degree	IP65			
Installation Style	Wall-mounted			
Warranty	5 years			

Deye
Ningbo Deye Inverter Technology Co., Ltd .
Add: No. 26 South YongJiang Road, Daqi, Beilun, NingBo, Zhejiang, China. | Tel: 0086-0574-86120560 | E-mail: market@deye.com.cn

APPENDIX C : SOLAR PANEL DATA SHEET

www.jinkosolar.com

JinKO Solar
Building Your Trust in Solar

TR 78M
565-585 Watt
Mono-facial

Tiling Ribbon (TR) Technology

Positive power tolerance of 0~+3%

Tiger Pro

KEY FEATURES

TR technology + Half Cell
TR technology with Half cell aims to eliminate the cell gap to increase module efficiency (mono-facial up to 21.40%)

MBB instead of 5BB
MBB technology decreases the distance between bus bars and finger grid line which is benefit to power increase.

Higher lifetime Power Yield
2% first year degradation,
0.55% linear degradation

Best Warranty
12 year product warranty,
25 year linear power warranty

Strengthened Mechanical Support
5400 Pa snow load, 2400 Pa wind load

PV CYCLE

TÜVRheinland CERTIFIED

CE

POSITIVE QUALITY™
Continuous Quality Assurance

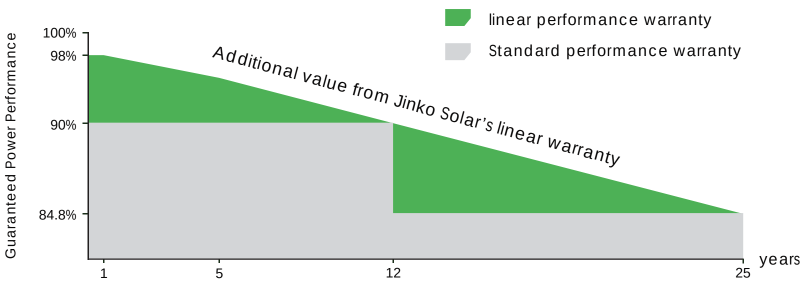
CLEAN ENERGY COUNCIL MEMBER

ISO9001:2015, ISO14001:2015, ISO45001:2018 certified factory

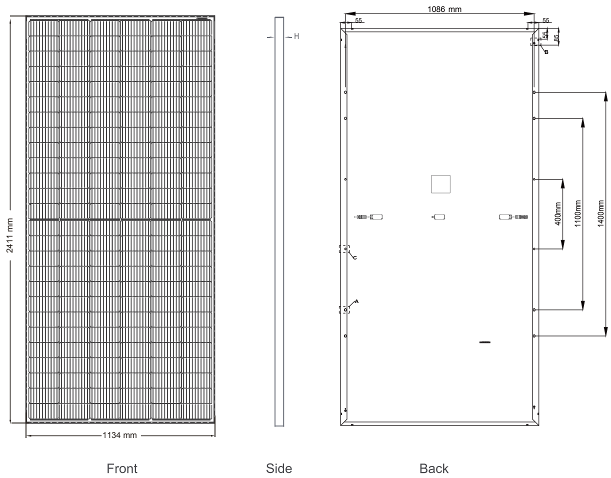
IEC61215, IEC61730 certified product

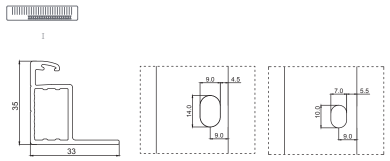
LINEAR PERFORMANCE WARRANTY

12 Year Product Warranty • 25 Year Linear Power Warranty
0.55% Annual Degradation Over 25 years



Engineering Drawings





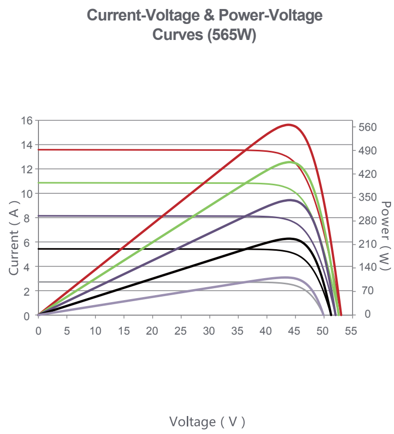
Length: ±2mm

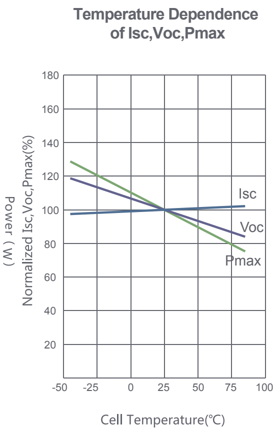
Width: ±2mm

Height: ±1mm

Row Pitch: ±2mm

Electrical Performance & Temperature Dependence





Packaging Configuration

(Two pallets = One stack)

