Cape Peninsula
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DEVELOPMENT OF A SMART ENERGY SYSTEM FOR RAILWAY STATION BUILDINGS

by

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DECLARATION

I, **Bonga Mpongwana**, declare that the contents of this thesis represent my own unaided work, and that the thesis 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.

Bonga

16 March 2024

Signed **Date**

ABSTRACT

The use of photovoltaic solar power is seeing a notable growth as an emerging energy source, playing a crucial role in the creation of renewable energy. This kind of energy is essential in the pursuit of meeting the established climate objectives in the near future. When strategizing for the implementation of novel photovoltaic installations, the design is influenced by several factors, including local variables such as weather, as well as system characteristics like tilt and azimuth angles. The objective of this thesis project is to develop a tool capable of simulating several solar systems and providing estimations for system sizes, grid interactions, and area needs for each system.

This research project's goals are to support the national plan to reduce carbon emissions in railway station buildings, to learn about and use advanced technologies in international building management, and to ensure energy savings, safety, and comfort in railway station buildings in a cost-effective way from the point of view of energy management, with expected energy savings of 20% or more using smart energy system controls. South Africans have had trouble getting power to their homes and businesses recently because the utility company didn't have enough. This is called "load shedding."

The primary drivers for transitioning to renewable energy are the challenges posed by climate change and the increasing demand for power. The primary objective is to demonstrate the use of model-based techniques in a grid-connected solar photovoltaic system designed for commercial purposes. The objective of this thesis is to develop a grid-connected solar PV rooftop system for the East London Railway station in East London, Eastern Cape, while considering various operational scenarios. To conduct these studies, multiple methodologies have been used, including site selection, roof selection, PV installation, and electrical string design. In order to streamline the design process, computer-based tools have been used. This presentation introduces a modelling tool called System Advisor Model (SAM) that is used for building, predicting, and analysing Commercial PV systems. The simulation yielded system performance data on an hourly, monthly, and yearly basis. The SAM program utilizes the provided installation, running expenses, and system design characteristics as inputs to generate performance projections and cost of energy estimations for this system.

The primary conclusions of this research indicate that the East London train station has the necessary technological capacity to implement distributed photovoltaic systems. The yearly energy output of these systems is 30.154 kilowatt-hours (kWh), which is enough to meet about 65.7% of the power requirements of the train station. The system's performance ratio of 0.897 indicates an effectiveness of 35.10 percent. The method that was constructed and simulated has the potential to significantly reduce the amount of CO_2 emissions in the East London region.

KEY WORDS: Grid-connected, carbon emission, PV, SAM

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DEDICATION

To myself, for all my efforts.

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LIST OF ABBREVATIONS

AC : Alternating Current
AI : Artificial Intelligence
AMI : Advanced Metering System
AHU : Air-Handling Unit
AMI : Advanced Metering Infrastructure
ANN : Artificial Neural Network
BA : Brainstorming Algorithm
BAS : Building Automation System
BEMS : Building Energy Management System
BES : Battery Energy Storage
BOS : Balance of System
BNEF : Bloomberg New Energy Finance
BMS : Building Management System
BTM : Battery Temperature Multiplier
CF : Cash Flows
CFF : Construction Financing Factor
CO2 : Carbon Dioxide
CRF : Capital Recovery Factor
CSP : Concentrating Solar Power
CSV : Comma Separated Values
CCTV : Closed-Circuit Television
DC : Direct Current
DAT : Discharge Air Temperature
DE : Differential Evolution
DER : Distributed Energy Resources
DoA : Days of Autonomy
DoD : Depth of Discharge
DoE : Department of Energy
DNI : Direct Normal Irradiation
DHI : Direct Horizontal Irradiation

DCR : Demand Charge Reduction

DSM : Demand side management

DSR : Design Science Research

EE : Energy Efficiency

EEI : Energy Efficiency Index

EMF : Electromotive Force

EMS : Energy Management System

ESS : Energy Storage System

GA : Genetic Algorithm

GAMS : General Algebraic Modelling System

GSA : Gravitational Search Algorithm

GHI : Global Horizontal Irradiation

GHG : Greenhouse Gas

GTI **:** Global Tilted Irradiance

HBC : Hysteresis Band Control

HVAC : Heating, Ventilation, and Air Conditioning

IBEMS **:** Intelligent Building Energy Management Systems

IEA : International Energy Agency

IAM : Incidence Angle Modifier

IPPs : Independent Power Producers (s)

IRR : Internal Rate of Return

IRP2010 : Integrated Resource Plan 2010

kW : Kilowatt

kWh : Kilo-Watthour

KPIs : Key Performance Indicators

MAS : Multi-Agent System

MILP : Mixed-Integer Linear Programming

MIQP : Mixed-Integer Quadratic Programming

ML : Machine Learning

MPC : Model Predictive Control

MPP : Maximum Power Point

MPPT : Maximum Power Point Tracking

NASA : National Aeronautics and Space Administration
NEES : National Energy Efficiency Strategy
NLP : Non-Linear Programming
Ni-MH : Nickel-Metal-Hydride
NPC : Net Present Cost
NPV : Net Present Value
NREL : National Renewable Energy Laboratory
LCoE : Localized Cost of Energy
LP : Linear Programming
Li-ion : Lithium-ion
RES : Renewable Energy Sources
RET : Renewable Energy Technologies
SA : Simulated Annealing
SAM : System Advisor Model
SAPM : Solar Array Performance Model
SDM : Singe Diode Mode
SDG : Sustainable Development Goals
SES : Smart Energy System
SOC : State of Charge
SEMS : Smart energy Management Systems
SM : Spectral Modifier
SRHC : Stochastic Receding-Horizon Control
SMPC : Stochastic Predictive Model Control
QP : Quadratic Programming
PFF : Project Financing Factor
POA : Plane Of the Array
PSM : Particle Swarm Optimizer
PV : Photovoltaic
PVDEP : Present Value of Depreciation
P**VGCS** : Photovoltaic Grid-Connected Systems
PWM : Pulse Width Modulation
ROI **:** Return on Investment

TFPV	: Thin-Film Photovoltaic
TOU	: Time of use
TMY	: Meteorological Year
UNDP	: United Nations Development Programme
OAT	**:** Outside Air temperature
O&M	: Operational and Maintenance
LCoE	: Localized Cost of Energy
WACC	: Weighted Average Cost of Capital
WCA	: Water Cycle Algorithm

LIST OF SYMBOLS

I : Current

I_{ph} : Phase current

V : Voltage

V_i : Voltage across the module

n : Voltage at nth module.

Rs : Series Resistor

Rp : Parallel Resistor

Voc : Open Circuit Voltage

Vsc : Short Circuit voltage

Isc : Short Circuit current

Ioc : Open Circuit current

Pmax : Maximum Power Point

Rs : Series Resistor

Rp : Parallel Resistance

k_i : Temperature coefficient of Isc

T_{STC} : STC temperature at 25°C

E : Operational irradiation

E_{STC} : STC irradiation (1000 w/m2)

$P_{Required}$: Total Power required by the system.

P_{Load} : Load

P_{grid} : Electrical energy delivered to the grid.

P_{AC} : Alternating current power.

$P_{inverter_{out}}$: Output power of the inverter

ɳ : Efficiency

$N_{Panels-Required}$: Number of panels required.

$N_{Parallel\ String}$: Number of Parallel strings

V_{min} : Inverter Minimum voltage

V_{min} : PV array voltage

I_{Rated} : Rated current.

$V_{Battery}$: Nominal Voltage of the battery

$\boldsymbol{Z}$: Altitude

$\boldsymbol{\theta_{Z-rad}}$: Zenith angle in radians

$\boldsymbol{\theta_{Z-deg}}$: Zenith angle in degree

$\boldsymbol{\theta_{T}}$: Tilt angle in degree

$\boldsymbol{\beta}$: Angle of sun’s altitude

Si : Silicon

GaAs **:** Gallium Arsenide

Cu2S **:** Copper Sulphate

mono-c-Si **:** Monocrystalline silicon

p-Si **:** Polycrystalline silicon

multi-c-Si **:** Multi-crystalline silicon

CdTe **:** Cadmium Telluride

CIGS **:** Copper Indium Gallium Selenide

a-Si **:** Amorphous thin-film Silicon

$\boldsymbol{G}$: GHI

$\boldsymbol{G_{diff}}$: DNI

$\boldsymbol{\lambda\ \alpha}$: Earth surface albedo

R/kWh : Rand value per kilowatt-hour

1. CHAPTER 1: PROJECT PROPOSAL

1.1. Introduction

The use of renewable energy sources has become more important in the fight against global warming, as well as in addressing the escalating global and national energy requirements, while concurrently alleviating the depletion of natural resources. Solar energy, due to its plentiful and freely available nature, has been used across several scales, ranging from individual-level applications to the establishment of expansive solar farms. The expeditious adoption of renewable energy technology has been widely acknowledged by several international organizations as a primary strategy to address climate change. This approach has gained significant political traction, emerging as a key policy priority in numerous countries worldwide. The United Nations Development Programme (UNDP), recognized as a prominent entity in this field, plays a crucial role as the governing body for international development within the United Nations. Its primary objective is to assist nations in formulating effective policies, enhancing leadership capabilities, fostering partnerships, and bolstering institutional capacity. The Sustainable Development Goals (SDGs), often called global objectives, are the target of these endeavours. According to the UNDP, the SDGs were agreed by all member states of the UN in 2015 and constitute a thorough call to action to end extreme poverty, protect the environment, and ensure that all people enjoy peace and wealth by 2030 [1]. The attainment of Goal 7, which is focused on cheap and clean energy, places significant emphasis on the investment in renewable energy as a means to lessen the detrimental impacts of climate change. The emergence of recent crises has exacerbated the financial burden associated with the use of fossil fuel resources in centralized energy systems. The current situation is characterized by significant fluctuations in petroleum products and gas prices, which have reached unprecedented levels. Moreover, the ongoing COVID-19 epidemic continues to impede restoration operations. Consequently, individuals are increasingly concerned about their ability to meet the financial demands associated with energy expenses. Simultaneously, the discernible manifestations of climate change caused by human activities are more evident. In accordance with the findings of the IPCC (2015), a substantial number of people, ranging from 3.3 to 3.6 billion, now reside in regions that are extremely susceptible to climate-related risks[2] .

In the realm of energy from the sun, indeed been a notable growth in the prominence of PV in terms of both scholarly investigation and practical implementation. In 2021, the global power production from solar PV sources amounted to 994.0 terawatt-hours (TWh), whilst electricity output from solar thermal technologies reached 18.6 TWh. Power production from solar photovoltaics has increased significantly within the previous decade, which has seen a multiplication factor of 15.6. Similarly, solar thermal energy production has also witnessed growth, although at a lower rate, with a multiplication factor of 6.4 [3]. Figure 1.1 presents data on global solar PV power output from the years 2000 to 2021. The rapid growth in solar PV electricity generation projects can be attributed to several factors. Firstly, there has been a significant decrease in the costs associated with solar PV systems, particularly in relation to PV panel prices. The fall in pricing has expanded the client base for solar PV, allowing a wider range of customers to afford it. Additionally, in order to encourage the widespread use of solar PV technology, it has been essential to provide carefully crafted incentives and subsidies. An increase in the proportion of power generated by renewable sources is the intended outcome of these policies. By providing financial support and other benefits, these incentives and subsidies encourage individuals and organizations to invest in solar PV systems. Public education initiatives stressing solar power's advantages over more conventional energy generation techniques dependent on fossil fuels have also contributed to the technology's broad adoption on a variety of sizes. This increased awareness has contributed to a shift in public perception and a greater acceptance of solar PV as a viable and sustainable energy option. In summary, the combination of decreasing costs, well-designed incentives and subsidies, and public awareness campaigns has fuelled the rapid growth of solar PV electricity generation projects. All of these things have worked together to make solar PV technology so popular, and they've all helped to increase the share of sources of clean energy in the power generation industry. While certain countries have implemented incentives that primarily employ an inductive approach, emphasizing individual use of PV systems, others have prioritized the transition of national electricity generation from fossil fuel-based technologies. A massive amounts solar power facility with a high capacity has therefore been their primary area of concentration.

Currently, the costs of generating electricity using photovoltaic systems are on level with, or even lower than, the suggested retail cost of power from other sources, particularly rooftop installations. Prices for energy on a network may be really high since they contain a lot of different things, such taxes, grid fees, margins, and the costs of maintaining distribution networks and conversion systems [4]. The power demand of the buildings may be met by the use of PV systems installed on the roofs. This method is classified as self-consumption. Various forms of financial assistance, including as subsidies, premiums, feed-in tariffs, and incentives, have been established to promote self-consumption of rooftop PV schemes. The aim of these measures is to reduce the overall cost of such systems below the prevailing grid price. Consequently, self-consumption enables buildings to minimize their power bills, so generating monetary value [5]. Power costs from PV systems might be cheaper than grid pricing even without subsidies due to the longevity of these support measures. This is shown by several examples, including German, China, and India [6].

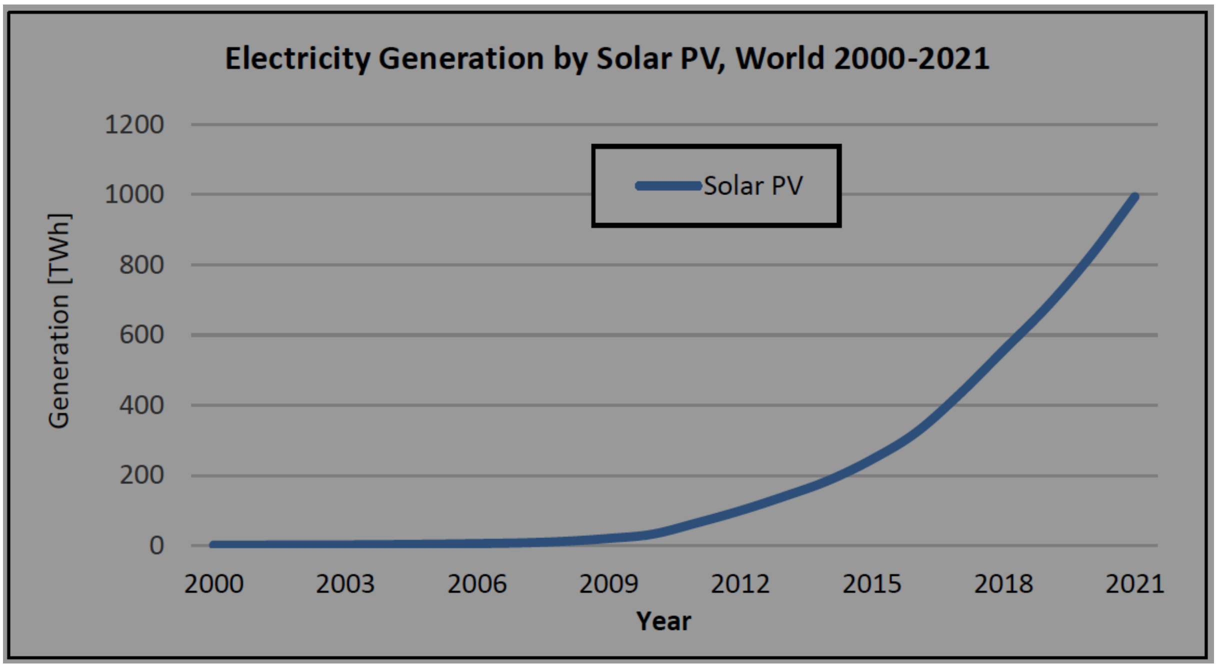


Figure 1. 1: Global Solar Photovoltaic Electricity Production from 2000 to 2021 [6].

In light of the scarcity of available fossil fuels, maximizing efficiency in the use of energy and other scarce resources has become not only a pressing survival issue, but also an economic and environmental conundrum that can be solved only by the most competent experts. There is a great opportunity for savings and a commensurate need for ethical behaviour because a large proportion of the nation's energy use is utilized in buildings. The building sector uses a large amount of water and accounts for as much as forty percent of the world's major energy consumption. The purpose of building energy management systems (BEMS) is to maintain a comfortable climate and manage the structure's carbon dioxide emissions. Due to the influence of humans, BEMS is insufficient.

Along with the growth in rooftop solar, there has been an uptick in the number of battery installations as well, with 23,796 small-scale installations expected by 2020. As battery technology advances and prices drop, we may anticipate a continuation of current installation patterns. Efficiency of energy and emission reductions of greenhouse gases (GHG) targets are becoming more important for businesses due to the growing threat of climate change and the increasing cost of electricity. The devastating bushfires that swept South Africa in 2019 and 2020 brought the issue of global warming to the forefront for many companies, heightening the need to cut greenhouse gas emissions. The timing couldn't be better for renewable energy, which can now reap the benefits of lower prices and less greenhouse gas emissions. This study found that the following factors are preventing businesses from using clean energy sources: a shortage of familiarity with the technologies that are available, difficulty in calculating cash flow, difficulty in comparing grid integration costs, and the need for expert knowledge to design a reliable renewable energy system [7]. There exists a potential avenue for mitigating the intricacy associated with renewable energy initiatives for enterprises possessing less expertise in this domain, however evincing a keen inclination towards reaping the advantages thereof. Organizations concerned with the sustainability of renewable energy sources, the mitigation of carbon dioxide emissions, or both need an understandable report to help them evaluate the possibility of cost reduction and the ideal system size for a specific site. While the ultimate goal of communication is simplicity, it is essential to assess a suitably built and cost-effective method before disseminating the findings. Consequently, a methodology that takes advantage of companies' specific energy needs to design solar power generation and storage systems, with the goal of finding the best payback time, should greatly increase the use of clean energy in manufacturing.

1.2. Background of problem

As the global population has grown throughout the ages, so has the need for and supply of energy. The effects of enormous releases of greenhouse gases and the shortage of natural resources like gasoline have made it quite evident that we must immediately begin to transition to alternate energy sources. In this energy shift, renewable power sources play a vital role. Particularly notable is the influence of the constantly expanding solar power production system. The energy transition is not a small change and will bring up some new problems that will need to be addressed. Congestion is more likely to occur in a dispersed grid than in a system that uses centralized power lines. The rise of the prosumer (end-users who create and use power) is a major factor since it introduces new, difficult-to-predict situations. Good system management on the part of the prosumer, however, may alleviate this congestion issue. And because of their adaptability in terms of electricity consumption, with the right management system in place, they may become invaluable assets for the electrical system. Energy management systems (EMS) are essential for improving the administration of green power-based systems, which is just as important as improving the systems themselves.

Train stations are at the core of a public transportation system; they are categorised as system entry points and serve as essential meeting sites for South Africans. They help individuals to travel about by linking them to other communities where they live, work, go to school, and so on. Railway stations must be smart to satisfy their function as an important part of our lives and to adapt to the different demands of consumers and operators. To guarantee that everyone has fair access, a smart station may adjust to the preferences of its customers. By putting in place efficient energy management, you can cut your power bill in half. The stations' flexibility generates a strong feeling of community in the stations and links local communities. Renewable energy production, energy waste reduction, and the usage of energy-efficient equipment are all part of smart energy's vast scope. These energy techniques outlined above may be used to railway station buildings to assist cut emissions while saving money and energy. To improve public health, cut down on pollution, and save money on fossil fuels, railway facilities are increasingly adopting smart energy systems. The study suggests that high-tech solutions be used to improve the country's economic growth. Another vital element to consider during the research is proper insulation, which is necessary for ensuring maximum interior comfort as well as energy savings and efficiency [8].

The solar photovoltaic business in South Africa is expanding at a healthy rate, driven by falling prices for renewable technology [9]. Rising demand for solar photovoltaic systems installed on residential rooftops is a key factor fuelling the expansion of the energy services industry [10]. A combination of factors, including rising energy service prices and the availability of alternative financing options for system installation and hardware, has led to a dramatic growth in the use of solar photovoltaic systems. Over 100,000 systems with a combined installed capacity of more than 170 MWp were anticipated to be operational in South Africa in 2016 according to the PQRS database [9].

Based on the PQRS statistics, Figure 1.2 shows that the commercial and industrial sector has had the highest degree of increase in solar photovoltaic adoption. The installed capacity in this sector is estimated to be slightly below 120 MWp.

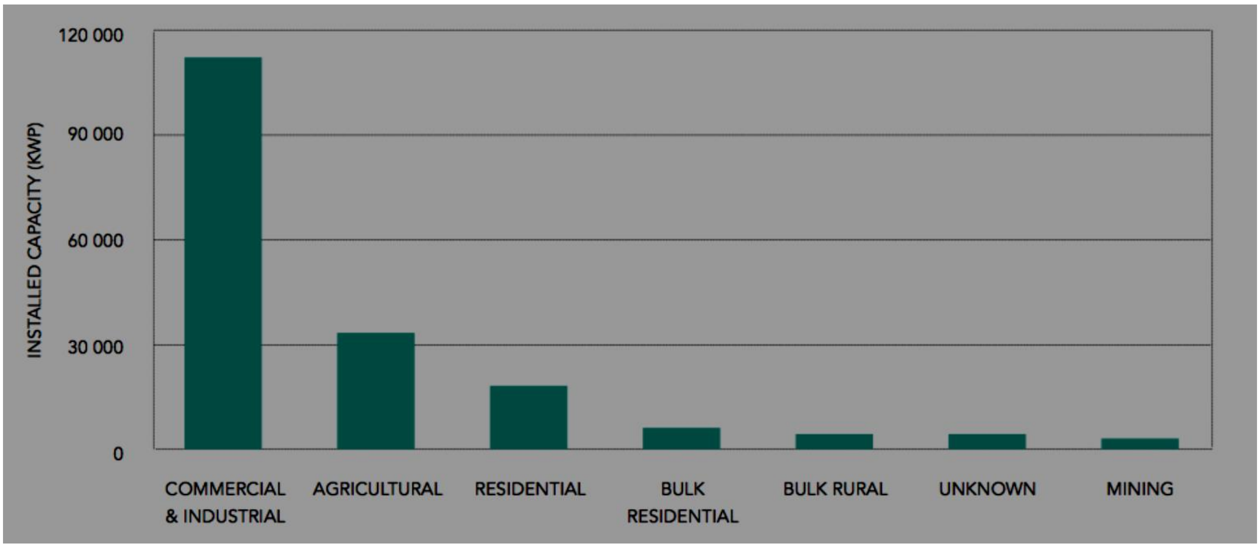


Figure 1. 2: Distributed solar photovoltaics throughout many end-users industries [9].

1.3. Problem statement

Monitoring and control systems are one of the factors that contribute to the rising global level of electric energy consumption in recent times. Despite the knowledge that this is one of the causes, no urgent measures are being implemented to decrease the quantity of energy from electricity being utilized, which is why this is happening. Because there is a mismatch between the amount of power created and the amount of power required by users, energy monitoring and conservation have become more important in today's world. Given that fossil fuels, the primary source of today's energy, will eventually run out, measures must be taken to monitor and regulate use [17,18]. Since the operation of systems that include technological advances in the form of new devices entails intensive resource usage, measuring electric energy consumption is useful [17]. Measure, monitor, regulate, and predict energy consumption in a conventional station building so that its energy performance may be compared to that of similar facilities with a smart energy management system (SEMS). With the help of the SEMS, energy consumption in every conventional Station building can be tracked and managed from a single location. Energy consumption in the Station building's many functional areas, such as electrical machines, HVAC, lighting, and office equipment, is managed by this system [18]. Another prevalent issue in our station building is the unequal distribution of energy expenses among various processing activities based only on square footage and similar measurements, as well as bad power factor and poor operations operating electric equipment when they are not meant to be. As another instance, it is uncommon for people to leave on lights in unoccupied stations all day long because they just forget to turn them off. This is one reason for the growing amount of wasted electricity at our stations. The proposed system's in-station display of current power use is intended to make users more mindful of their energy footprint.

Stations are the nerve centre of each public transit system, and train stations are no exception. This dissertation, titled "Development of a Smart Energy System for Railway Station Buildings," sets out to accomplish these two goals via the strategic planning and execution of smart building designs for railway stations. With the objective of reducing emissions and boosting energy efficiency in railway station constructions, energy conservation is a major problem in railway stations, and this research will investigate one of the techniques that may be taken to reach that goal. It is becoming clearer that reducing energy use is critical to the long-term health of all global businesses [8]. Every company is becoming more competitive to save expenses in the face of growing fuel prices, stricter environmental rules, and worries about energy security. Saving money on energy is a huge boon to the business' bottom line. By automating energy-saving measures and improving the building's utilization of renewable energy sources, smart energy management systems will assist the railway station building in increasing its usage of renewable energies and decreasing its dependence on the grid, which is crucial in light of the rising need for energy and the diminishing supply of fossil fuels [8].

This research project aims to design and implement smart energy keeping track for station buildings as a feasible solution to address issues such as high energy tariffs caused by unsupervised consumption, inaccurate estimates of generated energy consumption due to human mistakes, and the need to incorporate a control system to control running electrical loads.

1.4. Research Aim and Objectives

The study's overarching goal is to provide a framework for conducting thorough and accurate economic feasibility analyses of potential grid connected renewable energy generation at the East London railway station. By completing these tasks, the project would have fulfilled its purpose:

i. To propose a decision-making framework for determining what size renewable energy system would be most suitable for retrofitting into already-existing buildings.
ii. To study energy metering data is used to test and assess the established technique for determining the optimal size of renewable energy producing systems.
iii. To identify the most economically viable renewable energy systems. This will be achieved by using a well-established methodology and simulation software to analyse and evaluate the suggested system sizes. A comprehensive analysis will be conducted to assess the advantages and disadvantages associated with each system size, providing a complete breakdown of their respective benefits and downsides.
iv. To address the energy management problem in grid-connected solar PV systems by developing an optimization model that considers the inherently unpredictable solar PV production, load demand, and grid tariff, as well as the constraints imposed by the network architecture.

1.5. Research question

In order to achieve the purpose of the study, it is necessary to answer the following main research questions and supplementary questions:

What kind of smart energy management system would be most effective in lowering a train station's energy consumption?

Here is a breakdown of the sub-questions to ensure that the problem statement is fully addressed in the study's final analysis:

i. How to identify the most economically viable renewable energy systems
ii. How to model adaptability and flexibility energy management system for railway station building?

iii. How can we minimize our reliance on fossil fuels via smarter regulation of electricity and heating?

v. How to address the energy management problem in grid-connected solar PV systems?

iv. How may smart controls help lower energy costs as compared to conventional methods of operation?

1.6. Significant of problem

The aims of a smart energy system can only be realized if energy efficiency is maximized. To satisfy future energy needs, renewable sources have a better chance of becoming viable options if current consumption levels are lowered. Cutting down on fossil fuels and making rail stations more efficient are two of the most pressing issues. Green railway station buildings may save water use and power use, while also creating a pleasant atmosphere for staff. The Metro Rail Management will get suggestions from the research to fix the following problems:

i. There is a poor balance between thermal comfort and energy efficiency in most railway station structures.
ii. Develop a framework for the efficient administration of energy management systems.
iii. Integrated planning across departments to provide a smooth process from concept to completion.
iv. Provide a more comprehensive and efficient method for designing PV systems.
v. Create PV system designs that are both accurate and accepted by financial institutions.

As a consequence, this will help boost plant output while cutting system expenses, which will reassure investors and lessen their exposure to risk. South African customers may have better long-term odds of having access to sufficient and inexpensive electric power, while independent power providers (IPPs) may see increased profitability as a result.

1.7. Scope of the thesis

This work aimed to provide a guideline for the modelling and simulation of a combined system including numerous rooftop grid-tied PV systems. This guideline may be used for the modelling and simulation of both decentralized and centralized energy generating systems, in regions with one or more kinds of roofs. A comprehensive explanation is provided on how to understand the outcomes of simulations and modelling procedures. Additionally, the losses that should be taken into consideration are provided. It is important to acknowledge that neither this guideline nor this study incorporates considerations of economic feasibility or detailed environmental impact assessments. Rather, it primarily focuses on technical feasibility, supplemented by calculations of avoided CO2 emissions for the entire system. The ideal selection of renewable energy systems over a 25-year period was accomplished by minimizing the levelized cost of energy (LCOE) and return on investment (ROI), while concurrently increasing the net present value (NPV). This strategy provides a variety of feasible alternatives for organizations. Because the market is very volatile and results beyond 10 years are unpredictable, this inquiry has limited the analysis to projecting expenditures only until the year 2035.

1.8. Research motivation

Existing literature on the size of solar photovoltaic has mostly concentrated on the residential domain, whereby the cost estimation is based only on the most recent year of investigation [11,13]. Moreover, the existing body of research pertaining to the commercial-industrial scale in the South African market is either incomplete or limited to the present year of investigation. This study distinguishes itself from previous literature by integrating degradation rates of both production capability, providing cost forecasts for grid energy until 2048, and including anticipated reductions in installation and maintenance expenses for generation. Additionally, this approach involves the optimization of the size of the solar photovoltaic system so as to minimize grid curtailment, while simultaneously maximizing self-generation within realistic limits. In addition, it offers system designs that aim to maximize Net Present Value, minimize capital costs, or minimize Levelized Cost of Energy, so providing enterprises with a range of investment alternatives. This study utilizes literature sources and market-available items to ascertain the cost-effectiveness of various technologies, assess their potential economic implications, and select the most favourable year for their best installation.

The research primarily focused on conducting case studies to demonstrate the feasibility of integrating renewable energy systems into train station buildings and manufacturing businesses. In these case studies, we modelled the energy consumption statistics of the chosen businesses and proposed an alternative energy source to them. The goal was to build a business model for the sponsorship partner and to get the case study firms' thoughts on whether or not the suggested system would be adopted.

1.9. Research limitations

The data obtained for the simulations pertains to the electricity usage of the train station, as provided by the utility provider. Obtaining meteorological data from a source other than SAM may result in discrepancies with the actual measurements. In case of this study, the data source is from SAM and not from any meteorological station situated in the environs. Ultimately, the simulations conducted using SAM exhibit notable disparities from those achievable in actuality, mostly as a result of program constraints and inherent approximations.

1.10. Research design and methodology

Design Science Research (DSR) was selected as the technique for this research due to its potential for creating real-world solutions. DSR is an approach that creates an artifact that may assist people in meeting their requirements, resolving their issues, and seizing new possibilities in addition to describing, clarifying, and predicting the problem. According to [11] and [12], the DSR is a paradigm that combines the notion of basic knowledge with an awareness of problem design and a solution that is attained via the creation and use of artifacts. An artifact is defined here as a created thing with the intention of being able to address the issue at hand [11]. The DSR process consists of six steps: problem definition and inspiration, solution objectives, brainstorming and development, presentation, evaluation, and feedback [13]. The research advanced utilizing a problem-centred technique, building on the knowledge and observation of the massive need for power in the Republic of South Africa.

1.11. Expected outcomes.

The project's overarching objective is to develop an intelligent system management to cut down on the energy consumed by railway station buildings from the national electrical grid, in response to the rising need to cut down on high end-use energy consumption in office buildings. HVAC and lighting account for half of a building's total electrical use. Getting these structures to use little energy will need cutting-edge automation and control technologies to be developed by researchers. This research explored the feasibility of using photovoltaic to power HVAC and lighting systems within a building, along with a suitable control method during peak hours, to increase energy savings. This is especially important in office buildings, which have been the subject of complaints about excessive electricity usage. Occupant activities, weather condition changes, load consumption, and PV energy changes are to be simulated as input to the lighting and HVAC control systems by the intelligent system.

1.12. Simulation Tool

The System Advisory Model (SAM) is a tool created by the National Renewable Energy Laboratory (NREL), a division of the U.S. Department of Energy. Its purpose is to assess the technical and financial aspects of renewable energy systems. The software allows for the creation of technical reliability models for various renewable energy systems, including solar PV with battery storage, solar CSP, wind, geothermal, and biomass projects. It also offers a range of financial models, such as domestic, commercial, power purchase agreements, and third-party ownership.

The SAM generates performance models for grid-dependent power projects based on defined system design characteristics and cost variables provided to the model. The submitted information on the project's location, equipment type, installation and operating costs, and financial considerations are used for the detailed analysis. Conducting sensitivity and uncertainty analysis allows for testing the system's resilience. To produce a SAM file, the first stage involves using a technical and financial model choice that offers the most optimal combination for technical modelling. The work focuses on developing and analysing a detailed grid-connected photovoltaic system model with for railway station building.

1.13. Contributions of research

The following have been recognized as benefiting from this research:

i. Railway station building managers: By implementing the strategies outlined in this research, they should be able to reduce their monthly power costs. As a bonus, they'll be able to consume as much or as little power as they want, for whatever long they like.
ii. Power Company: As a result of the research, peak demand will be lowered, the grid's efficiency will increase, and the need for costly modifications will be mitigated.
iii. The Authors: This research will provide background information and further details for studies pertaining to smart energy management.

1.14. Organization of the study

The project thesis outlines the necessary procedures for constructing and implementing an intelligent energy system for a railway station building, with the aim of accomplishing both overarching and specific objectives. Following is a comprehensive overview of the thesis:

The opening chapter provides coverage of the background and aims. Describes the issue that the thesis aimed to resolve in its entirety. Chapter 1 not only analyses the general and specific objectives, but also discusses the scope and significance of the research study in solving societal issues. Chapter 2 focuses on an in-depth examination of the relevant literature, presenting a succinct evaluation of its distinctions from the existing studies. By doing this, it is illuminating the gaps that need to be addressed in order to make a significant contribution to the scientific community. The research approach and its execution to meet the goals are further forth in Chapter 3. In addition, chapter 4 provides a detailed description of the software requirements necessary for the iterative validation of the thesis. The SAM simulations are described in Chapter 5 coupled with the system analysis design. Chapter 6 goes deep into the important analysis step by addressing the acquired facts in graphical representations and some basic statistical analysis. Chapter 7 presents the study results and possible ideas for further work on the smart energy system for railway station buildings.

2. CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Good architectural design, efficient energy systems, and diligent upkeep and management all contribute to the low energy use of train stations. A large portion of the nation's total electricity consumption is attributable to building energy consumption. Research into this topic must give top priority to the creation of energy-efficient technologies and approaches for reducing energy consumption in railway station constructions. Energy-efficient building exterior materials, smart sensors, ventilation and air quality management systems, and highly efficient heating and cooling systems are only some of the modern technologies that assist to lower the building's overall energy consumption. Modern buildings benefit from efficient energy management systems made possible by recent advancements in building control technology. Researchers are working to enhance BEMS's performance by addressing several issues that currently limit its utility. These include the need for more precise and dependable sensors, more robust control systems and algorithms for automatically optimizing building system performance, more stringent safeguards for sensitive data, and more efficient energy harvesting to power the sensors and control systems [11].

Concerns about GHG emissions and, by extension, global warming, have arisen in response to the fast increase in energy use throughout the world. In 2018, the worldwide demand for energy increased by 2.3%, which is roughly double the average annual increase since 2010. Historically, the building sector has been heavily criticized for contributing to the current state of affairs with regard to the excessive use of fossil fuels and the release of carbon dioxide emissions. A major contributor to the increasing worldwide use of energy and emissions is the growing need for HVAC systems in the building industry. Energy consumed by gadgets, illumination, heating and air conditioning, and other equipment constitutes the bulk of overall energy use in both business and dwellings, according to the U.S. Energy Information Administration [10]. Knowing how to reduce energy use and the accompanying problems requires an understanding of the construction sector's energy consumption and environmental effect [12]. It is possible to divide the energy-saving technologies into several different categories, depending on the point of view one takes. Building geometry, exterior wall insulating material, and window assemblies are all examples of passive techniques systems; illumination and electrically powered equipment are examples of building service equipment; HVAC, renewable energy, and domestic hot water systems are examples of active systems; and building energy management and centralized energy control are examples of operation design [13]. This study presents a thorough review of the scientific literature on power and environmental systems optimization for building tools, as well as on planning and modelling, with the goal of reducing the use of energy in buildings and release of greenhouse gases. To summarize recent advances and paradigm shifts in the subject, this study used a systematic review approach [12]. To help with these global concerns of lowering building energy usage and carbon emissions, energy-related solutions including passive design and active system strategies have recently been created and recommended. Room temperature and air quality are two of many concurrent factors that these technologies should consider while designing and operating to provide a high-quality indoor environment with low energy cost[12],[14].

2.2. Global energy forecast

According to [15], worldwide energy consumption is expected to increase by 37% by the year 2040. As economies and populations throughout the world continue to develop, it's expected that energy consumption will rise considerably. The necessity for effective policymaking is exacerbated by this growth in several nations. Many worries about energy security and efficiency accompany the energy forecast. As a consequence of other problems, such energy consumption and shortages, the demand for efficient policy execution in the energy industry has grown. Demand patterns might vary depending on the energy source due to the wide range of potential uses for that source. Transitioning away from energy systems that are dependent on burning fossil fuels (like coal) and toward those that use renewable sources of energy has become an issue of increasing importance as of late[16]. Renewable energies such as wind and solar power, which produce very little carbon dioxide and may help balance the grid's electrical demand, are expected to see tremendous growth in the next 30 years. Natural gas consumption is part of this expansion since more and more people are switching to gas for home heating and cooking. The political tensions between Qatar and it's the Arabian Gulf neighbours and the war between Russia and Ukraine have reignited worries about energy security [16]. Coal is readily available, and its use in the future is limited by efforts to minimize air pollution and lower global carbon (CO2) emissions. According to projections, global demand for coal will have climbed by 15% by 2040 [17].

Renewable energy technologies (RETs) had a rapid increase in popularity in 2013, due to a substantial $120 billion in subsidies provided globally. RETs are integral components of low carbon energy systems that have a negligible impact on carbon emissions [16]. By 2040, green power is anticipated to account for over half of the globe's energy production [18], due to substantial reductions in expenses and ongoing assistance. The energy mix will continue to vary as the global economy expands and as governments adopt new policies. The most notable increase is anticipated in gas from the earth, while renewable power sources and nuclear power are anticipated to have robust growth.

2.3. Overview of RSA power sector

The mineral coal remains the predominant energy source in RSA because to its affordability, as stated by [19]. RSA obtains 59% of its basic energy from coal, but also uses renewable sources such the sun, wind, water, biomass, and even nuclear fission. The electricity network lines, which include the production, transmission, and distribution processes, transport the majority of primary energy to the final consumers. Figure 2.1 displays South Africa's major energy supply in 2015.

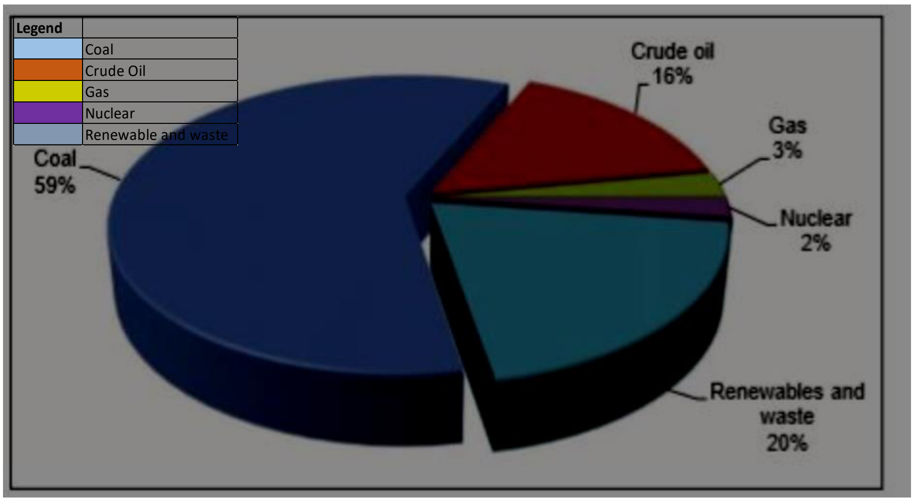


Figure 2.1 : South Africa's energy market in 2015 [19].

2.4. Building energy consumption

There is a lot of worry throughout the globe right now about things like energy availability, technological usage, energy reserves, environmental effect, etc., since energy demand has expanded tremendously along with the population. According to the energy use monitoring data, the ultimate electrical demand for buildings grew by around 6 EJ between 2010 and 2016. However, the efforts aimed at improving energy utilization have not kept pace with the growing need for larger total surface areas [20]. The building sector is responsible for around 40% of worldwide net CO2 emissions and over 50% of the world's electrical power usage [21]. This makes it the greatest user of both energy and carbon dioxide. Without proper controls and initiatives, the proportion of energy consumption attributable to buildings is expected to continue rising at a pace of around 3% per year , reaching 30% by 2060. There are several factors contributing to the rapid increase in building energy demand, including greater access to electricity in developing nations, the proliferation of energy-hungry gadgets, the construction of more and more buildings to house the expanding human population, and people spending more time inside their homes [21]. Figure 2.2 displays the typical percentage of global energy used by each industry. The advancements in sustainable infrastructure and environmental cleanliness are being made, but the corresponding resolutions have not yet reached a level that can meet the increasing demands of the building sector. It is a difficult but possible and attainable policy aim to significantly cut energy usage and carbon emissions in the building industry [22]. Since buildings have such a large potential for energy savings, acting on them is of major importance[23].

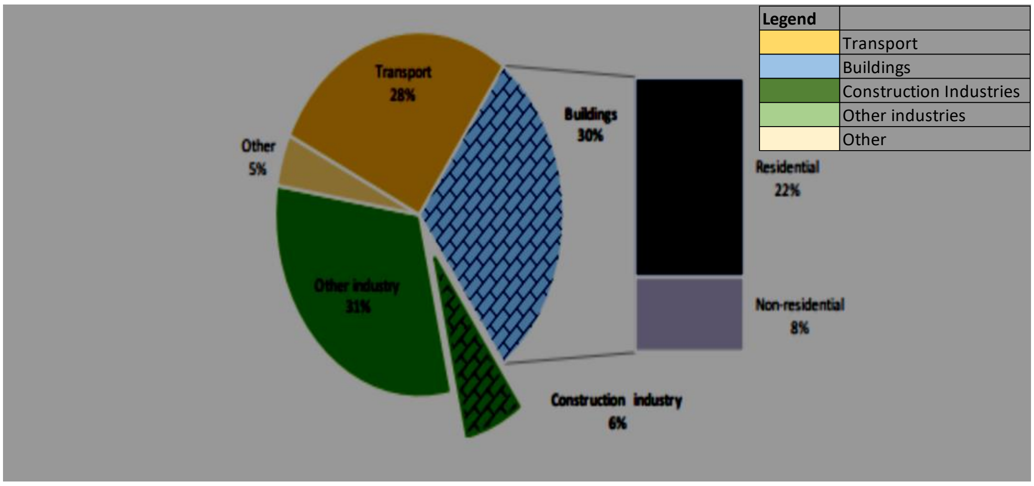


Figure 2.2 : A breakdown of 2015's worldwide final energy consumption by industry[22].

2.5. Current energy situation

Costs associated with conventional fossil fuels are on the increase, making renewable energy sources more competitive. The other 30% of electricity should be split between renewable energy producers, or IPPs, using sources like the sun and the wind. In 2003, ESKOM committed to accept a 70% ownership in power generation after the government authorized private sector involvement. The Independent Power Producer Programme for green energy was established in 2010 to encourage both private and public funding in renewable energy sources such as sun, wind, biomass, and small-scale hydro power. Its goal is to increase the electrical grid's power generation capacity. In 2015, around 14725 MW of electricity was generated through renewable sources [20]. Figure 2.3 depicts the net production capacity.

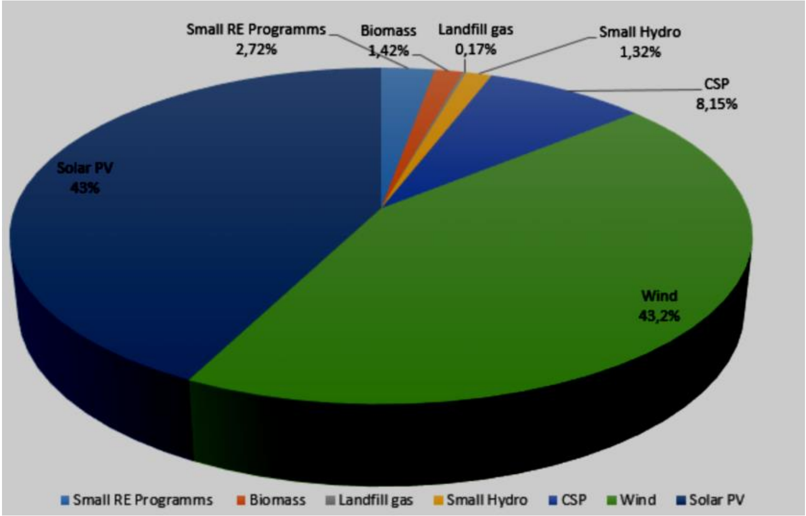


Figure 2.3 : Capacity of Renewable IPP. [20]

Approximately 5.2% of the worlds confirmed uranium reserves are in South Africa, making it one of the top nations with uranium reserves [22]. This amounts to an estimated 279,100 tons of uranium.

When mining for gold or copper in South Africa, uranium is a common by-product. Using uranium as its fuel source, nuclear power plants provide around 2% of the world's energy.

2.6. Energy profile

A customer's load profile may provide a detailed account of their energy use through time [24]. The word "load" has several meanings and is thus confusing. Load often refers to energy (in kilowatt-hours (kWh) or demand (kilowatt (kW). Demand is the load over a certain time period because to the obvious difference in units between energy and demand [25]. The term "demand" will be used extensively throughout this thesis to describe the quantity of energy required rather than the quantity used during a certain interval of time. The varying energy loads over time are often represented by charts and tables. Developing and utilizing an energy profile offers a multitude of noteworthy advantages, which may be realized by addressing the following inquiries:

i. At what time did the peak transpire, and was it of such magnitude that it overwhelmed the power company's capacity?
ii. Did the demand shift make sense?
iii. Did the predicted decline in demand coincide with the actual decline in energy consumption?
iv. How did the night/weekend load compare to the expected demand? How come?

To draw the right conclusion and make the right choices for increasing efficiency and other contributions, a thorough and precise study of the energy pattern is required [25]. Sustainable growth on the energy and financial fronts requires a decrease in reliance on the grid, which may be achieved via the implementation of better energy management practice. One of the most successful techniques to decrease grid reliance is load shifting, which is made possible by numerous innovations that include on-site generation of clean energy or effective battery backup [26].

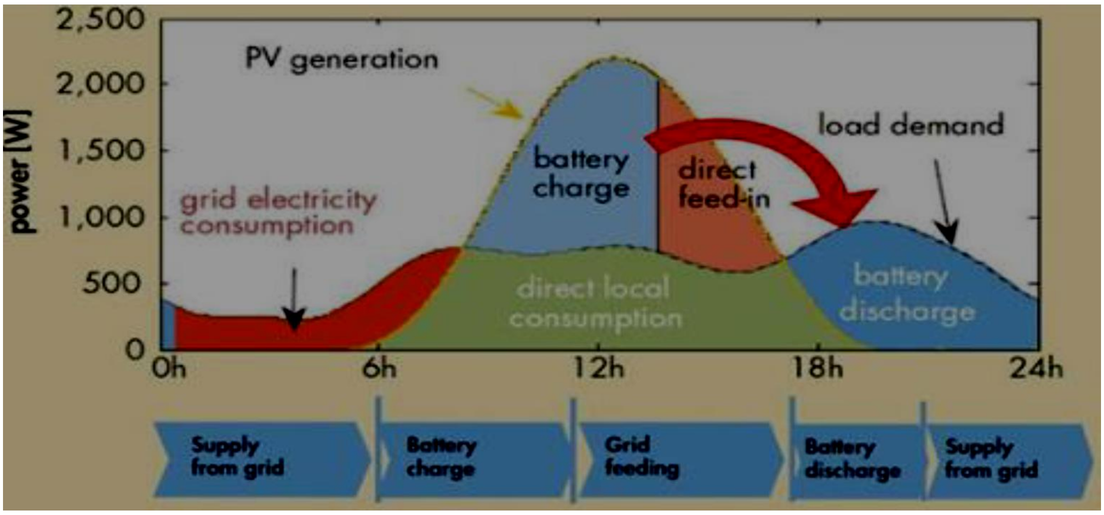


Figure 2.4: Load shifting description [27].