31pcs/pallets, 62pcs/stack, 496pcs/ 40'HQ Container

Mechanical Characteristics

Cell Type	P type Mono-crystalline
No.of cells	156 (2×78)
Dimensions	2411×1134×35mm (94.92×44.65×1.38 inch)
Weight	31.1 kg (68.6 lbs)
Front Glass	3.2mm,Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP68 Rated
Output Cables	TUV 1×4.0mm^2 (+): 290mm , (-): 145 mm or Customized Length

SPECIFICATIONS

Module Type	JKM565M-7RL4-V		JKM570M-7RL4-V		JKM575M-7RL4-V		JKM580M-7RL4-V		JKM585M-7RL4-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	565Wp	420Wp	570Wp	424Wp	575Wp	428Wp	580Wp	432Wp	585Wp	435Wp
Maximum Power Voltage (Vmp)	43.97V	40.93V	44.09V	41.04V	44.20V	41.15V	44.31V	41.26V	44.42V	41.36V
Maximum Power Current (Imp)	12.85A	10.27A	12.93A	10.33A	13.01A	10.40A	13.09A	10.46A	13.17A	10.52A
Open-circuit Voltage (Voc)	53.20V	50.21V	53.32V	50.33V	53.43V	50.43V	53.54V	50.54V	53.65V	50.64V
Short-circuit Current (Isc)	13.53A	10.93A	13.61A	10.99A	13.69A	11.06A	13.77A	11.12A	13.85A	11.19A
Module Efficiency STC (%)	20.67%		20.85%		21.03%		21.21%		21.40%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1500VDC (IEC)									
Maximum series fuse rating	25A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.35%/℃									
Temperature coefficients of Voc	-0.28%/℃									
Temperature coefficients of Isc	0.048%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

*STC: Irradiance 1000W/m^2 Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m^2 Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

APPENDIX D : BATTERY DATA SHEET

freedom WON

PLUG INTO THE **CURRENT FUTURE**

Li^TE Home and Business HV Range

Li^TE Home 40/32 HV

Max Energy [kWh]	40
Energy, 90% DoD [kWh][1]	36
Energy, 80% DoD [kWh][1]	32
Nominal Voltage [V][2]	410
Max/Min Operating Voltage [V]	454/365
Max/Cont. Discharge Current [A]	150/100
Max/Cont Discharge Power [kW]	61/40
Max and Cont Charge Current [A]	100
Weight [kg]	327
Dimensions on or against wall excluding protuberances such as glands and breaker handle -Height x Width x Depth [mm]	1260x640x290
DC Connection – Integrated Cables [no. per electrode][3]	1 x 25mm²
External Interfacing	CAN Bus
Enclosure	Aluminium – powder coated white, IP54 enclosure rating, Home – wall or floor mount, Business – floor mount
Protection	Shunt Trip Circuit Breaker sized to suit max current, can be tripped by BMS if critical fault incl. overcurrent, cell under and over voltage, temperature, weak cell detection, minimum SOC control, manual reset
Human Interface	State of Charge Display (0 to 100%), Error light, Error Reset Button, USB Plug for Programming
Service Life[4]	10 year (or 4000 cycles) warranty for 80% average DoD, 13-15 yrs (>5 500 cycles) expected life at 70% DoD, 15-20 years at 50% DoD (>7 000 cycles)

Notes to Specification Sheet

1 DoD = Depth of Discharge, recommended up to average daily 80% DoD for extended life, 50% average DoD for ultra-long life. Max allowable DoD is 90%.
2 Voltage suitable for various high DC voltage inverters. Please enquire with Freedom Won for pairing support.
3 Fly Leads 1,8m long (15/12; 20/16; 30/24 HV). Fly Leads 4m long (40/32; 60/48; 80/64 HV). Power cable Red = Positive, Black= Negative, conductors in table refer to one electrode i.e. per positive and negative connections. Longer cables available on request. Multiples of 6mm2 DC cables available on request for inverters fitted with MC4 type connectors for the battery input.
4 End of Life (EoL) defined as cell dropping to 60% of Beginning of Life (BoL) capacity for expected life and as 70% of BoL capacity for warranty.