2.7. Supply-and-Demand Management

With DSM, the power provider may influence how its customers use and produce power. For consumers to adapt their usage and monitor the amount of power consumption, DSM entails the planning, implementation, and management of end-user activities [28]. DSM strategies are implemented, either directly or indirectly, by the provider [29]. Electricity consumption may be reduced in several ways when DSM techniques are put into practice. Load switching strategic preservation, strategic load growth, peak clipping, and valley filling are some of the load management approaches shown in Figure 2.5 [30].

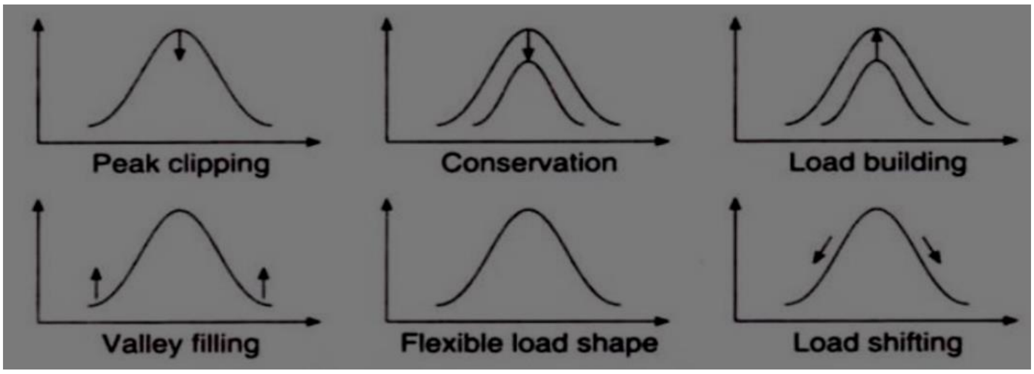


Figure 2.5: Strategies for DMS load management [29].

Load shaping methods are described as follows in [31]:

i. Utilities utilize peak clipping to minimize demand from customers' load profiles at peak times by either tariffs or direct load management.
ii. What We Did The phrase "valley filling" describes the process of increasing demand during off-peak hours to mitigate the severity of demand drops during valleys.
iii. Strategic conservation is utilized to achieve load shape via customer-side demand reduction measures. By switching to more efficient equipment or lowering daily use, conservation may lighten the strain.
iv. Load in a building may be maximized by raising its overall consumption throughout the day using this tactic.
v. The load shifting method switches the use of certain electrical equipment from peak to off-peak times by taking use of their inherent temporal independence.
vi. The reliability of the smart grid is guaranteed by an adaptable load strategy, which involves incentivizing customers to be controlled during critical demands periods in exchange for their loads.

2.8. The solar power setup

The PV system is well recognized as a power system that harnesses energy from sunshine via the unique features of semiconducting materials, without the need for traditional procedures such as heat engines or spinning equipment. Hence, the attributes of a photovoltaic scheme are inextricably linked to the solar irradiation it receives and the precise placement of the sun's rays relative to its unique geographical location. Solar PV technology has emerged as a highly developed and swiftly advancing kind of renewable energy technology. It is anticipated to assume a significant position in the imperative shift towards cleaner energy sources throughout the energy transition. Consequently, PV systems have seen substantial global growth in recent years, including both academic and business sectors. According to the discoveries made by the International Energy Agency (IEA) [32], in 2019, there was a notable increase of 22% in Solar PV generation. This increase in solar PV production ranked second in terms of absolute growth among various renewable technologies, slightly trailing wind power and surpassing hydroelectricity. Moreover, it is expected that there would be additional expansion within the framework of sustainable growth the circumstances, illustrated in Figure 2.6.

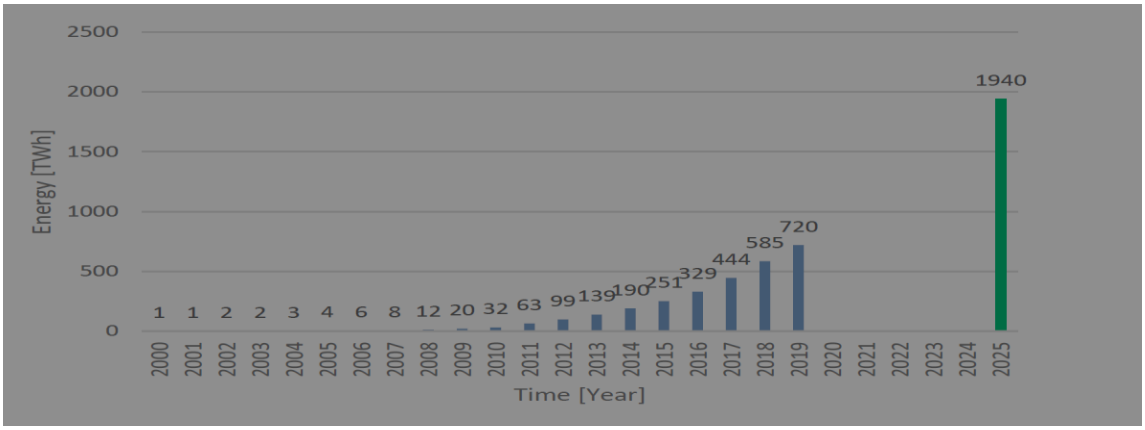


Figure 2.6 : The increase of PV generation and its implications for achieving sustainable development objectives [32].

The drop in price of PV modules may be attributed to the market expansion and technological advancements, which have led to increased production scale and continued manufacturing improvements. This decrease in price is especially remarkable considering that photovoltaic modules now constitute 50% of the overall expenses of a PV system [33]. A proliferation and increased use of PV systems has led to a notable diversity within this technology.

2.8.1.The development and proliferation of PV technology

Becquerel conducted the first observation and subsequent research of the photovoltaic phenomena, with the aim of investigating the impact of light on electrolytic cells. At present, there are four main types of PV panels: thin film, monocrystalline, polycrystalline, and transparent solar cells. The photovoltaic cell, which operates as a focused semiconductor materials diode, has the ability of transforming daylight into electrical power. Nevertheless, it is important to acknowledge that some photovoltaic cells have the capacity to directly transform infrared or ultraviolet light into direct current electricity [34]. The term "photo" is derived from the Greek word meaning "light," while "voltaic" originates from the concept of "voltage." The Earth's surface receives solar radiation at a consistent rate known as the solar constant, which is estimated to be about 1000 watts per square meter (1000W/m²).

This inverter's job is to convert DC from the DC source into alternating current (AC) output which can be synced with the power network. Some small loads, such lights, TVs, radios, and DC drives may be powered directly by the array of solar cells or panels. In most PV applications, power conditioners are essential for the correct processing of the solar device's produced energy. As a result of temperature and sunlight fluctuations, the values of the load-side converters, which control the current and voltage, are not constant. Therefore, an MPPT mechanism is required to track the device's Maximum Power Point (MPP) and control the flow of power within the grid system [35]. Manufacturing PV modules begins with the assembly of individual solar cells into bigger components and continues with their interconnection in a parallel-series configuration, as described in [34]. The amount of sunlight reaching a photovoltaic cell—also called a solar cell—during operation determines the photocurrent, which in turn determines the voltage that the cell produces. Comprehensive and efficient PV systems need PV structures that are reliable, easy to use, and affordable. Consistently meeting consumer load demand or network energy production requires power-conditioning equipment, such as DC-to-DC converters, which must be acknowledged [36].

2.8.2.Theory behind the photovoltaic effect's operation.

The functioning of a solar energy cell is based on the photovoltaic effect, which is its basic operating concept [37]. The process of creating a voltage differential at the interface of a P-type and N-type semiconductor is known as a photovoltaic effect. The creation of pairs of electrons and holes occurs when a material absorbs light. However, the charge carriers are affected by the loss of the layer's electromagnetic field when they reach the P-N junction. As can be seen in Figure 2.7, the migration of holes towards P-type materials and electrons towards N-type materials is caused by this electromagnetic field [38]. An increase in the energy levels of the electrons inside a material occurs when that material absorbs greater amounts of energy from the sun. .

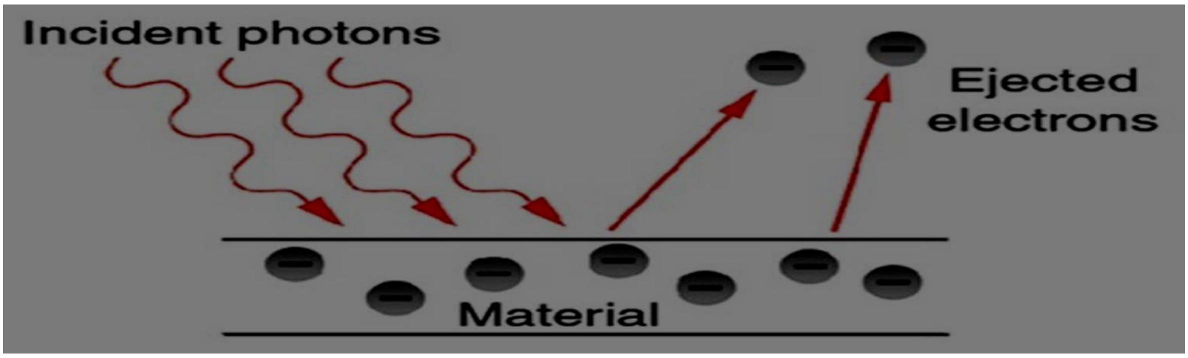


Figure 2.7: The occurrence of the photoelectric effect [39].

2.8.3.Solar photovoltaics in South Africa

South Africa's very high irradiating intensity, as indicated in the heat diagram displayed in Figure 2.8, indicates that the country has enormous opportunities for solar energy. Particularly, the Karoo region stands out as an optimal location for PV systems due to its consistent and elevated levels of irradiation per unit area.

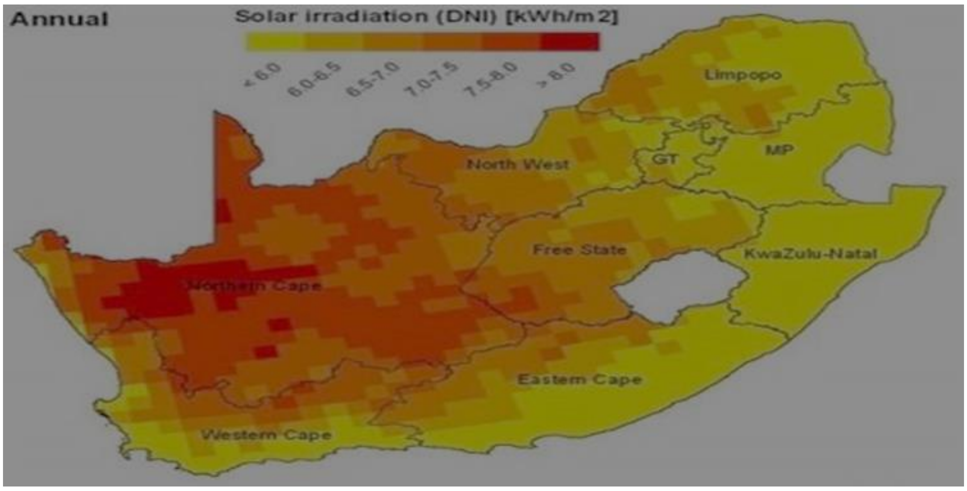


Figure 2.8: Average annual global horizontal irradiation in kilowatt-hours per square meter of South African soil [40].

South Africa exhibits a growing economy and serves as a nation where PV systems are conveniently accessible, uncomplicated to build, and straightforward to maintain. PV technology is widely used in both household and business RESs. The current issue at hand pertains to the disparity between our peak energy demand and our available energy capacity. Eskom has shown that solar energy may be effectively used for PV generation prior to the recognized peak demand periods in the country. These peak demand periods occur from 17:00 to 19:00 in winter and from 18:00 to 20:00 in summer seasons. Moreover, Figure 2.9 exhibits the power profiles of a standard home demand in conjunction with the power produced by a PV system.

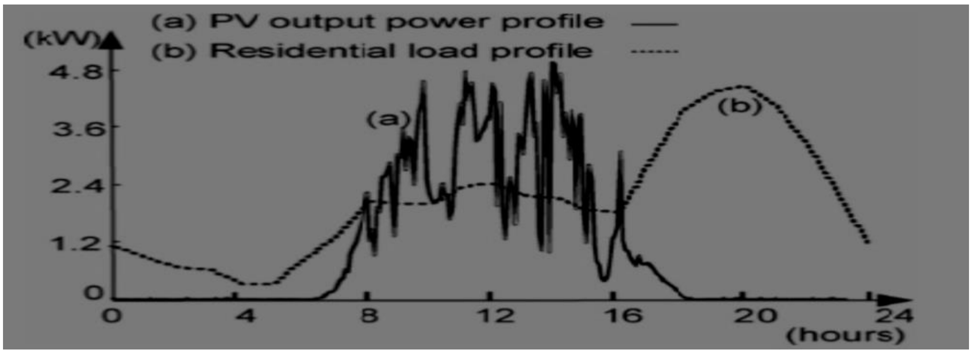


Figure 2.9 : Power output characteristics [41].

2.8.4.Different PV System Types

PV systems may be categorized based on many criteria, with the two most prevalent being their applications and the solar cell technologies used, which determine their cell materials and structure. PV systems consist of several components, each designed to fulfil a certain function. The Photovoltaic Grid-Connected Systems (PVGCS) consist of many significant components.

i. PV modules
ii. Inverters
iii. The installation of support structures and other components of the balance of system (BOS), including wiring, protective measures against overcurrent and over earth fault, surge protectors, instrumentation, and monitoring systems (such as Scada or DCS), and isolation devices.

2.8.4.1. Photovoltaic effect

PV modules are essential for turning solar irradiation into electrical energy by harnessing the phenomenon called the photovoltaic effect. The solar energy effect is facilitated through the use of semiconductor substances such as copper sulphate (Cu2S), gallium arsenide (GaAs, and silicon (Si). A material's capacity to conduct electricity depends on the amount of power that can be temporarily applied to the crystal lattice, a property shared by a class of materials called semiconductors. When light hits the solar cell's surface, and it raises the energy level of the electrons inside the cell's lattice, allowing them to flow freely across the semiconductor. The displacement of electrons from their initial locations results in the generation of positive charges referred to as holes.

2.8.4.2. Technology of PV module

A variety of solar energy systems are available today, and they all have their own unique set of electrical and optical specs. These disparities result in some categories of modules exhibiting superior performance in particular locations or circumstances compared to others. There are two primary varieties of photovoltaic modules: those made of crystalline silicon and those made of thin film. Figure 2.10 shows that there are even more subcategories within these two main groups.

i. **Monocrystalline silicon solar cells:** Circular silicon ingots are used in the production of these solar power cells, which are also called single-crystalline solar cells. To make Mono-c-Si PV modules, the Czochralski process is utilized to make silicon wafers, which are subsequently cut into four equal pieces, giving them their unique look. Figure 2.10a shows that solar cells in Mono-c-Si modules have a consistently black and homogenous coloration. This is likely because their composition is made from one high-purity silicon seed crystalline. Exceptional effectiveness, often between fifteen and twenty percent, is achieved by solar panels made of monocrystalline silicon (mono-c-Si) [42,51].
ii. **Multi-crystalline silicon solar cells:** This specific method of making cells is known as polycrystalline silicon, or p-Si. To make multi-crystalline silicon (multi-c-Si) cells, the material

is first melted and then poured into a square mold. After cooling, the material is meticulously cut into rectangular strips. As can be seen in Figures 2.11c and 2.11d, the presence of discernible perimeters and borders of grain causes multi-crystalline silicon cells to generate a spectrum of colors as shown by references [42] and [43].

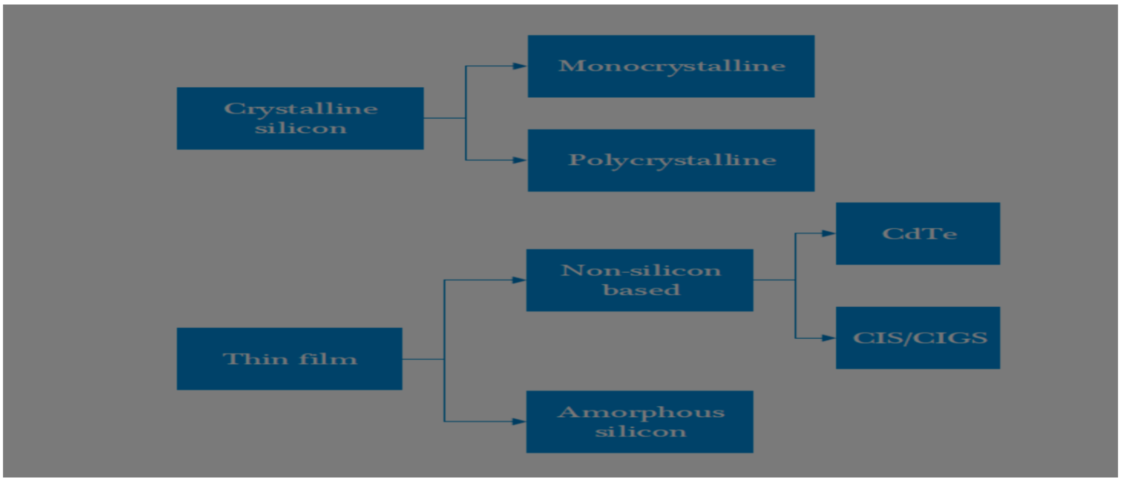
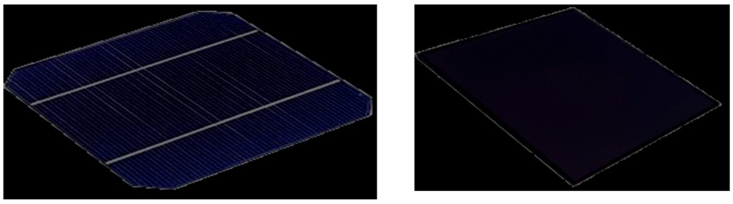


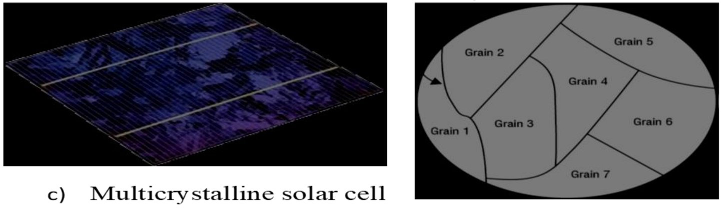
Figure 2.10: Photovoltaic Cell Technologies

iii. **Thin film solar technology:** The production of thin film modules involves covering a substrate which might be made of either metal, glass, or plastic—with thin layers of photovoltaic material. Amorphous thin-film silicon (a-Si), constructed from silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) are among the several variations of thin film photovoltaic (TFPV) solar panels used commercially. The efficiencies of TFPV modules are often seen to be lower [42],[43] in comparison to their crystalline counterparts. However, TFPV modules provide the advantage of being more readily amenable to mass production and typically exhibit reduced susceptibility to high temperatures and shade[43]. The Thin Film solar cell is seen in Figure 2.11.b.



a) Monocrystalline solar cell

b) Thin Film solar cell



c) Multicrystalline solar cell

d) Grain boundaries in multi-c-Si cells

Figure 2.11: Classifications of photovoltaic modules [43].

2.8.5.Inverters

In order to convert the direct current energy produced by solar PV panels into alternating current electricity, solar power inverters are necessary. Because of this, the energy may be used by other appliances on-site or sent to other consumers via the power grid. In addition to their primary function, inverters possess a wide range of utility and are often employed in many contexts.

a) The goal is to maximize power point tracking's (MPPT) ability to capture energy from the solar array.
b) Following all rules and restrictions set forth by the grid operator is essential while connecting the PV system to the grid.
c) Offering fundamental surveillance and supplementary functions.

There exist several topologies of inverters, each characterized by distinct architectural features and capacities. Consequently, these inverters demonstrate certain advantages and disadvantages, rendering them more appropriate for some PV systems compared to others.

i. **String inverters:** The nomenclature of these inverters is derived from their association with a single string or many strings of PV modules. In the case of a breakdown or disconnection of one inverter during maintenance operations, this design ensures that the other working string inverters in the design may continue to produce electricity, reducing the total system risk.
ii. **Microinverters:** Microinverters are smaller versions of solar inverters that are specifically engineered to transform DC into AC power right at the solar panel. Along with power optimizers, microinverters are a kind of component known as module level power electronics (MLPE).
iii. **Central inverters**: Central inverters and string inverters have similarities, while central inverters possess larger dimensions, enabling them to accommodate a greater number of strings. A common combiner device is used to join the strings in a central inverter setup, as opposed to a string inverter design.

2.8.6.Mounting Systems

The installation method of a system's modules affects the system's cost and efficiency. It is possible to broadly classify ground-based systems into three main categories:

Fixed tilt: The sub array is arranged in a predetermined angle of tilt (θ_T)and angle of azimuth (ϕ_c). The azimuth is defined by the orientation perpendicular to the equator, while the latitude angle is usually used by designers as the tilt angle of choice. In particular, places in the southern hemisphere are pointed in the north direction, whereas places in the northern hemisphere are pointed in the south direction.

Single axis: Installed at a constant inclination angle, the subarray tracks the sun's nocturnal journey along the north-south axis, from east to west. The tracker's rotation limit, θ_R., defines the subarray's extent of rotation in both the eastern and western directions. In order to avoid mutual shading caused by the sun's movement, certain single axis tracking systems use a method called backtracking. This involves adjusting the alignment of the arrays of solar modules.

Azimuth tracking: By keeping the subarray at a fixed tilt angle as it rotates on a horizontal surface, we can track the sun's frequently path without worrying about its azimuth angle.

Dual axis: Following the sun's regular path, the subarray rotates from east to west, much like a tracking system with one axis. On top of that, it moves in the same north–south direction that the sun does all year round. The mounting strategies that were previously addressed are schematically shown in Figure 2.12.

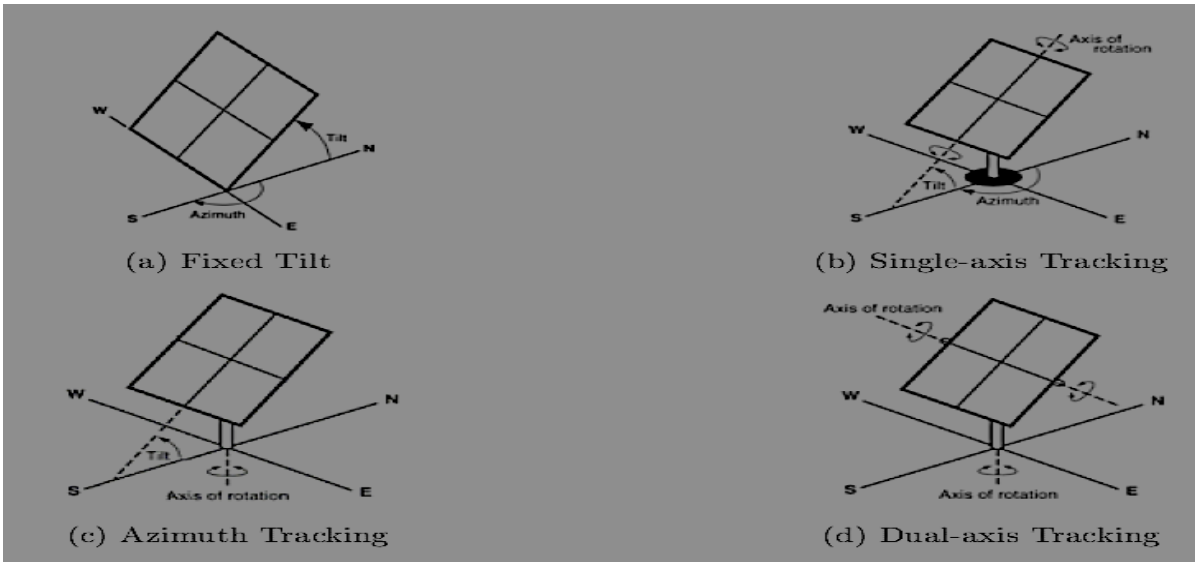


Figure 2.12: The mounting techniques as per SAM[44].

2.8.7.Different Forms of Applications

It is possible to classify solar PV systems into three main groups according on the uses they are put to [45]. Figure 2.13 graphically displays these categorizations.

i. **Grid-tied solar PV system:** This particular solar installation is rather basic, consisting just of a standard grid-tied inverter. There is no energy-storing battery in the grid-dependent PV system. Production and consumption of energy are constrained to the daylight hours in a grid-dependent system. In addition to being very inexpensive, the aforementioned system is also very easy to handle and requires very little maintenance. Reducing energy-related expenses is the main objective of the grid-tied method. A direct-to-grid technology's limited operating capability during daylight hours is one of its limitations.

ii. **Off-grid solar PV system or Standalone:** By storing energy in batteries, disconnected from the grid solar PV systems may utilize the electricity generated throughout the day for later usage or in times of emergency, including when the sun isn't shining or when it's too dark outside. In some instances, these systems may be equipped with auxiliary power generators to mitigate the effects of prolonged periods of solar deprivation.

iii. **Hybrid System:** This setup combines the best features of grid-tied and disconnected from the grid power sources. Widespread incentives have the potential to contribute to the reduction of consumers' power expenditures. With the energy stored in the battery reserve being usable in such unexpected situations, these systems may also serve as an additional power source to the electrical grid during power outages.

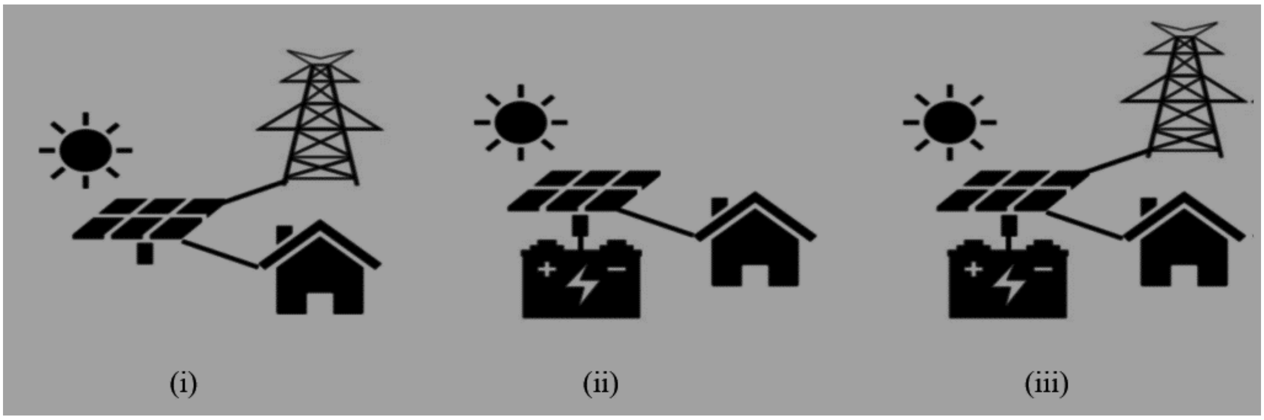


Figure 2.13: (i) Grid-tied PV system (ii) Off-grid PV system (iii) Hybrid PV system [45].

2.8.8.Photovoltaic systems' electrical properties

One of the many types of photovoltaic models is the single diode model (SDM), which is the simplest. The conjugation process at the P-N junction may be better understood by plugging the idealist factor (n) into the updated Shockley diode formula. A single diode linked in an antiparallel fashion to the power supply demonstrates this. Figure 2.14 shows that the PV cell's accuracy at its maximum point cannot be precisely measured due to the model's simplicity [52].

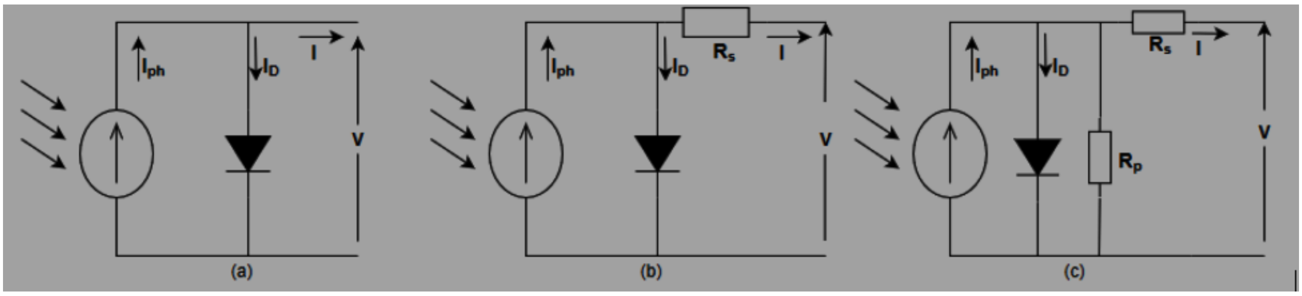


Figure 2.14: The comparable solar cell circuit includes the ideal SDM, the 4-pole and the 5-pole [38].

By including an additional series resistor into the revised model, the model is improved to a value of (4-p). The present study does not need this specific improvement. The first expression shows the evolution of a one-dimensional model into a 5-p model. Because of its great experimental accuracy, this model is often used in research projects [38].

$$I = I_{ph} - I_d - I_p = I_p - I_o\left[e^{\frac{V+IR_S}{nV_t}} - 1\right] - \frac{V+IR_S}{R_p} \qquad \ldots\ldots (2.1)$$

The electrical characteristics of a photovoltaic cell are shown in the equation 1 which also shows the connection between the cell's internal power, the output current, and the series resistor ($\boldsymbol{Os}$). The reduction in voltage across P-N junctions is explained by the series resistor. Recombination in space charge may be described by the diode reverse current, as stated in [38], while leakage currents at the cell's edges can be shown by the parallel resistance ($\boldsymbol{Op}$).

There is no clearly stated solution for either voltage or current in the PV circuit that corresponds to the 5-p model, as indicated in equation 2.1. This circuit presents considerable complications. Nonetheless, by gradually increasing the diode voltage in an Excel file until a similar current value is reached, the current-voltage (I-V) characteristic of the diode may be ascertained [34] . You may see a plot illustration from the previously described method in Figure 2.15 [39]. The red curve shows the features of the current-voltage (I-V) relationship, whereas the blue line shows the electric power output, which is the result of multiplying the voltage and current produced by the photovoltaic cell.

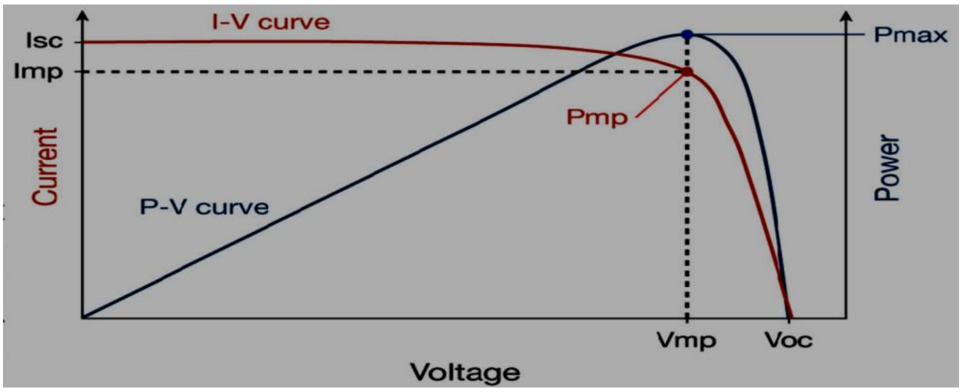


Figure 2.15: I-V and P-V curves [46].

The maximum voltage that a photovoltaic panel may produce in an open circuit condition, when no load is attached, is called the open circuit voltage (Voc). Throughout the lifetime of the solar energy system, the relevant value surpasses the maximum point voltage ($\boldsymbol{Vmp}$). It all comes down to the total number of solar panels linked in a series arrangement, which determines the value at stake[47].

There may be limitations to the practical usability of these cells for different applications due to their comparatively modest voltage output of 0.5V per cell. A series arrangement is used to increase the output voltage, while a parallel configuration is used to increase the output current [48]. The PV module, which is made up of many cells linked in a series arrangement, is the main element of a PV array. Nevertheless, the overall voltage is obtained by adding the voltage across all of the modules. Equation 2.2 expresses this link, as stated by [49].

$$V = \sum_{i=1}^{n} V_i \qquad \ldots\ldots (2.2)$$

Where:

- V stands for total potential difference.
- V_i stands for potential difference of the module.
- n stands for voltage at nth module.

$$I = \sum_{i=1}^{n} I_i \qquad \text{…… (2.3)}$$

Where:

- I stand for the total current.
- I_i stands for the current across module.
- n is the current at nth module.

The construction of an array is achieved by the use of series and parallel connections, as seen in Figure 2.16 (d) [50].

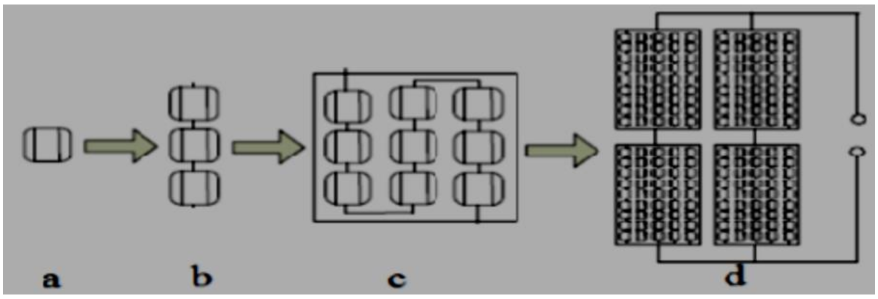


Figure 2.16: a) PV cell, b) Cell series string, c) Cell module, and d) PV array [50]

According to Rahim et al. [51], a PV module or PV array may be mathematically represented by multiplying the voltage that it produces by the amount of cells linked in series (Ns) and the current flowing from the output by the number of cells coupled together in parallel (Np).

$$I = N_p I_{ph} - N_p I_O \left[e^{\frac{1}{V_i}(\frac{V}{N_s}+\frac{IR_S}{N_p}} - 1 \right] - \frac{N_p}{R_p}\left[\frac{V}{N_s} + \frac{IR_S}{N_p}\right] \qquad \text{…… (2. 4)}$$

The power generated by solar systems may be determined by multiplying the product of $\boldsymbol{Vdc}$ and Equation 5.

$$P_{pv} = N_p I_{ph} V_{dc} - N_p I_O V_{dc} \left[e^{\frac{V_{dc}}{V_i}(\frac{V}{N_s}+\frac{IR_S}{N_p}} - 1 \right] - \frac{N_p}{R_p}\left[\frac{V}{N_s} + \frac{IR_S}{N_p}\right] V_{dc} \qquad \text{…… (2. 5)}$$

It is evident from Equation 5 that the PV system's power production is dependent on the voltage and current within the solar cell circuit, as stated in [49].

2.8.9. The impact of temperature and solar irradiation

The reliance of the solar cell on variables including temperature, load condition, and exposure to sunlight is the cause of this non-linear behaviour Equation 6 explains that the photo current is directly connected to radiation and shows a linear connection with temperature; hence, the current source is also dependent on the radiation from the sun and temperature [52].

$$I_{ph} = [I_{sc} + k_i(T - T_{STC})]\frac{E}{E_{STC}} \qquad \text{…… (2. 6)}$$

Where:

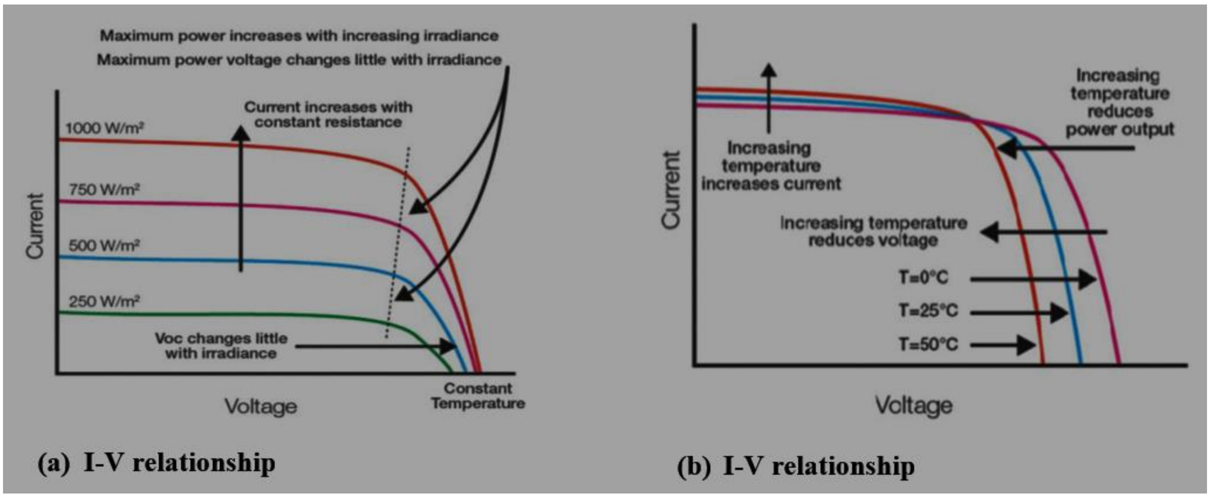
- I_{ph} represent hoto current
- I_{sc} represent short circuit current
- k_i represent temperature coefficient of ISC
- T_{STC} represent STC temperature at 20°C
- T represent operational temperature
- E represent effective irradiance
- E_{STC} Represent irradiation with STC (1000 w/m2)

According to Richardson [43], the voltage of the open circuit (Voc) is directly affected by temperature, and this is explained in Equation 2.7, which represents the open circuit voltage [39].

$$V_{oc} = V_{oc-stc} + k_v(T - T_{STC}) \qquad \text{…… (2.7)}$$

Where:

- V_{oc} = Operational voltage
- V_{oc-stc} = the voltage across an open circuit
- k_v = coefficient of thermal expansion for voltage
- T = temperature required for functioning
- T_{STC} = the temperature of the STC at 25°C



(a) I-V relationship **(b) I-V relationship**

Figure 2.17: Effects of temperature on a photovoltaic system under continuous illumination [51].

The provided figures, labelled as 2.17, depict the distinctive attributes of a standard reaction seen in a photovoltaic system under certain conditions of temperature and irradiance. According to Adhikari [47], variations in temperature and irradiance inside the atmosphere lead to minute-by-minute fluctuations in the maximum power point. Consequently, keeping an eye on and optimizing the system's maximum power point requires a technical solution. Keeping the frequency steady is critical for the whole system's effectiveness and productivity [57].

2.9. Solar resources and selection of site

With an emphasis on the grid-tied battery-less set up, this part will mainly cover the fundamentals of PV system development. When combined with other climatic variables, such as air temperature as well as wind velocity, a variety of solar radiation indices that fall under the umbrella term "solar resource" may be applied to evaluate the features of a given site. Accurate energy production forecasting and system performance modelling are made possible by combining meteorological and solar data with the sun's exact planetary location. One of the most important steps in determining if a solar PV development at a given location is feasible and viable is measuring the performance of the PV system. This estimate is very dependent on how well three critical components of the model work together.

2.9.1.Location of the sun in relation to earth

Figure 2.18 shows that the sun's position can be described by two main angles: the altitude (elevated levels) angle, θ, and the azimuth, or rotation, angle, ϕ. By plugging these values into the appropriate equations, we can determine the sun's altitude and the sun's azimuth angles for a given latitude (L), year (represented by a decline angle), and hour (H). All of the factors that are being thought about may be described as:

i. **Azimuth angle:** The rotation around the sun's axis relative to the north-south axis.
ii. **Solar altitude angle:** the right angle that forms when you put the horizontal surface right up to the sun's geometric centre. The zenith angle, which serves as its counterpart, is a significant component in several computations pertaining to solar phenomena.
iii. **Declination angle:** The right angle that forms when the equatorial plane meets the line that goes from the geometric centre of the sun to the geometric Center of the earth's surface. Figure 2.20 (see Equation 2.8) shows that the angle changes throughout the year as a result of the orbit of the Earth and the apparent vertical movement of sunlight over the seasons [53].
iv. **Hour angle:** The angular representation of time refers to the quantification of time as the number of degrees the Earth needs revolve to align directly over a certain line of longitude, which occurs at solar noon (as shown in Equation 2. 9).

$$\beta = sin^{-1}(cos\, L\, cos\, H\, cos\, \delta + sin\, L\, sin\, \delta) \qquad \text{...... (2.8)}$$

$$\phi_s = sin^{-1} \frac{sin\, H\, cos\, \delta}{cos\, \beta} \qquad \text{...... (2. 9)}$$

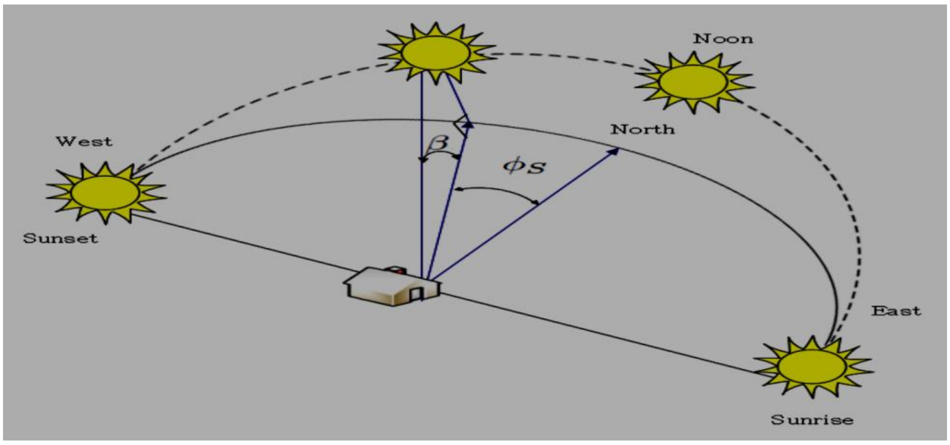


Figure 2.18: Graphical representation of the sun's altitude angle (ϕ_s) and solar azimuth angle (β) [53].

2.9.2.Solar radiation parameters

To find out how much solar power is available at a certain site, scientists usually look at three main factors that measure terrestrial radiation from the sun. This is the amount of solar power that reaches Earth from the surface of the planet, not from space. Here are they :[54]

- Global Horizontal Irradiance (GHI)
- Direct Normal Irradiance (DNI)
- Diffuse Horizontal Irradiance (DHI)

2.9.2.1. Global Horizontal Irradiance

The term GHI describes the total amount of solar radiation that a certain region of the horizontal surface receives. The two parts of solar irradiation that make up GHI—diffuse and direct beam—will be discussed in more detail in the sections that follow. Sun irradiation characteristics are shown in Figure 2.19.

2.9.2.2. Direct Normal Irradiance

One common way to refer to the beam component—the amount of energy received per unit area on a surface that is directly to the sun—is as DNI. Concentrating solar power (CSP) and solar photovoltaic tracking devices primarily aim to maximize the amount of sunlight that reaches their collectors. One may estimate the values of the DNI using equation 2.10 if they have access to the observed values of the DHI and the GHI [55].

$$G = G_{diff} + G_{dir}\ cos(\theta_z) \qquad \ldots\ldots (2.10)$$

Where:

G represent GHI.

G_{diff} represent DNI and

θ_z represent zenith angle of the sun.

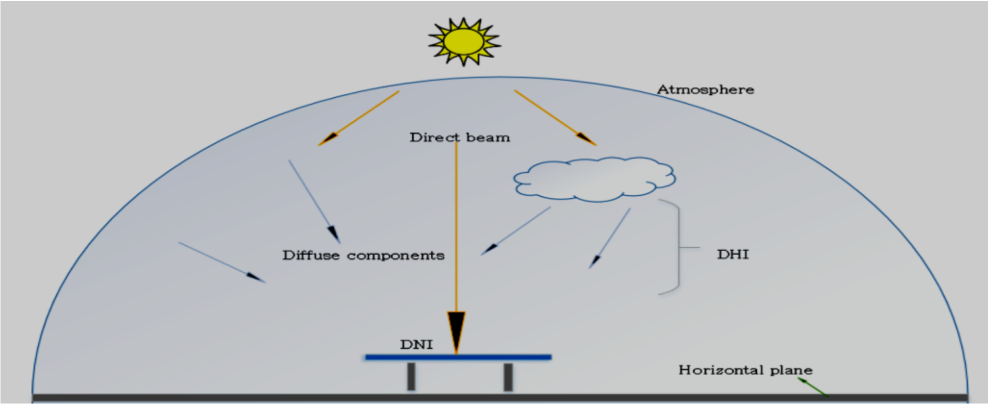


Figure 2.19: Parameters of the Sun's rays when they hit Earth [55].

2.9.2.3. Diffuse Horizontal Irradiance

DHI is the quantity of solar radiation that reaches a horizontal surface from a given region. This energy does not originate from the sun's rays but rather from a variety of sources, including the air particles that scatter irradiation before it reaches the surface. Solar power panels are typically angled at an angle θ_T. and positioned towards the centre of the earth for optimal energy output. The solar panel's cover is designed to absorb the greatest quantity of typical irradiance at an angle that corresponds to the latitude. The collector/surface azimuth position, abbreviated as ϕ_c, is another name for the orientation angle of the PV system. It stands for the angle formed by the horizon and the direction perpendicular to the PV module's surface [54].

2.9.2.4. Global Plane of Array

The total amount of sunlight that falls on an inclined surface as a percentage of its total area is called Global Tilted Irradiance (GTI). It is the goal of photovoltaic system engineers to maximize the average, long-term value of the Global Plane of Array Irradiance (GPOA). When reliable measured GPOA data is unavailable, it is necessary to determine GPOA as a function of time in order to correctly estimate PV system efficiency due to the ever-changing sun-to-module positioning relationship. Lots of factors determine the GPOA, which includes:

- The sun’s position.
- The arrangement or placement that constitute the Solar array's alignment and support system.
- Direct and diffuse illumination factors
- Reflection off the earth surface.
- • The presence of both local and distant obstacles that might cause shadowing, which can be mathematically expressed as:[53], [54].

$$G_{POA} = G_{beam} + G_{ground\_ref} + G_{sky\_diff} \qquad \text{...... (2.11)}$$

$$G_{beam} = G_{dir}\ x\ \cos\theta_{AOI} \qquad \ldots\ldots (2.12)$$

$$G_{ground_{ref}} = G * \lambda\,\alpha\,\frac{1-\cos\theta_T}{2} \qquad \ldots\ldots (2.13)$$

where:

G_{beam} is the irradiance in the array's plane that comes from the beam's direct direction.

G_{ground_ref} is the array-plane irradiance that has been reflected from the ground,

G_{sky_diff} represents the diffuse irradiance of the sky.

θ_{AOI} represent the angle at which the PV module's surface meets the sun.

$\lambda\,\alpha$ represent amount of sunlight that is reflected by the Earth's surface.

θ_T represent angle at which the photovoltaic panels are positioned.

2.9.3.Methods for Measuring Solar Radiation

Two common ways to collect data on solar resources are via the use of satellite imagery and physical measurements taken at the target location. Specialized devices, including pyranometers and semiconductor detectors, are used to gather data at regular intervals, usually on an hourly basis, but occasionally even shorter intervals, right at the site of interest. This allows for the acquisition of ground measurements. It is usual practice to use techniques for interpolating while acquiring long-term irradiance datasets, as there is a lack of big previous information from ground-based facilities [56].

Table 1.1: Distributed databases of solar resources

The data sources	**Nature**	**Coverage**	**Access**
SolarGIS	information gathered via satellites	60°N to 50°S, from either 1994 or 1999 (depending on the location) until the present.	Paid
SoDa Helioclim	information gathered via satellites	Most often throughout Europe, Africa, and the Middle East; from February 2003 till the present	Paid
Meteonorm	Earth surface data	global; encompassing a large portion of the	Paid

		globe from 1982 to 2011	
3Tier	information gathered via satellites	worldwide; beginning in 1997, 1998, or 1999 (depending on location), and continuing to the present	Paid
PVGIS	information gathered via satellites	world-wide, during the years 1981 and 2011, roughly.	Free of charge
NASA-SSE	information gathered via satellites	worldwide, from 1983 to 2005	Free of charge

2.9.4.Choosing a Location

A PV project's technical and financial viability are heavily influenced by the site selection process. Site selection is not a black-and-white process; still, numerous factors must be considered; after all, multiple initiatives have been successfully executed on upward slopes and at landfills [56]. Among the elements that are considered are:

i. How much sunlight reaches solar PV modules determines the plant's output power, which in turn is affected by weather and available solar resources.
ii. Several characteristics that affect PV module performance are affected by terrain and ground conditions. These include far shading, surface reflectance, and installation system selection.
iii. The available land area and land-use restrictions in the region, as well as other land-allocation and regulatory factors, are critical in deciding how modules are organized and how well they work on the field.
iv. The presence and proximity of a grid connection at the site is crucial to ensure minimal energy losses during transmission, since longer cables may result in significant inefficiencies.
v. When contemplating the installation of a photovoltaic plant in the area, it is important to weigh the potential benefits and drawbacks on the local people and the surrounding ecosystem.
vi. The assessment of costs and financial incentives is crucial in determining the financial feasibility of a PV project.

2.10. Performance parameters of photovoltaic systems.

This section will explore several measures used for evaluating the operational success of a plant, providing insights into both its financial and technical aspects. All throughout the energy production chain of solar systems, facility performance metrics are utilized to find ways to make the system more reliable, efficient, and profitable.

2.10.1. Energy generation

The electrically generated produced by a solar power plant is often used to measure a plant's performance. This approach has been widely accepted and used. The establishment of energy output as a primary objective in the design process is a common practice. To get the energy production in a theoretical framework, you multiply the system's entire power generation (which is, in kilowatts) by the length of the time period you're considering (in hours, usually).

$$Total\ Energy\ (kWh) = Total\ Power\ (kW)\ X\ Time\ (h) \qquad \ldots\ldots (2.14)$$

2.10.2. Plant specific yield

One way to measure a plant's efficiency is by looking at its Specific Yield, which is the ratio of its energy production to its maximum capacity currently in use. The use of a standardized scale is often employed to facilitate the comparison of operational outcomes across PV systems that have been developed using various technologies or layouts. The calculation of specific yield is determined using the following formula:

$$Specfic\ Yiel\ (kWh/kWp) = \frac{Total\ Energy\ (kWh)}{Peak\ Capacity\ (kWp)} \qquad \ldots\ldots (\ 2.15)$$

2.10.3. Ratio of Performance

One measure of a PV system's quality is the performance ratio, which is also known as the reliability factor . An alternative perspective on the PR might be seen as an indicator of a plant's efficacy in terms of energy use and dependability. The concept of PR serves to demonstrate the correlation between the tangible crop production and the hypothetical energy generation, often denoted as a percentage in accordance with Equation 2.16.

$$Performance\ Ratio\ (\%) = \frac{Plant\ output\ \ (kWh)}{Nominal\ calculated\ \ output\ (kWh)} \qquad \ldots\ldots (\ 2.16)$$

2.10.4. Capacity Factor

Power plant efficiency may be measured by looking at the capacity factor (CF), which is the ratio of the facility's actual production to its maximum potential output. As shown in Equation 2.17, the calculation must be done by subdividing the total energy produced by a plant under standard circumstances over a specific time period by the total energy that the plant would have produced had it operated at maximum capacity throughout that exact time frame. The result is the fraction or a percentage.

$$Capacity\ Factor = \frac{Total\ Energy\ Produced\ \ (kWh)}{Maximum\ Possible\ Energy\ Output\ (kWh)} \qquad \ldots\ldots (2.17)$$

2.10.5. Levelized Cost of Energy

The LCOE represents the total monetary outlay, expressed as a cost per kWh , for running a plant for its expected financial lifetime. When comparing various power generating methods, the LCOE is a useful indicator to keep in mind. Every expense related to the generating technology's lifetime and the power produced during that period are included in it. One practical way to assess grid profitability and near to grid equilibrium is to compare projects across different technologies, lifetimes, and capacities. At grid parity, the level of cost of energy generated by renewable sources is comparable to, or less than, that of power purchased from the grid. This method allows for a comprehensive assessment of projects, enabling a convenient means of comparison. The formula for calculating the LCOE in a simplified manner is as follows:

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \qquad \ldots\ldots (2.18)$$

Where:

N is the time frame for analysis.

C_n are the projected expenses for the project's nth year.

Q_n amount to the overall power output of the whole system in the year n measured in kilowatt-hours (kWh).

d $d_{nominal}$ & d_{real} display the price reduction rate as nominal (with inflation) and real (excluding inflation), correspondingly.

In order to include in investment expenditures, the annual spending totals begin at n = 0. On the other side, starting at n = 1, when the system starts generating energy, the total energy production is added up.

2.10.6. Losses

The evaluation of losses is a fundamental component in assessing the operational efficiency of a PV facility. When it comes to PV systems, inefficient operating conditions and component flaws are usually the main causes of wastage. The next sections elaborate on the aforementioned losses.

2.10.6.1. Incidence angle modifier losses

A decrease in the quantity of irradiation reaching the surface of the solar panel is one way to characterize the losses linked to the incidence angle modifier. This reduction occurs when the incidence angles deviate from the normal angle to the module surface, leading to reflectance. The laws of transmission and reflection at the interface of two transparent substances with different refractive indices (n1 and n2) are described by Fresnel's Laws, which are consistent with the phenomena of reflectance. The ASHRAE model, which uses a single PV module parameter, is often used in practical applications to simplify the calculation of irradiance hitting a PV cell's surface. The truth remains, nevertheless, that several computations—some of which may be complex—must be considered.

2.10.6.2. Shading losses

In a photovoltaic system, shading losses may happen when nearby obstacles cast shadows on the PV cells. This might also occur at certain times of daylight when modules in adjacent rows throw shadows on one another. Thorough examination during site selection may successfully reduce the impact of nearby trees, properties, and other impediments on utility size PV plants. In areas where there is a lack of available space, the inter-row shadows of PV modules are the main source of shade. Solar photovoltaic system designers rely on finding the optimum angle of tilt and row spacing of solar panel panels to reduce the impact of self-shading losses. There exist mathematical formulae that are used to compute the optimal row spacing in a PV system, ensuring that the derate factor resulting from shade remains below 2.5%. However, system designers employ several alternative approaches and algorithms to assess and minimize the impact of shading losses, as referenced in [57] and [58].

2.10.6.3. PV losses resulting from variations in irradiation levels.

In low-light conditions, a PV module's performance drops, which results in losses caused by irradiance. This effect occurs because, relative to the normal irradiation levels of 1000 W/m2, a PV module's effectiveness rises with increasing light intensity and decreases with decreasing light intensity. At different temperature settings, Figure 2.20 shows the connection between irradiation and module performance.

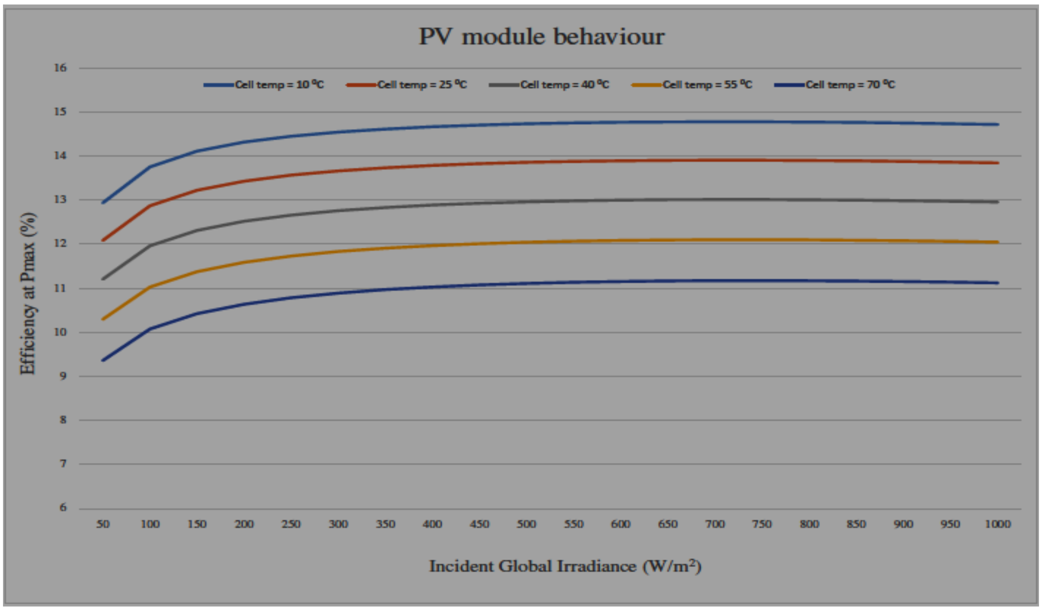


Figure 2.20: The impact of light on the effectiveness of modules over different cell temperature [58].

2.10.6.4. Soiling losses

A decrease in the efficiency with which photovoltaic cells convert sunshine into electrical power may occur if dirt accumulates on the surface of photovoltaic panels, obstructing some of the light that reaches the cells. Soiling is a common term for the act of collecting particles, soil, and other contaminants. There are a number of ongoing studies that aim to enhance methods of monitoring soiling-related losses. One potential approach for assessing soiling losses, which does not need costly equipment or complex methodologies, is using precipitation levels. The research conducted by ARUP in [57] examined module performance comparisons at several sites in South Africa. Soiling loss estimates may be seen in Table 2.2, which displays the monthly rainfall levels in millimetres.

Table 2.2: Ratio of soil loss

Precipitation per month (mm)	**Loss due to soiling (%)**
0-25	3
25-55	2
Greater than 55	1

2.10.6.5. Thermal losses

Solar PV panel temperature standards are 25 °C. In actuality, however, photovoltaic panels typically work in environments with temperatures higher than this benchmark. Thermal losses, also known as PV losses, are caused by increased temperatures and occur when the efficiency of modules decreases. Figure 2.21 illustrates the relationship between module efficiency and irradiance at various temperature settings.

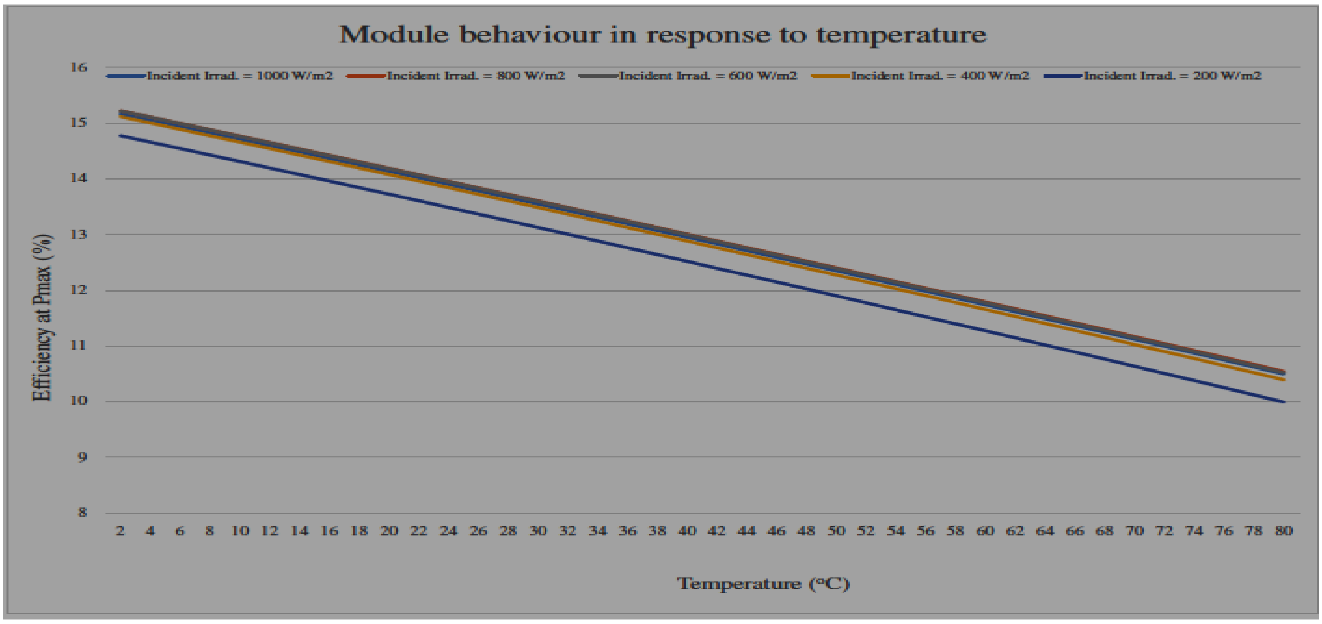


Figure 2.21: The relationship between module efficiency and temperature at various levels of irradiance [57].

2.10.6.6. Inverter losses

If we divide the power at the inverter's input terminals $P_{inverter_{in}}$by the power at its output terminals $P_{inverter_{out}}$ we get the inverter's efficiency. Consequently, we may describe the inverter losses, $P_{inveter_{loss}}$, as.

$$P_{inveter_{loss}} = 100\ x\ (1 - \frac{P_{inverter_{out}}}{P_{inverter_{in}}}) = 100\ x\ (1 - \eta_{inverter}) \qquad \text{...... (2.19)}$$

2.10.6.7. Direct current Ohmic loss

Direct current flow A major source of ohmic losses is the inherent resistance of the cables used to link the photovoltaic cells. On the other hand, the transition resistance in fuses and terminal connections might be to blame for these losses. It is common practice to compute DC ohms power losses in this way:

$$P_{DC\_Ohmic} = I^2\ R \qquad \text{...... (2.20)}$$

" I " stands for the average current via the direct current array, and " R " for its cable impedance. Voltage dips may occur in parallel strings when the lengths and diameters of the cables vary. This is because of the phenomena known as IR, which stands for current multiplied by resistance. Consequently, these voltage drops contribute to mismatch losses. As a result, it is common practice to aggregate DC ohmic losses and mismatch losses into a single figure representing overall losses [59].

2.10.6.8. Losses due to Mismatch

The main cause of mismatch losses is the fact that modules coupled in a string topology exhibit variable current drives. The current-voltage (IV) qualities and other electrical features of PV panels might vary from one kind of module to another [60]. On the other hand, a more common method is to calculate the mismatch losses by measuring the difference among the expected aggregate power of a string or arrays and its actual power, as seen :

$$CM = \frac{\sum_{n=0}^{N} P_{module\_max} - P_{array\_max}}{\sum_{n=1}^{N} P_{module\_max}} \qquad \text{...... (2. 21)}$$

Where:

P_{module_max} is the module's highest possible power output.

P_{array_max} represents the maximum total array power output that is theoretically feasible.

n represent the sum of all the data structure's modules.

2.10.6.9. Losses in external transformers and alternating current Ohmic

Reduced energy provided to the transformers is a common consequence of energy dissipation within the AC wire during transmission and conveyance of alternating current power from the inverter's output terminals to the utility meter. It is possible to integrate and estimate these losses, P_{AC}, using an alternate technique in situations when measured field data is unavailable.

$$P_{AC} = 100\ x\ \left(1 - \frac{P_{grid}}{P_{inverter_{out}}}\right) \qquad \text{...... (2.22)}$$

Where the amount of energy that is sent to the network is denoted as P_{grid}

2.11. Software for Modelling

The development of smart energy systems that use photovoltaics involves integrated and repeated techniques for financial and performance modelling. Financial models are used to estimate the costs of energy production, which include building and maintaining solar power plants and, in some cases, the anticipated profits from selling the energy to other users. The following steps are often included in designing a PV system and predicting its energy production using on an hourly basis or sub-hourly time periods inside simulator software:

i. The acquisition of weather data, including irradiance, wind speed, and temperature, may be achieved via several sources. Certain simulation software packages include pre-existing meteorological data libraries, allowing users to import data for locations not covered by these libraries.
ii. In the event that the Direct Normal Irradiance data is absent within the dataset, decomposition models may be used as a means to estimate or approximate it based on the existing irradiation datasets.
iii. The quantity of irradiance obtained on the surface of a slanted array is computed using transposition models.
iv. As part of the current project, we need to simulate the PV system's effectiveness and energy production given the site's unique operating conditions, in addition to designing and sizing the entire system.
v. Utilizing the appropriate losses.
vi. The plant performance report is generated by using a range of system performance metrics.

There exist many software programs for solar photovoltaic PV modelling, with options accessible both for free and for a fee. The various software packages also include distinct qualities that make them more appropriate for certain jobs in comparison to others [61]. The selection of an appropriate design tool is a crucial consideration for PV system designers, as it must align with their specific objectives, be compatible with their preferred platform, and remain within their allocated budgetary constraints. During our research, we saw a variety of design tools that may be broadly categorized into five distinct groups.

A. **Payable**: Plan4Solar, PVSyst, PVComplete, PVscout 2.0 Premium, and SolarPro are among the software programs often used in the PV area. To build, analyse, and plan PV systems, these software packages are useful. Another piece of software that sees regular use in the PV sector is PV F-Chart PV. Sol Premium, Homer, PolySun, EasySolar, HELIOS 3D Solarparkplanung, and Solarmapper are software applications that are used in the area of solar energy planning and analysis.

B. **Free of charge:** Software tools like as SAM, PVLib, RETScreen, HOMER Legacy v.2.68, SKELION, and HYBRID2 are often used in the field.

C. **Online:** The following are examples of free software used in the field: SISIFO, PV-GIS, PVWATTS, PV*SOL, DIAFEM, and EASY-PV. In contrast, premium applications like SolarGis PV Planner, Helioscope, SolarDesignTool, Focus Solar, Solar Analytics, PolySun, EasySolar, and Solarmodel are also often used.

2.12. Site Assessment

The assessment of site suitability is a fundamental consideration when introducing solar PV clusters for private, commercial, or agricultural use [62]. The identification of the location and orientation of the panels is a critical stage in the design of a photovoltaic system, subsequent components will be aligned accordingly. Several key principles and guidelines should be considered while doing a site evaluation.

2.12.1. Shade Analysis

Unfortunately, solar panels have it tough when shade is present since it lowers their optimum energy production. There are other aspects that contribute to the problem at hand. The primary causes of shadow on a solar panel include: 1) shadow resulting from nearby trees and buildings, 2) Inclement weather conditions characterized by cloud cover, and 3) Shade cast by adjacent solar panels [63]. In order to get the most out of your solar PV unit, you should look at these factors thoroughly before you install it. The sun's pathfinder is a popular tool that shows the annual journey of the sun's rays as well as the quantity of sunlight that a given place might expect to get [64]. In addition to possessing this instrument, it is essential that a thorough site evaluation be conducted in order to identify the optimal location, taking into consideration all relevant factors.

2.12.2. Sun hours

The measurement of sun hours is crucial for determining the necessary level of solar irradiance needed to provide the desired wattage output. This attribute provides information on the duration of maximum sunshine received by a certain area [62]. The availability of internet data has been facilitated by technological advancements, allowing unrestricted access and use by anyone. Thorough examination of data provided from NASA and the NREL has been conducted. However, for the purpose of our study, we have decided to use the data provided by NREL. This particular dataset offers more precise information on the number of sun hours in closer proximity to East London.

2.12.3. Angle of Tilt

The optimal arrangement of solar panels to collect the most amount of radiation is called the tilt angle. The ideal tilt angle is related to the longitude of that particular area. Since the sunlight hours change throughout the year due to the sun's tilt in different directions in the winter and summer, it is best to employ moveable panel frameworks to account for these variations.

Therefore, in order to get the highest brightness throughout the year for a stationary panel, a certain tilt angle is determined for each given region. Solar panels get the lightest in the afternoon while facing southward, so there's another good reason to point them that direction. A pyranometer and an inclinometer are two common tools for measuring the brightness incident on a panel at a given tilt angle. On the panel, you can see an inclinometer that measures the angle in degrees; from there, you may calculate the latitude of the area. At the exact moment when the Sun reaches its highest point in the sky, this calculation is made when the panel is positioned tangent to the rays of the Sun. If you want to know how much sun light will reach your lens at a certain degree of tilt, you may use a pyranometer. Watts / square meter (W/m^2) is the unit of measurement for solar irradiation [62].

2.13. Key financials, energy, savings, and costs

In the context of an economic pre-viability study, the model's execution produces a number of outputs that may be used to evaluate the solutions and determine the ideal size of the solar power system. For every possible system with the input parameters (ranging from orientation to incline) and specifications (provided during the input stage), the aforementioned outputs are obtained. Important results include the following: implementation cost, a first-year money saved, net present value, internal rate of return, and NPV. Three separate sets of results are possible: energy and power, savings, income and expenditure, and critical financials. It is important to note that the outputs from one group are used as inputs for the subsequent group.

2.13.1. Energy and electricity outputs

First, the system's AC power output, including all configurations within the range, is output. Aggregating the outputs of each subsystem that defines the system yields the output. The output is created every 15 minutes, year-round. Remember that 15-minute usage and AC output measurements are in kW. Electricity output is calculated by dividing power output by four. Self-consumption and grid feed-in (surplus production) are calculated by comparing 15-minute usage to system AC output. Self-consumption equals production when consumption surpasses output, and surplus is zero. When production exceeds consumption, self-consumption equals production, and surplus equals output minus consumption. The above outputs are accessible for each 15-minute interval throughout the year. Additionally, the self-consumption rate is the ratio of annual self-consumption to annual solar production. The self-sufficiency rate is the ratio of annual self-consumption to electricity consumption. The monthly drop in peak-power consumption is calculated by aggregating the energy production (measured in kilowatt-hours) during peak hours across a month, dividing by the number of peak hours, and multiplying by the number of days. The annual reduction in Kw/day is estimated from monthly peak-power use.

2.13.2. Revenue and savings

The cost reductions resulting from the implementation of a PV system are assessed within the context of the second category. The cost savings resulting from the decision to not purchase power are calculated by multiplying the amount of self-consumed electricity (measured in kilowatt-hours) by the appropriate tariff rate for each 15-minute time period. The cost savings resulting from the decrease in peak-power use may be calculated by multiplying the monthly reduction by the set tariff for peak-power consumption. The proceeds generated from the sale of excess power to the grid are determined by multiplying the quantity of electricity (measured in kilowatt-hours) by the relevant feed-in tariff. The aforementioned results are furnished at regular intervals of 15 minutes, as well as on a yearly basis. The aggregate yearly savings are derived from the combination of these three sources of savings.

2.13.3. Costs

A photovoltaic system's overall cost comprises the original investment or installation fee, insurance premiums, periodic servicing, and a new inverter. Three solar project developers provided this study's expenditures. Installation costs include modules, inverters, system balance, construction, and authorization. System size and installation method—ground-mounted, roof-inclined, or roof-mounted—determine cost. Calculating this cost requires information from various photovoltaic project developers. Annual insurance and maintenance costs depend on system size and original investment cost. PV project developers estimate that inverters must be replaced every 10 years. Inverter replacement costs depend on system size.

2.13.4. Important finances

The best system design depends on key financial metrics and the initial investment cost. IRR, NPV, and payback length (years) are crucial financial measures. PV system economic assessments typically last 25 years, therefore the yearly cash flows depicted are for that time. Initial investment costs in year zero are included in cash flows. From year 1 to 25, profits are solar photovoltaic system savings minus servicing and insurance costs. This lets us calculate these numbers for all platforms. Both 10- and 20-year plans account inverter replacement expenses. Annually, maintenance and insurance costs are modified for Equation 2.23 adjusts annual savings for PV system depreciation and energy inflation.

$$Savings_{Year-i} = Savings_{Year-1} - (1 - Degradation)^{i} x\ (1 - inflation)^{i} \qquad \ldots\ldots\ (2.23)$$

An investment or project's Net Present Value (NPV) is a finance statistic that considers all of the Cash Flows (CF). It is calculated using Formula 2.24 and requires a discount rate to be included.

$$NPV = \sum_{t=0}^{25} \frac{CF_t}{(1+discount\ rate)^t} \qquad \ldots\ldots\ (2.24)$$

The internal rate of return (IRR) is the discounted factor at which prospective cash flows have no net present value (NPV). By solving Equation 2.25, we may get this value.

$\sum_{t=0}^{25} \frac{CF_t}{(1+IRR)^t} = 0$ …… (2.25)

The payback phase is when cumulative cash flows become positive. First, find the latest year having a negative cash flow. The fractional payback time is the entire negative cash flow from the most recent negative year divided by the predicted cash flow. Add the proportion of the repayment time frame to the most recent year with a negative compounding cash flow to determine the payback time.

2.14. System operations

2.14.1. PV array sizing

$P_{Required} = \frac{P_{Load}}{\eta}$ …… (2.26)

Where:

$P_{Required}$: Total energy needed by its operation
P_{Load} : Energy demand at the peak hour of maximum solar radiation.

η : System efficiency

In the worst situation, solar peak hours for a region last four hours. Although there is a mean of seven hours of sunshine each day, peak solar hours are just three to four hours. The quantity of solar energy a location would get if the sun shone at its brightest for a specified time is called "peak sun hours". Peak sun hours vary by region, with the worst-case scenario being the lowest average.

$N_{Panels-Required} = \frac{P_{Required}}{P_{Load}}$ …… (2.27)

Where:

$N_{Panels-Required}$: $Number\ of\ panels\ required$

$P_{Required}$: $Total\ power\ required\ by\ the\ system$
P_{Load} : $Load\ Wh/\ Worst\ ca\ se\ sun\ peak\ hours$

$N_{Parallel\ String} = \frac{V_{min}}{V_{pv}}$ …… (2.28)

Where:

$N_{Parallel\ String}$: Quantity of parallel threads

V_{min} : Minimum voltage required for an inverter.

V_{pv} : Voltage of the photovoltaic panel

The lowest possible voltage of an inverter is the lowest voltage required for it to operate. The photovoltaic system's voltage is the designated voltage of the Solar arrays, often set at 24V. The PV array will consist of two parallel strings, each containing two panels that are linked in series. When two panels are linked in series, the resulting output voltage will be 48V. Conversely, when the panels are connected in parallel, the current will be increased.

2.14.2. MPPT charge controller

$$Total\ array\ power = Power\ output\ of\ the\ photovoltaic\ system\ (W))\ *\ Quantity\ of\ solar\ cell \quad \ldots.\ (2.29)$$

$$P_{Total\ Array} = P_{pv}\ x\ N_{Panels} \quad \ldots\ldots\ (2.30)$$

$$I_{Rated} = \frac{P_{Total\ Array}}{V_{Battery}} \quad \ldots\ldots\ (2.31)$$

Where:
I_{Rated} : $Current\ Rating$
$V_{Battery}$: Nominal voltage of the battery

2.14.3. Inverters

When picking an inverter, it is crucial to consider the pertinent requirements, which include the following:

i. Input battery voltage range

The voltage level at which power is being discharged from the batteries (often 48V, 24V, or 12V).

ii. Power output maintained at 25°C

The most potential power that an inverter can safely produce at a given temperature, expressed in watts.

iii. Surge power

Certain appliances have been seen to use 2-3 times their allocated power during the first startup phase. The inverter must possess the necessary capability to effectively manage and accommodate these sudden increases in power. The majority of inverters are designed to accommodate power surges that are double the magnitude of their power output.

iv. Efficiency (η)

The importance of efficiency cannot be overstated when considering inverters, since a low-efficiency inverter results in power loss during operation. The efficiency of inverters varies between 90% and 95% depending on the manufacturer.

2.14.4. Financial evaluation

The value of an investment may be determined using a number of different economical methods. The two methodologies used in this thesis are payback time and the localized cost of energy (LCoE).

2.14.5. Payback period

"Payback time" is the period of time in which an individual may expect to get a financial profit or profit from the money they have invested. In this specific situation, payback time denotes the period, quantified in days or years, necessary for the client to recoup the original capital expenditure. The formula for determining the Payback time is as follows: [29].

$$Payback\ Time\ = \frac{Initial\ Capital\ Cost + Cost\ of\ Maintainance}{Yearly\ savings} \quad \ldots\ldots (2.32)$$

$$Yearly\ savings\ = Yearly\ energy\ production(kWh)\ x\ Average\ utility\ rate \quad \ldots\ldots (2.33)$$

The annual solar radiation has a considerable influence on the payback time of the photovoltaic installation. The correlation between the orientation of the photovoltaic panel and the placement of the system is a pivotal aspect that must be considered. Typically, areas with higher levels of sunlight tend to generate more energy and have a shorter period of time required to recoup the initial investment. One additional component that influences the duration of payback is the grid tariffs since greater prices result in a shorter payback period.

2.14.6. Localized Cost of Energy

The Localized Cost of Energy (LCoE) is a commonly used economic tool in many energy system situations. The document provides information on the cost per kWh of energy generated across the whole lifespan. The use of the PV energy system provides valuable insights for consumers to assess the comparative advantages of adopting this system over purchasing power from the grid. The calculation is performed in the following manner [6].

$$Total\ investment\ = Initial\ captal + Maitenance\ cost\ over\ the\ years \quad \ldots\ldots (2.34)$$

$$Cost\ per\ year\ = \frac{Total\ investment}{Life\ time\ of\ system\ (n)} \quad \ldots\ldots (2.35)$$

$$LCoE\ = \frac{Cost\ per\ year}{Yearly\ energy\ production\ (kWh)} \quad \ldots\ldots (2.36)$$

The LCoE may vary depending on variables such as the geographical location and the initial capital investment required for the Photovoltaic installation. Additionally, it is crucial to acknowledge that the choice of interest rate used in the calculations will have a substantial influence on the LCoE. The LCoE is a dependable measure used to evaluate the cost competitiveness of certain energy systems.

LCOE is a mathematical method utilized to assess and compare different methods for generating energy. It involves calculating the present value of yearly expenses during the lifespan of a technology and dividing it by the total power generated during that period. The aforementioned technique is widely used and facilitates the determination of a monetary value per kilowatt-hour (kWh), enabling a direct comparison with grid supply expenses. Based on what Tao and Finenko [6] have said about Payback Period , Net Present Value and Internal Rate of Return, this statement gives part of the financial feasibility examination. The SAM LCOE computation is based on the 1995 NREL publication "A manual for the economic evaluation of energy efficiency and renewable energy technologies" by Short, Packey, and Holt. The Levelized Cost of Electricity is represented by equation 2.37, according to the National Renewable Energy Laboratory (2021).

$$LCoE\ = \frac{FCR\ x\ TCC + FOC}{AEP} + VOC \quad \ldots\ldots (2.37)$$

The annual return on investment (ROI) divided by the capital cost is represented by the fixed charge rate (FCR). It is a measure of the income generated relative to the amount of investment needed to pay the cost of the investment. The total capital cost, denoted as TCC, represents the aggregate amount of capital invested or installed in a project, measured in rands. FOC, or fixed annual operating costs, refers to the expenses incurred for the ongoing operation and maintenance of the project, also measured in rands. AEP, standing for annual electricity production, quantifies the amount of electricity generated on an annual basis, expressed in kilowatt-hours (kWh), and computed with the help of SAM. Finally, the fluctuating cost of operation, or VOC, is the cost per kilowatt-hour (R/kWh) for repairs and replacements. The explanations provided by the National Renewable Energy Laboratory deserve our gratitude. Equations 2.38, 2.39, and 2.40 CFF define the Capital Recovery Factor (CRF), the Project Financing Factor (PFF), and the Construction Financing Factor (CFF), respectively, that make up the Fixed Charge Rate.

$$FCR = CRF\ x\ PFF\ x\ CFF \qquad \text{…… (2.38)}$$

$$CRF = \frac{WACC}{1 - \frac{1}{(1+WACC)^N}} \qquad \text{…… (2.39)}$$

$$PFF = \frac{1-(TAX\ x\ PVDEP)}{1-TAX} \qquad \text{…… (2.40)}$$

Capital Recovery Rate (CRF) calculations in SAM are based on the Weighted Average Cost of Capital (WACC) and other predefined inputs. Equipped with the effective tax rate (TAX) and the current value of the degradation (PVDEP), the Project Financing Factor (PFF) integrates project financing expenditures. One financial indicator developed for large-scale projects with long construction durations is the Construction Financing Factor (CFF). The projected small scale system sizes and anticipated building periods of less than three months lead to the assumption that the CFF (building Financing Factor) is equal to 1, hence nullifying the claimed impact by SAM (National Renewable Energy Laboratory, 2021).

If the cost of grid energy supply is higher than the LCOE for the proposed systems, which considers the costs of the battery system, then the project may be considered economically feasible. When doing a comparison between the LCOE for PV systems alone and PV systems combined with battery storage, it is evident that the latter option will exhibit a notable rise in prices. This is because of the increased operating and servicing costs and the increased capital expenditure needed to include batteries into such systems. Nonetheless, despite these elevated costs, the LCOE for PV plus battery systems continues to serve as a valuable metric for evaluating and comparing grid-related expenses. A solar PV system's expected lifetime is usually 25 years, which is the same as the guaranteed period given for the modules. The end of solar PV modules' operational viability has been widely recognized since a suitable replacement is anticipated to be provided by newer more effective panels.

2.15. Related studies

Numerous developing nations are now facing difficulties in meeting their electricity requirements and addressing the task of adapting their power system to better accept renewable energy production, particularly in the form of distributed generation. Hence, it is crucial for the future to construct grid infrastructure, enhance the capacity of power plants, and extend the coverage of transmission and distribution lines [65]. When incorporating new renewable energy technologies into current power systems, it is crucial to create the most efficient system and configuration. In order to optimize the advantages of multiple power generating choices for both providers and end-users, it is necessary to maintain the safety and functionality of the system's operation.

Intermittent renewable power production has distinct issues, including unconventional energy generating timing and a considerable influence on local electricity supply from utilities [66]. Multiple lobbying campaigns have been conducted to oppose the adoption of decentralized solar energy. These campaigns are based on the belief that decentralized generation is not in the best interest of utility companies. This is because decentralized generation promotes self-consumption and reduces the size of the utility's market. Additionally, policies require utilities to buy excess generation from customers at a higher price than they sell it. In the process of formulating energy laws and policies, it is crucial to assess how utilities might interpret and execute rules in order to prioritize their own interests rather than those of customers and society [67]. Alternative policies and methods are required to promote, rather than restrict, the use of renewable energy resources. Therefore, it is necessary to conduct studies like this one to provide policy makers with information regarding the technological, environmental, and economic advantages and results of integrating rooftop PV systems. This integration is expected to become more common in the future, so it is important to develop adaptable strategies that benefit both utility companies and consumers.

2.16. Summary

This chapter introduced the basic principles behind solar photovoltaic systems. This text discusses several aspects related to solar PV projects, including favourable circumstances, the components of a PV system, performance characteristics, the fundamentals of system design, and the use of simulation software in the design and assessment process. The objective of this chapter was to emphasize the fundamental components that constitute the PV system and its design process as a framework for the implementation of design optimization processes in the thesis.

3. CHAPTER 3: RESEARCH METHODOLOGY AND DESIGN

This chapter outlines a series of recommendations or techniques that have been specially designed to calculate the potentials described before. Firstly, the necessary data required to do this research is provided. Secondly, the procedure for selecting the region to be examined is outlined. The third section of this chapter provides a discussion on key considerations for the selection of software to be used in the context of modelling and simulations. The fourth and fifth parts of the chapter include a comprehensive examination of the approaches used in the modelling of rooftop PV systems and energy storage systems, respectively. The last portion of this chapter provides a full explanation of the technique used for analysing and interpreting the results.

3.1. Overview of study methods

A quantitative technique was used to investigate the research concerns, using power metering data acquired from the selected investigation site. Data has been gathered over a period of 12 months, with measurements recorded at hourly intervals. All of the individuals involved in the case studies had their usual working conditions mirrored in this dataset. The average, minimum, and the highest daily energy consumption were determined using the data collected from smart meters. By comparing the total power consumption with what was billed for the same every month, we were able to find the average daily electricity draw profile for each 60-minute period. From power providers' records, together with the relevant metering and payment details, we were able to determine each case study's off-peak hours, shoulder area, and peaking use times.

After that, using the initial estimating method as a guide, we ran the numbers to see what the ideal location was for renewable energy system sizes. We found a weather facility that was geographically closest to the case study site, collected meteorological data, and converted it so that it could be used with the SAM. Afterwards, the data was processed to detect and fix any cases of corrupt or missing data. When new data was needed, appropriate sources were consulted. The processed data was then imported into the SAM.

3.2. Choosing the study area

When using this guideline, it is important to consider certain factors when determining the field of study. One primary consideration is the accessibility of the necessary data in the appropriate format. In the event that the data pertaining to the designated region is inaccessible owing to insufficient measurement and generation of the necessary data, other areas should be considered. Ensuring the suitability of the study area for rooftop PV applications is of paramount significance. Figure 3.1 displays the long-term daily and annual total averages of worldwide horizontal irradiation as provided by the worldwide Solar Atlas [68]. This map is a valuable resource for obtaining a broad understanding of the aggregate global horizontal irradiation that is received by a certain geographical region. If the location under consideration exhibits low levels of irradiance in relation to the anticipated energy use, it is advisable to explore other areas.

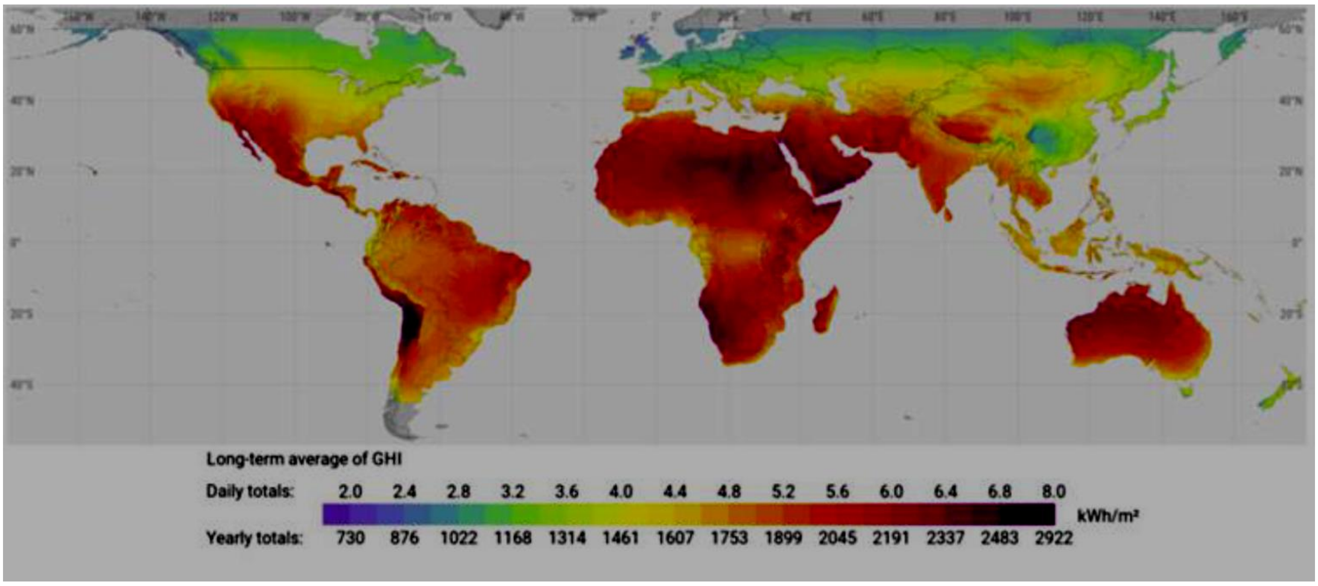


Figure 3.1 : Daily and annual total averages of worldwide horizontal irradiation [68].

Another aspect that warrants notice is the classification of rooftops in the region. The determination of permissible pitch angles for roofs by governmental organizations and institutions within the specified region, as well as the corresponding legislations, has significant importance. Moreover, in instances when the configurations of building roof designs are intricate, such as those with sides with varying pitch angles or the inclusion of dormers.

3.3. Necessary data

The primary data required for implementing the modelling and simulation techniques outlined in this research include meteorological data, power consumption statistics for the specific region, and information on the accessible rooftop space. Given that all simulations are performed at one-hour intervals over the course of a year, it is necessary to collect all time-dependent data at intervals of one hour or less, such as 15-minute intervals. In order to calculate avoided CO_2 emissions once results are acquired, it is also important to collect information regarding the energy mixture and greenhouse gases emissions as a percentage of principal energy supply in the chosen area.

3.3.1.Meteorological Data

The use of meteorological data is crucial in determining the potential energy generation of PV panels. Sunlight radiation, air temperature, speed of the wind, humidity percentage, dry bulb temperature, dew point temperature, and purity index are only a few of the important variables that affect the outcomes of simulations. The data on solar irradiance includes a number of measures, such as normal beam irradiance, uniform horizontal irradiation, diffuse horizontal irradiation, and global horizontal irradiation. The irradiance data has paramount significance in solar PV simulations, since it serves as the foundational input for all models, in conjunction with the clearness index. The efficiency of the system's components, including PV panels, is affected by the surrounding temperature. Wind speed, humidity percentage, dry bulb temperatures, and the temperature of the dew point are some of the variables that impact the outcomes of the simulation. The effect of these parameters on the results of the simulations has been the subject of much experimental study. Furthermore, studies have been carried out to create models that faithfully represent the effects of these components under different weather scenarios [35-39].

The selection of meteorological data for computations is contingent upon the chosen theoretical model and associated assumptions used in the simulations. Nevertheless, the primary variables remain unchanged, namely irradiance and ambient temperature. Academic literature and non-academic field activities often use various weather data formats and databases. Solar irradiation data from the TMY2 and TMY3 datasets is widely used for building models in both academic and professional settings. Software for solar photovoltaic design and simulation, including PVsyst and Helioscope, heavily relies on weather information from the Meteonorm program. Solargis data is available in time series or TMY forms, and PVGIS meteorological information is used in PVGIS software for simulations. Other prominent sources include NASA-SSE, NREL’s National Solar Radiation Database (NSRD), many more. Wind plans are a valuable resource for obtaining wind velocity data in cases when such information is not readily accessible in datasets that primarily focus on solar irradiation data. Certain datasets in this collection possess a geographical orientation, namely pertaining to locations such as the United States of America or Europe. Hence, it is essential to verify the availability of data pertaining to the designated time frame, namely on an hourly basis, for the region under investigation. In addition, the generation of synthetic data may be used in cases when the availability of hourly meteorological data for certain places is limited. An example of this is the use of Helioscope software, which employs Meteonorm software to stochastically create hourly values based on monthly irradiance measurements [69]. Hence, it is imperative to consider several factors when selecting a database or data format for implementing this guideline. These factors include the geographical location of the area where the guideline will be applied, the availability of relevant data in proximity to the intended simulation site, the choice of design and simulation software, and the compatibility of the software with the chosen database or data format. Furthermore, not all weather-related information formats contain all weather information, and not all software programs utilize all weather data. For example, PVsyst software does not benefit from Aerosol Optical Depth or Precipitable water data, which Solargis may never offer[69].

3.3.2.Energy consumption data

In order to ascertain what proportion might be met by the proposed system, data on the area's power usage is necessary. Researching and analysing regional usage patterns is also critical for building the best battery storage solution. There is a chance that the electricity output from rooftop PV systems will exceed the amount of demand. Consequently, gathering this information is crucial for informing the different stages of the design process and for getting the outcomes. Keep the data in the same format as the outcomes of simulations and document it at least once per hour. If the data is not already in the necessary unit, it should be converted accordingly. The evaluation of consumption data should include an analysis of monthly total consumption to assess the presence of seasonal patterns in consumption, as well as hourly averages to examine variations in consumption between day and night. Additional examination may be undertaken on consumption data in accordance with possible system requirements. The evaluation of consumption data should include an analysis of monthly total consumption to assess the presence of seasonal variations in consumption patterns, as well as hourly averages to examine the diurnal fluctuations in consumption levels. Additional examination may be undertaken on consumption data in accordance with possible system requirements.

The inclusion of individual building consumption data would enhance the richness of the simulations. In the event of unavailability, the construction of the region's building will be regarded as a single entity, whilst the rooftop PV systems will be simulated as decentralized generating units. In the event that specific data is accessible, such as user behaviour information (e.g., residential or commercial electricity user) or details about the equipment inside a building, there exist methods that may be used to simulate the particular utilization patterns of each structure.

3.3.3.Accessible Rooftop Space

For some places, building blueprints may provide information about rooftop space. The data on rooftop areas is gathered and stored by several statistics organizations, either public or private. After obtaining the data, there are few different ways to calculate the usable rooftop space if this information is accessible. Data about available rooftop area may not be readily available, however satellites imaging applications or websites like as Google Earth, Google Maps, Bing Maps, etc., may include a location or distance option that might be used. In this regard, the quality of the satellite images is crucial. Nonetheless, high-resolution photos, particularly those of cities, are often accessible for free on the internet.

Certain solar simulation programs use integrated tools to determine the amount of accessible rooftop space. These programs consider and compute the available area without accounting for shadowing factors, which might result in PV application being impractical or inefficient. Nearby buildings or trees cast shadows on the rooftop under investigation, as can air conditioning units and chimneys; these elements might be far away, like mountains or hills, or close by, like nearby buildings or trees. For instance, Helioscope has a built-in application that simulates the shadow area that a near-shading equipment mounted on the roof would create. It then computes the rooftop's shadow-free area, or the amount of accessible rooftop area. Using 3D scenario building programs, you may shape the rooftop and adjacent shadowing characteristics around other shading aspects. One way to find out how much rooftop space is available is to utilize this tool, which measures the amount of area lost to shadows and replicates the shadows produced by other items on the rooftop. The software provides complicated calculations for distant shadings along the horizon line.

One may use one or more of these techniques to determine the available rooftop space, comparing the results to get the most practical answer.

3.4. Selection of software

There exists a wide array of software tools that cater to both commercial and academic domains, specifically tailored for the purpose of modelling and simulating renewable energy systems. Several software programs are available that specifically target PV systems, including PVsyst, PVSOL, PVGIS, SAM, and Helioscope. Additionally, there are software tools that cater to the design of integrated systems, which include distributed production from numerous renewable energy sources. One such software is HOMER Grid [42-44]. Additionally, mathematical modelling tools like as MATLAB Simulink may be used.

In their 2022 study, Milosavljević et al. compared several programs and simulations that frequently get utilized for solar energy system design and modelling. The findings indicate that PVsyst demonstrates high efficiency as a software tool, offering various system component configurations and the capability to do repeated assessments and comparisons [70]. According to the research done by Kumar [69] , the comparative analysis of various software demonstrated satisfactory performance. Notably, Helioscope and PVsyst emerged as the top-performing software, followed closely by SAM [71].

3.4.1.Software used for simulation.

An all-inclusive tool, SAM was created by the NREL as part of the United States Department of Energy. This model is created with the express purpose of assisting decision-makers in the renewable energy sector with efficiency and financial assessment. Project designers, technology developers, researchers, and policy specialists are just a few of the many professions that SAM serves [72]. It has been continuously improved since 2009 and has gained widespread recognition, being utilized in numerous publications and validation studies, thus establishing its reliability. The 2021 software version of SAM offers a range of capabilities, as outlined in Table 3.1 [72]. It is important to note that SAM is freely accessible for personal, commercial, and academic purposes.

Table 3.1: Performance and financial based models of SAM

Performance-based Models	**Financial based Model**
Panels for photovoltaic (flat-plate and concentrated)	Home (power tariffs for retail use)
Energy storage in batteries	Commercial (retail rates)
Concentrating solar electricity using parabolic trough technology	Third party ownership from host or developer perspective
Power tower concentrating solar power (molten salt)	Community solar Power purchase agreement, PPA (utility-scale or power generation project)

Linear Fresnel concentrating solar power (heat transfer fluid and direct steam)	
Industrial process heat models for parabolic troughs and linear collectors	Only proprietor
Conventional fossil-fuel thermal	Effectual completion of leveraged collaborations
Commercial and household solar water heating systems	Partnership undergoes radical transformation
Wind power (large and small)	Repurchase sale
Wind, wave, and tidal energy converters for the ocean	Industrial plant for merchants
Electricity generated from geothermal sources	The fixed charge rate technique is used by a simple LCOE calculator.

The aforementioned features provide the necessary adaptability for this study, whereby inputs were modified to accurately replicate financial models specific to South Africa. Because of its versatility and capacity to serve both small and big energy users, SAM was determined to be the best software for this task by the study team. SAM's flexibility and ability to give detailed data were key factors in its suitability for this study. SAM encompasses several inputs and variables, with particular emphasis on those of utmost significance. This section will discuss these key inputs and variables, using a consistent methodology and settings throughout all case studies offered in this thesis, unless explicitly stated differently.

3.4.2. System components selection

Careful consideration of the system's requirements should go into selecting every element before moving on to the modelling and simulation phases. The policy structure and legal framework of the selected geographical area may restrict the variety of studable choices. For example, in several nations, there are incentives in place that promote the practice of procuring components for PV systems from local sources, or in other cases, it is mandated [73], [74]. The process of selecting system components involves first choosing the PV panel, followed by the selection of optimizers and inverters.

3.4.3. Optimization of panel orientations

Typically, it is recommended to multiply the latitude angle by 0.87 and then add 3.1 degrees to get the best tilt position for PV panels when the latitude angle of the deployment site is between 25° and 50°. An additional guideline posits that the optimal inclination angle may be determined by augmenting the latitude of the investigated region by 15 degrees during the winter season, and conversely, by deducting 15 degrees from the latitude in the summertime. In addition, most solar photovoltaic models software includes optimizers for tilt and azimuth angles, also known as panel orientation, which provide the ideal panel orientation to achieve the desired optimization objective. The objective may include attaining the maximum energy yield throughout the summer, winter, or over the course all during the year.

Every building that is part of the modelling and simulation has to have its azimuth and tilt angles optimized according to the optimization goal that was stated. The potential location of PV panels and the resulting maximum energy production are influenced by factors such as the direction, size, and form of the structure.

3.5. Rooftop PV systems design

It is important to consider the unique power needs of the region being studied when designing rooftop solar energy systems. The systems must be designed to optimize self-consumption if the purpose is to attain a high degree of self-reliance in the area. In addition to self-consumption, system objectives may include peak shaving, total or partial islanding, and other related goals. Hence, it is imperative to comprehend the requirements of the consumers, specifically the utilization patterns of the structures. In order to establish a self-sustaining system, it is essential to design rooftop PV systems in a manner that allows for surplus power generation, which may be stored and then supplied to buildings during periods when demand exceeds the PV system's production capacity.

When evaluating systems, it is important to examine the policies and economic limitations of a country. Nevertheless, it is important to note that these elements are not considered in the initial design phases of this research, since it primarily focuses on assessing practicality of the task. When planning the system, it is important to think about potential losses such as incidence losses, losses due to near-shading, losses due to PV in relation to temperature and irradiance, losses due to array mismatch, losses due to light-induced deterioration, losses due to wires, losses due to soiling, losses due to system unavailability, and losses due to inverters. Optimisers are standard in solar power plants simulators; they find the best way to place panels inside a given area, taking the space's dimensions and shape into account, in order to maximize electricity output. The use of these optimizers in conjunction with panel orientation optimizers represents a straightforward and efficient approach for ascertaining the attributes of the ultimate rooftop photovoltaic system configuration.

3.6. Analysis and Explanation of the Findings

The following are some suggested results that should be evaluated and interpreted once the simulations have run:

i. The electricity outputs of rooftop solar energy systems are evaluated at many time intervals, including hourly, daily, monthly, and yearly intervals, both collectively and for each individual system. Furthermore, if deemed suitable, seasonal assessments may be carried out.

ii. The aim of this research seeks to evaluate the relationship between the results of rooftop photovoltaic systems and energy consumption data over various time periods, namely on an hourly, daily, monthly, and yearly basis. The objective of this study is to assess the need of including energy storage devices and to measure the degree to which the PV system outputs can meet the hourly demand or total consumption.

iii. The effectiveness of a photovoltaic system is often described as the proportion of the power it generates compared to the total amount of solar energy that is accessible.

iv. The performance ratio refers to the ratio between the output achieved by a system and the maximum output that might potentially be obtained.

v. The percentage of daily consumption that is fulfilled during sunlit hours, when solar PV generation is feasible, serves as a metric for assessing the extent to which rooftop PV systems meet the user's energy requirements.

vi. The sum of energy lost each hour, day, month, and year.

vii. The aggregate and individual cumulative outputs of the system, including hourly, daily, monthly, and annual intervals.

viii. Overall system effectiveness and efficiency.

3.7. Summary

The technique described in this chapter was developed to consider the key elements and indicators that impact the financial viability of a renewable energy system. The methodology first used a broad approach and then refined it by using increasingly intricate and comprehensive modelling techniques, ultimately arriving at the optimal system size. The process of modelling culminates in the development of manually created systems, which are then subjected to critical analysis using important metrics in order to select the most optimum system. The case study results provide a thorough examination of these systems, along with conclusive suggestions given at the end of the case study. The aforementioned methodology was used in subsequent chapters to ascertain the suitable dimensions of solar PV and systems for industrial buildings.

4. CHAPTER 4: THE STRUCTURE OF THE MODEL

This chapter presents the modelling and simulations done in accordance with the technique outlined in Chapter Three.

4.1. Studied Area: East London railway station.

The main railway station in the East London city, which is located in the Eastern Cape region of South Africa. There is a Metrorail commuter service that goes to Mdantsane and Berlin, and the Shosholoza Meyl intercity trains that go to Johannesburg and Cape Town also terminate here. You can find the East London railway on Station Road, just adjacent to the edge of the city's main business district. The layout of the station is designed as a terminal, including a configuration that includes five tracks specifically designated for passenger trains.

4.2. Acquisition of data

4.2.1. Meteorological data for East London railway station

In this research, the National Solar Radiation the field of databases was utilized for the meteorological data. The data acquired from the database was juxtaposed with the data collected from the Meteonorm 8.0 database. The results of the comparison reveal that there is a 90% match between the dataset of the NSRDB and the data acquired from Meteonorm 8.0. The gathered meteorological data includes a number of hourly parameters, such as cleanliness measure, temperature in the air, wind speed and direction, humidity level, horizontally beams radiation, normal beam radiation, horizontally diffused irradiation, and global horizontal irradiated.

The NSRDB, which stands for National Solar Radiation Database, is a comprehensive and advanced compilation of meteorological data that has been meticulously created by the NREL. Based on physical principles, the current research's solar model calculates meteorological variables using data retrieved from satellites. The model has a comprehensive geographical scope, including the whole of the United States as well as many overseas sites. Covering the years 1998–2022, the NSRDB provides time series data with a geographical resolution of 4 km and a time frame of sixty minutes. The dataset comprises measurements of solar radiation, specifically GHI, DNI, and DHI, along with various weather variables including atmospheric pressure, ground-level temperature, wind speeds, and cloud coverage [75].

4.2.2.Electricity consumption data of East London railway station

The data on power use at the train station for the year 2022 was obtained from the electrical provider, Buffalo City Metropolitan Municipality (BCMM), at intervals of sixty minutes. Figure 4.1 displays the graphical representation of the monthly power usage observed at the station. The yearly energy usage of the railway station amounts to 44043 kWh for years 2022. The given data pertains to the year 2022 and provides information on the average active power usage for each hour during the year. The graphical representation in Figure 4.1 depicts the monthly consumption for these years. It reveals that there is an elevated power consumption throughout the period from May to July, which corresponds to the winter season in South Africa. This increase in consumption may be attributed to the increased heating load experienced by the building during this time.

Figure 4.2 displays the graph illustrating the hourly averages of power consumption for the station which indicate the high consumption during winter season as per the statement mentioned above and slight decrease during December as most of the division at PRASA are on holidays however the operations and maintenance department are currently working, and consumption further pick up in January as all department are full swings, and everyone is back from holidays.

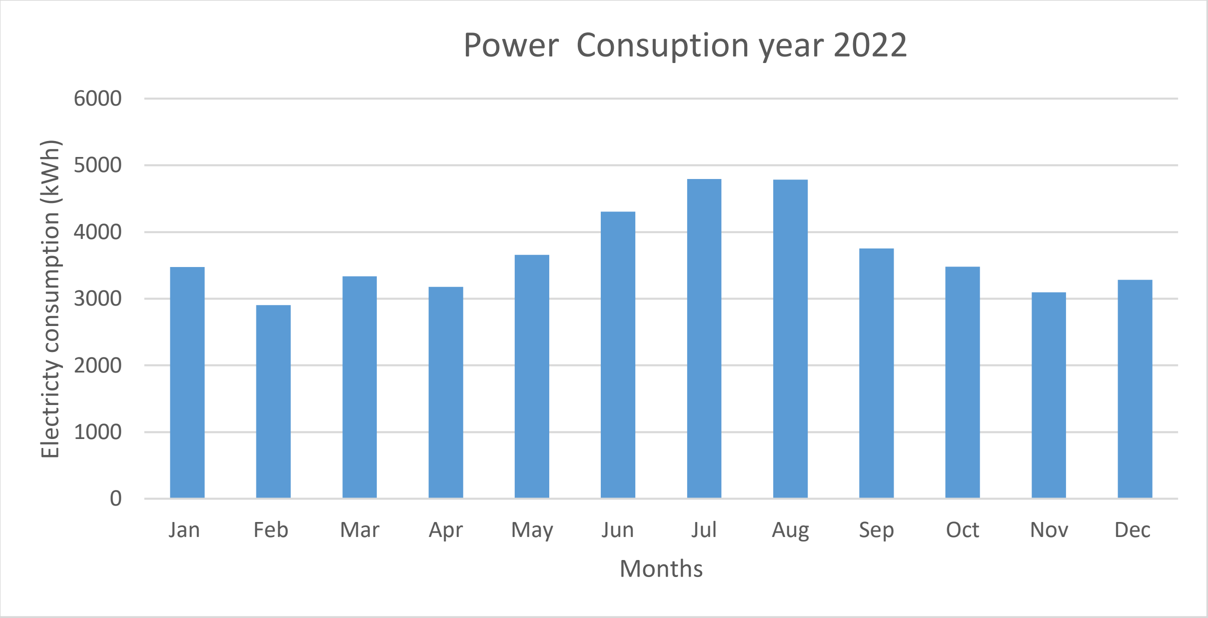


Figure 4.1: Power use per month in 2022

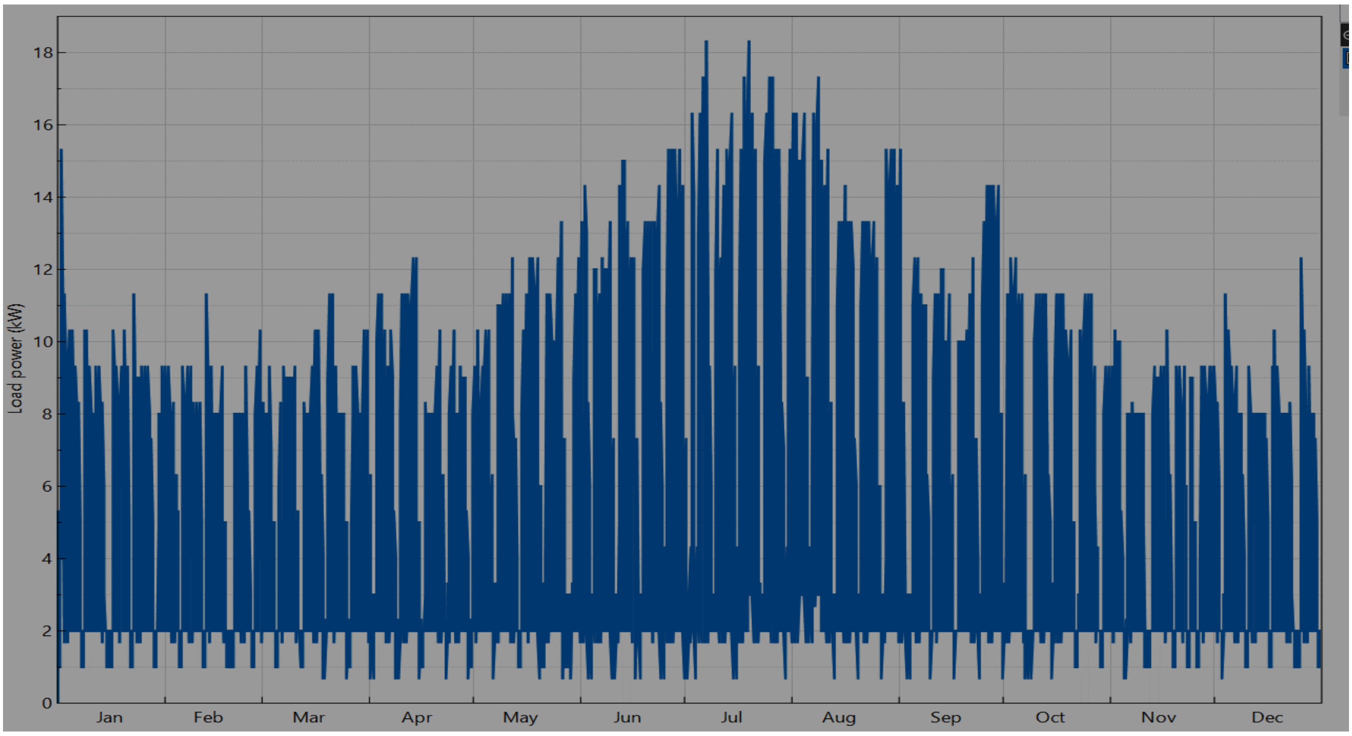


Figure 4.2: Hourly load for the year 2022

4.2.3.Available rooftop Area

The availability of data pertaining to rooftop space in some East London railway station may be easily accessed via construction plans obtainable at geo-spatial offices. Various statistics entities, whether governmental or commercial, are responsible for the collection and maintenance of data pertaining to rooftop areas. Upon obtaining the necessary data, it is feasible to use several methodologies to deduce the extent of rooftop space based on the gathered information. Using telescopic projection websites or software programs like Google Earth, Maps by Google, Bing Maps, and other comparable platforms that provide integrated length or size measuring capabilities might be useful if freely accessible data on the available rooftop space is not available. The quality of the image from the satellite inside this specific setting is what makes it significant. Nevertheless, it is common for high-resolution photos, particularly those depicting metropolitan areas, to be readily accessible at no cost on the internet.

4.2.4.Physical layout

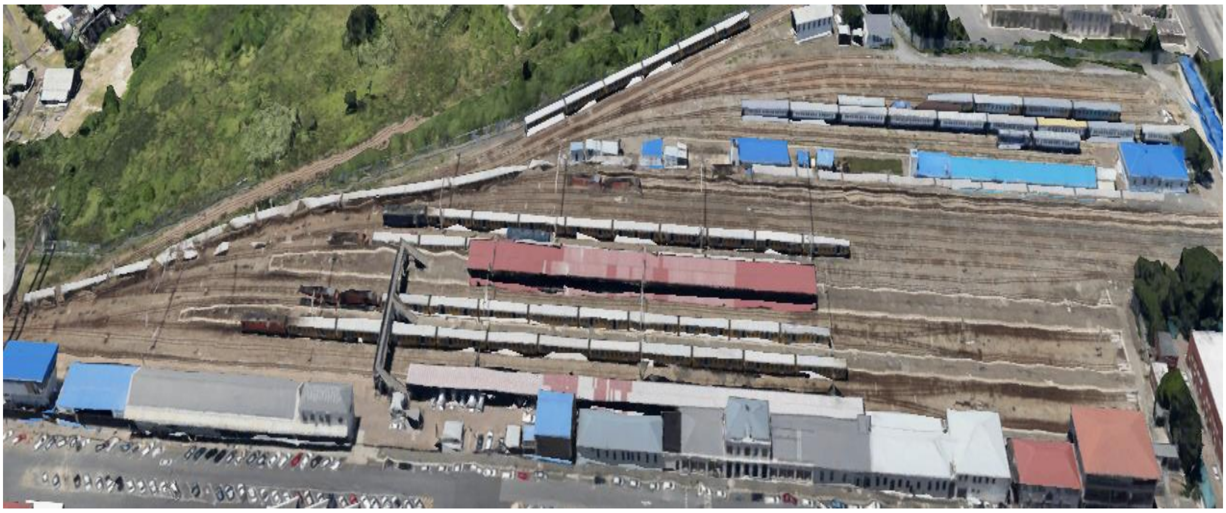


Figure 4.3: East London railway station [75].

4.3. Choosing the parts of the system

4.3.1.Choice of Photovoltaic Panels

The careful selection of PV modules is a critical aspect of the design process, since it directly impacts the project's overall cost, string size, and energy output. The selected module for this project is the Centrosolar America CP72 300SW Module, which exhibits the following attributes:

Table 4.1: The Electrical Properties of PV Modules

Electrical Data	
Peak rated power (V)	300 Watts
Highest Possible Voltage	37 Volts
Highest Amperage (A)	8.1 Amperes
Voltage across an open connection (V)	46.5 Volts
The current of short circuit (A)	8.5 Amperes
Efficiency of the module (%)	15.47%

Table 4.2: Thermal Ratings for PV Models

Temperature information	
Maximum allowable temp for a cell	44 degrees Celsius
Coordinate of Temperature _Pmax	- 0.470 %/° Celsius
Coordinate of Temperature _ Voc	- 0.350 %/° Celsius
Coordinate of Temperature _ Isc	0.008 %/° Celsius

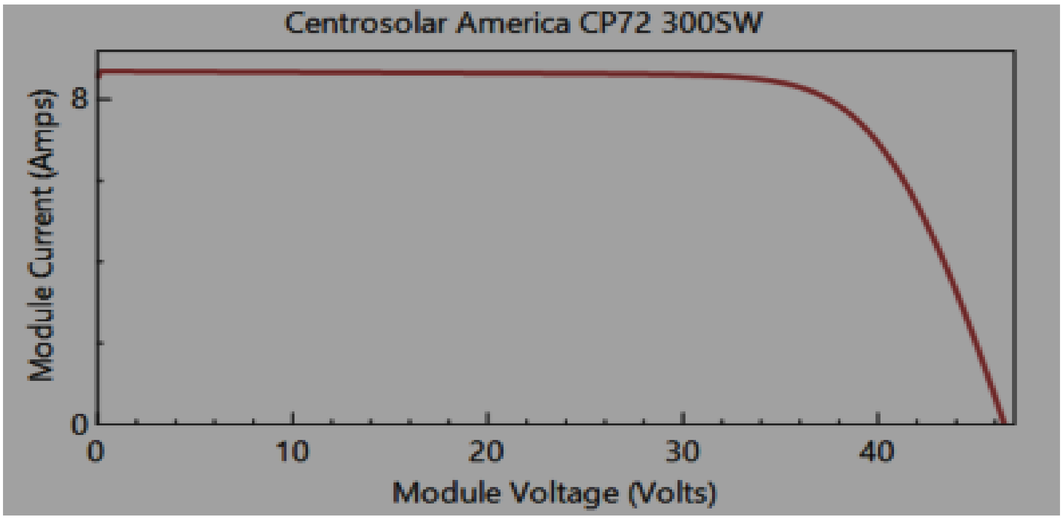


Figure 4.4: Properties of the module's current and voltage

4.3.2. Selection of the Inverter

The chosen PV project, with a capacity of 30kW, is considered to be rather modest in scale. To mitigate losses, the Altenergy Power System Inc DS3 string inverter has been selected. Table seven shows the characteristics of the selected string inverter:

Table 4.3: Inverter data

Direct current production	
Maximum PV Power	896kW
Maximum DC input Voltage	923 V
MPPT Voltage ranges	36 V- 43 V
No. of MPPTs	1
Alternating current production	
AC Energy Output Rating	2500 kilowatts
Energy Production at Highest Surge	2500 kilowatts
Maximum Voltage Discharge	240 V
Maximum AC Output Current	23.6081 A
Power Factor	0.96

Figure 4.5 shows that under the present schedule, MPPT-low is responsible for 96.845% of the modules production. In addition, the present strategy assigns 96.313% of the modules efficiency to Vdco and 96.489% of the modules usefulness to MPPT-hi.

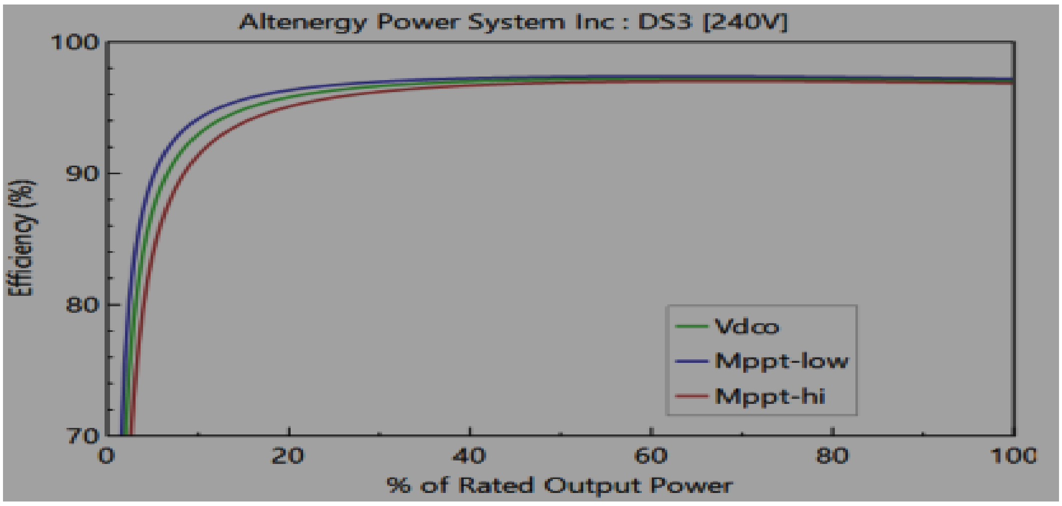


Figure 4.5: Efficiency curve of the Module

4.3.3.System Design

Once the photovoltaic panel, inverter, and length of the string have been decided, the development of the photovoltaic power station could start. You may find a brief overview of the suggested system in table 4.4. The authors were able to choose the appropriate location, determine the amount of modules per string, and the total amount of strings connected simultaneously with the aid of SAM software. About 30 kW of DC electricity is produced by this system.

Table 4.4: System configuration of power plant

System Data	
AC Power	25.088kW
DC Power	30.020 kW
DC/Ratio	1.2
Number of Strings	100
String Power	25.088kW
Tilt angle	20 degrees
Description of Equipment	
Power of Inverter	25.858kW
Power of Module	100.50 W
Type of PV modules	
Equipment Description	
Number of Inverters	28
Number of Modules	100

Each kind of module has its own unique requirements, including the maximum and minimum Voc values. In order to choose the most suitable module category, it is important to determine the highest and lowest temperatures in the region. When considering the optimal inverter capacity and how to control the panels' output voltage in relation to the highest and lowest number of panels connected in series, these criteria are helpful. Since the SAM software is only compatible with one kind of inverter, it cannot fully replicate a PV system. However, on the array's configuration the site, you may specify how many inverters are integrated into the system [76]. The measurements of the system and the quantity of modules involved determine the amount of inverters, which designers may choose. This arrangement allows for the use of either one or two inverters, while accommodating a total of about 1488 modules.

4.3.4. SAM software simulation

Implementing the SAM into engineering course requirements is the primary goal of this development. The NREL has created SAM, an open-source techno-economic software model that has significant value. It is extensively used by professionals in the renewable energy sector to facilitate well-informed decision-making processes [61]. By incorporating the SAM into the curriculum, students will acquire practical skills in using this software, enabling them to get industry-level expertise. This experience will enhance their readiness for prospective career prospects within the renewable energy sector. This program will provide individuals with valuable practical skills and expertise that are highly sought after by businesses within the sector.

The last phase in the procedure involves using suitable software to simulate the system and ascertain the energy output. The comprehensive PV option of the model has seven tabs that serve the purpose of system definition. The key components of a solar PV system may be categorized into the following academic terms: a) Geographical Placement and Available Resources, b) Photovoltaic Module, c) Power Inverter, d) System Configuration, e) Shading Analysis and Array Layout, f) Energy Losses, and g) Grid Connection Constraints.

The meteorological data for a standard year, known as the Typical Meteorological Year (TMY), has been obtained for the specified geographical coordinates (33°01'02"S 27°54'30"E) under the Location and Resource section of the project. The Perez model was used to transform the DNI and DHI into front and rear POA radiation. A bifacial modular has been selected, enabling it to receive irradiance from both the front and back sides. Hence, the determination of the albedo value of the site location plays a critical role in reflecting the irradiance received from the ground on the rear side. For the simulation to run, the application will utilize the climate file's albedo parameter.

4.4. Orientation of PV panel

The placement and angle of solar PV modules are designed to minimize the effect of the sun's motion on the amount of usable energy produced by the sun. Solar photovoltaic panels can only produce as much electricity as the quantity of sunlight reaching them in their immediate vicinity. According to Ebhota and Tabakov [77], optimizing the inclination and orientation of a photovoltaic panel during installation is crucial for maximizing the absorption of solar radiation on a daily basis. According to the available data, solar PV panels work best when the angle that defines their collecting surface lies directly opposite the direction of the sun's rays [78] [79]. The locations of two angles, azimuth, and tilt are parameterized and often used in photovoltaic submissions [80]. The horizontal coordinate system is the preferred choice for this purpose. The main reference plane in this case is the observer's horizon. In order to maximize the on a daily basis renewable power intake of PV panels, tracking systems are used in some photovoltaic installations. These systems precisely monitor the sun's movement. Nevertheless, the use of these devices is limited due to their exorbitant costs and the substantial energy consumption necessary for their functioning. Consequently, certain tilt and azimuth angles are employed [81].

Optimal tilt and azimuth angles, which are the angles of implementation, are initially evaluated when building a permanent solar system. The optimal yearly photovoltaic power output would be maximized by selecting the appropriate angles. In this regard, it is standard practice among specialists to tilt PV module surfaces in a way that corresponds to the site's latitude and then align them with the equator. Report by Chen et al., 2018 [80]. Prior to installation, it is essential to consider the direction, orientation of the roof, and degree of slope.

4.4.1.Azimuth angle

The optimal alignment of solar panels is crucial for achieving maximal performance A large body of research indicates that whereas the southerly hemisphere's best panel orientation is northward, the northerly cerebral hemisphere ideal panel orientation is southerly. From what we can see, countries like India, China, Canada, and Europe benefit greatly from having their solar panels oriented southward. Countries in the southern hemisphere, including South Africa, New Zealand, Brazil, and Indonesia, would get the most out of their photovoltaic panels if they were pointed north.

4.4.2.Angle of tilt

In most cases, the geographic region of the Earth determines the optimal tilt and azimuth angles. An ideal southerly direction is favoured in the North Hemisphere, whereas a northward inclination is preferable in the Southerly Hemisphere [82]. Typically, emphasis is placed on the spatial arrangement of PV modules with the objective of optimizing their energy performance on a daily, monthly, and yearly basis. Numerous research has shown that the inclination of solar modules is contingent upon factors like as geographical location, time period, and length. To determine how tilt angle affects solar energy collection, several theoretical and practical efforts were made. The rationale behind the optimal tilt angle is that sunlight is most efficiently collected when it strikes an Earth's surface at an inclined point of impact. The ideal tilt angle for sunlight collector has been the subject of many suggested methods. One method for estimating the best tilt angle is to use a model of radiation from the sun on clear days. Finding the ideal tilt angle over the course of six months by averaging the summer and winter months is one method. You may also average the tilt angle over the course of a year by adding up all the months. Every day, every month, and yearly solar energy collection, as well as the best tilt angles for the months of spring and autumn, and the wintertime, were all studied by Bakirci [81].

It is necessary to determine the optimal azimuth, a fixed latitude of 20° was selected, accompanied by a series of angles spanning from -100° to 100°, with increments of 10°, to represent the range of longitudes. This suggests that a consistent tilt angle of 30° was used while the Azimuth angles were changed. A tilt angle of 30° was selected based on recommendations from prior research conducted by La Rous [82].

4.5. Detailed summary of the simulation

To evaluate the physical and economic performance of the whole PV system, including every electrical system component, an open-source application called the SAM was used to conduct an hourly model. Together with Sandia National Laboratories and the Solar Energy Technologies Program of the United States Department of Energy (DOE), the NREL created SAM. Included in SAM are information about the endeavour's costs and economic assumptions, regional meteorological data, and parameters describing its efficiency features.

Climate information: In order to mimic a given location's solar resource, the SAM modelling engine makes use of per hour meteorological reports. For energy computations, the climate file includes radiation information wind speed and direction, temperature, snow cover, and other variables to mimic the effect of surface reflectivity and the ambient temperature on the efficiency of the system.

Economic development and cash resources: A lot of things pertaining to the project's budget decide the monetary and budgetary parameters to the SAM model. The examination time frame, which stands for the lifetime of the entire system, is one of these factors. Others include the rate of discount, costs of living, lending amount, and lending rate. The anticipated cost of the PV array is R 32.19 per watt, but the railway station's power tariffs are R1.20 per kWh. That brings the total annual power cost for the train station to R 2.42 million.

Efficiency of the system: In order to convert hourly weather data into accurate predictions of hourly AC electrical generation, SAM employs complex computational methods created by the NREL, SNL, and the School of Engineering of Wisconsin. In order to calculate the system's total annual output, SAM adds together all 8,760 hourly observations.

Money Outlays: SAM uses two separate types of costs to calculate economic metrics and cash flow projections. Expenses related to installing modules, inverter systems, and balance-of-system elements are included in capital spending. The continual outlays for servicing, repairing, and replacing machinery are known as "operation and maintenance costs."

Information on output: The Levelized energy costs, return rate, payback period, and net present value are some of the result metrics provided by the SAM approach. Hourly, monthly, and year forecasts of the system's performance are provided. As part of this process, we must ascertain the average net electric generation as well as the component efficiency.

5. CHAPTER 5: SYSTEM ADVISOR MODEL

5.1. Outline

The US Ministry of Energy provides funding for SAM, an application for modelling established by NREL [50]. Solar, wind, and geo-thermal technologies may be technically and economically analysed with the help of SAM, a free application. SAM is a very intuitive program specifically developed for students, academics, and professionals. SAM is applicable for doing a feasibility study. By utilizing an extensive database of PV system components, including detailed pricing and datasheets from manufacturers, we are able to construct a realistic model of a solar power system. A comprehensive evaluation of the project's technical and financial viability may be carried out using this model via simulations. Prior to commencing any installation work, we can input location-specific weather data and utility electricity rates to ensure accurate results. The software has an extensive assistance module that offers a wide range of resources to cater to users of all types. The study and development of a solar power system is the main emphasis of this project. This chapter will provide a systematic guide on how to construct PV systems using SAM, following a sequential process. We carefully analyse all the many aspects and limitations that are necessary for an effective design.

5.2. Determine the system's size

It is crucial to accurately measure a solar energy system. Each element of the system must be appropriately dimensioned to guarantee optimal efficiency. The optimal size of a photovoltaic system is contingent upon the following factors:

i. Needs for loading
ii. Limited space
iii. Limited financial resources
iv. Needs for utility connections
v. Power tariffs for utility companies
vi. Factors related to geography and climate

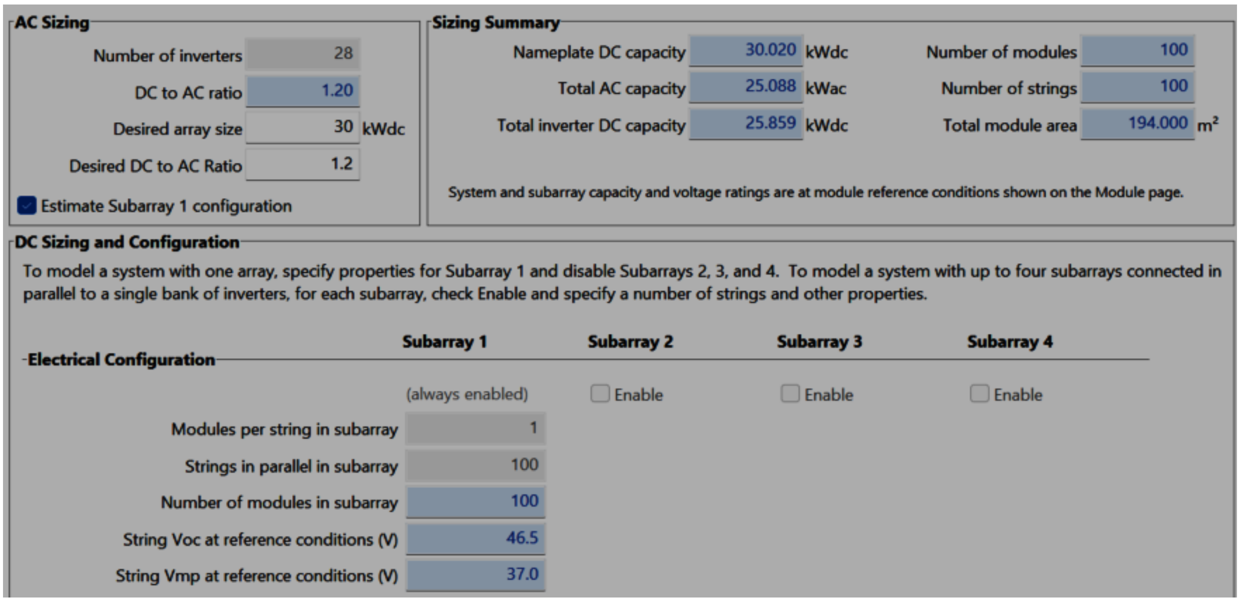
Both the PV modules and the inverter have a significant role in determining the system size; the former is size-dependent while the latter is size-dependent.

5.2.1.Installed size

In photovoltaic systems, the "nameplate size" could be either the direct current capability of a solar panel in kilowatts or the alternating current capability of the entire system, which is basically the inverter's performance. Though it is not frequently this way, the DC and AC capacities should be equal. An example that demonstrates this is as follows: imagine you want to create an 10kW photovoltaic system utilizing 15 PV modules, each with a power rating of 450W. Ideally, we need an 10kW inverter. However, if we happen to find a more favourable offer for a 11kW or 8kW inverter, we may go with that arrangement as well. This matter gives birth to a concept known as the DC to AC ratio.

$$DC - AC\ Ratio\ = \frac{DC\ capacity\ of\ PV\ modules}{AC\ capacity\ of\ inveter} \qquad \ldots\ldots (5.1)$$

The optimal DC-AC ratio is around one or slightly more than one, considering the gradual decline in performance of PV modules during their lifespan.



AC Sizing

Number of inverters: 28
DC to AC ratio: 1.20
Desired array size: 30 kWdc
Desired DC to AC Ratio: 1.2
☑ Estimate Subarray 1 configuration

Sizing Summary

Nameplate DC capacity: 30.020 kWdc
Total AC capacity: 25.088 kWac
Total inverter DC capacity: 25.859 kWdc
Number of modules: 100
Number of strings: 100
Total module area: 194.000 m²

System and subarray capacity and voltage ratings are at module reference conditions shown on the Module page.

DC Sizing and Configuration

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a system with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

Electrical Configuration	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Modules per string in subarray	1			
Strings in parallel in subarray	100			
Number of modules in subarray	100			
String Voc at reference conditions (V)	46.5			
String Vmp at reference conditions (V)	37.0			

Figure 5.1: Scaling System in System Advisor Model

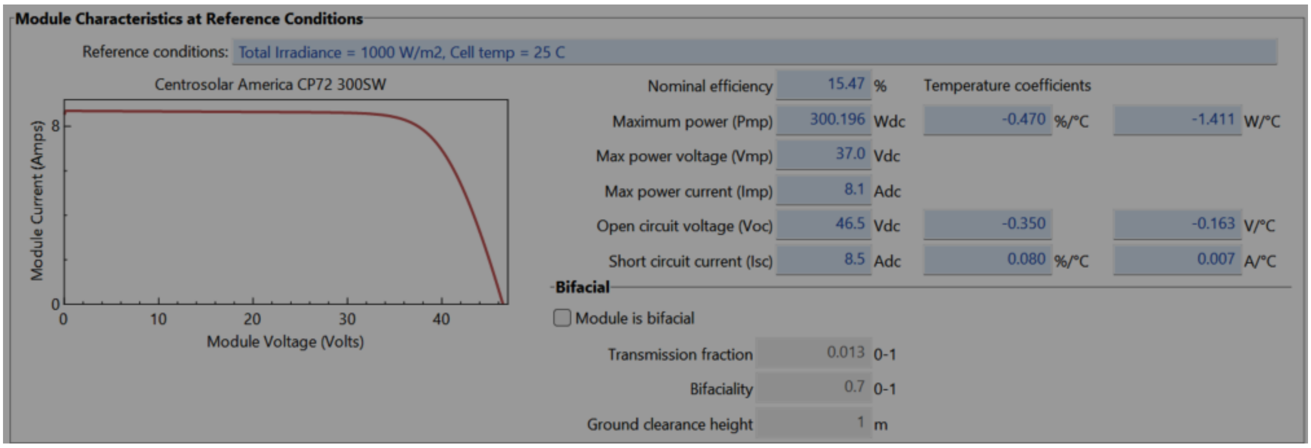
It is recommended that the DC-AC ration be close to one. Because the inverter can't manage the excess power and will cut off the additional production if the DC capability is much more than the AC capability, inefficiencies will occur. On the other side, upfront expenses would rise due to the need of investing in a larger inverter capacity in the event that the DC power is much lower than the AC power. Keep in mind that the quality of solar modules declines with time. As time goes on, the power output of the photovoltaic panels would gradually decline when compared to a brand-new system. Additionally, SAM could take this into account. When it comes to SAM, the average rate of degradation is 0.7% every year. If the performance of PV modules improves in the future, this figure may be adjusted accordingly.

5.2.2. Sizing of PV Module

A number of factors determine the DC size of the system:

- The string voltages at the point of greatest power (Vmp) is determined by the amount of photovoltaic cells linked in series per string.
- The size of the system is amplified by increasing the quantity of threads in conjunction, and the inverse is also true. Both Voc and Vmp strings are unaltered.

Within the SAM software, we have the option to determine the size of the DC system in two ways. The first method involves defining the desired array size and allowing SAM to automatically compute the optimal string configuration to meet the needed array size. Alternatively, we may manually enter the exact modules and inverters we want to use. The framework's scaling module may receive this data, as seen in figure 5.2. With SAM, the dimension characteristics are taken from the manufacturer's data sheet and used under standard testing conditions. We can't understand the variations in the actual findings' output unless we run a modelling procedure using specific locations' carefully selected meteorological data.



Module Characteristics at Reference Conditions

Reference conditions: Total Irradiance = 1000 W/m2, Cell temp = 25 C

Centrosolar America CP72 300SW

			Temperature coefficients			
Nominal efficiency	15.47	%				
Maximum power (Pmp)	300.196	Wdc	-0.470	%/°C	-1.411	W/°C
Max power voltage (Vmp)	37.0	Vdc				
Max power current (Imp)	8.1	Adc				
Open circuit voltage (Voc)	46.5	Vdc	-0.350		-0.163	V/°C
Short circuit current (Isc)	8.5	Adc	0.080	%/°C	0.007	A/°C

Bifacial

☐ Module is bifacial

Transmission fraction 0.013 0-1

Bifaciality 0.7 0-1

Ground clearance height 1 m

Figure 5.2: Module requirements

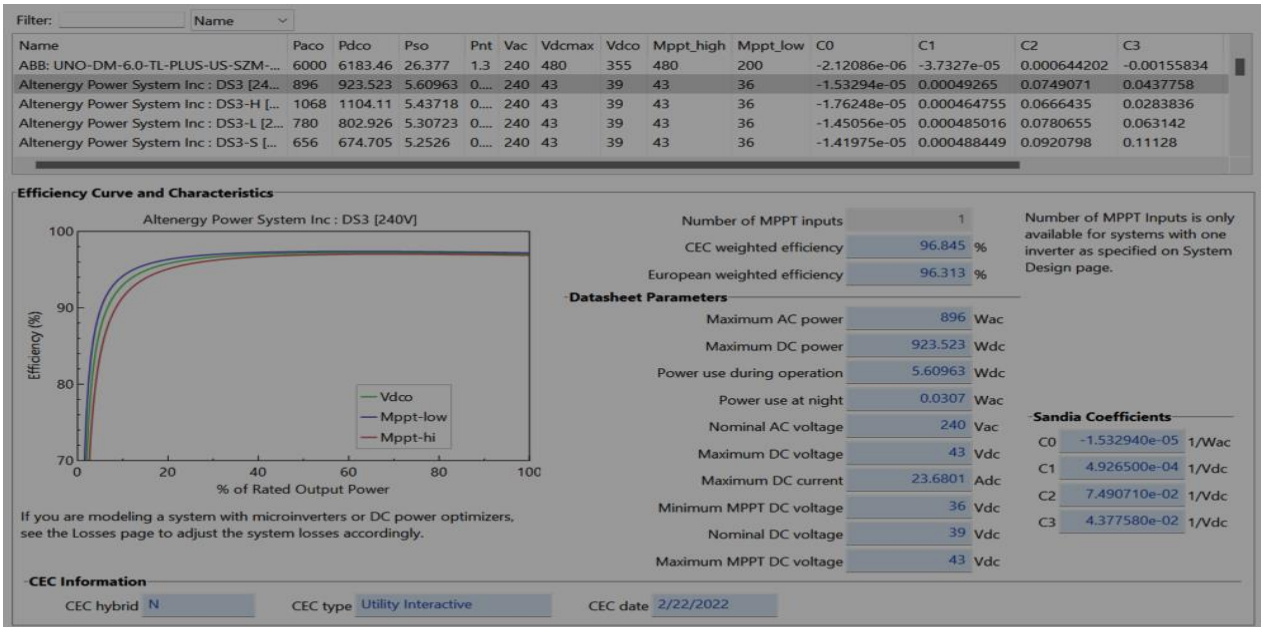
Importantly, the inverter's lowest and highest MPPT Vg readings must be included in the spectrum of Voc and Vmp. This ensures that the inverter's highest power point spectrum is within the PV model's operational spectrum.

5.2.3. Appropriate inverter size

There are presently three distinct inverter types available from SAM:

- String and Central
- Micro
- Direct Current Optimizer

Every such setup would result in a unique set of system losses.



Name	Paco	Pdco	Pso	Pnt	Vac	Vdcmax	Vdco	Mppt_high	Mppt_low	C0	C1	C2	C3
ABB: UNO-DM-6.0-TL-PLUS-US-SZM-...	6000	6183.46	26.377	1.3	240	480	355	480	200	-2.12086e-06	-3.7327e-05	0.000644202	-0.00155834
Altenergy Power System Inc : DS3 [24...	896	923.523	5.60963	0....	240	43	39	43	36	-1.53294e-05	0.00049265	0.0749071	0.0437758
Altenergy Power System Inc : DS3-H [...	1068	1104.11	5.43718	0....	240	43	39	43	36	-1.76248e-05	0.000464755	0.0666435	0.0283836
Altenergy Power System Inc : DS3-L [2...	780	802.926	5.30723	0....	240	43	39	43	36	-1.45056e-05	0.000485016	0.0780655	0.063142
Altenergy Power System Inc : DS3-S [...	656	674.705	5.2526	0....	240	43	39	43	36	-1.41975e-05	0.000488449	0.0920798	0.11128

Number of MPPT inputs 1
CEC weighted efficiency 96.845 %
European weighted efficiency 96.313 %

Number of MPPT Inputs is only available for systems with one inverter as specified on System Design page.

Datasheet Parameters

Maximum AC power 896 Wac
Maximum DC power 923.523 Wdc
Power use during operation 5.60963 Wdc
Power use at night 0.0307 Wac
Nominal AC voltage 240 Vac
Maximum DC voltage 43 Vdc
Maximum DC current 23.6801 Adc
Minimum MPPT DC voltage 36 Vdc
Nominal DC voltage 39 Vdc
Maximum MPPT DC voltage 43 Vdc

Sandia Coefficients

C0 -1.532940e-05 1/Wac
C1 4.926500e-04 1/Vdc
C2 7.490710e-02 1/Vdc
C3 4.377580e-02 1/Vdc

If you are modeling a system with microinverters or DC power optimizers, see the Losses page to adjust the system losses accordingly.

CEC Information

CEC hybrid N
CEC type Utility Interactive
CEC date 2/22/2022

Figure 5.3: Choosing an inverter and its features.

A wide variety of inverters in a range of sizes are available in SAM's extensive database. When choosing an inverter, we have three possibilities:

- Look for information in the CEC registry.
- Fill out the inverter details taken from the supplier's specification.
- Input of information based on assessed effectiveness.

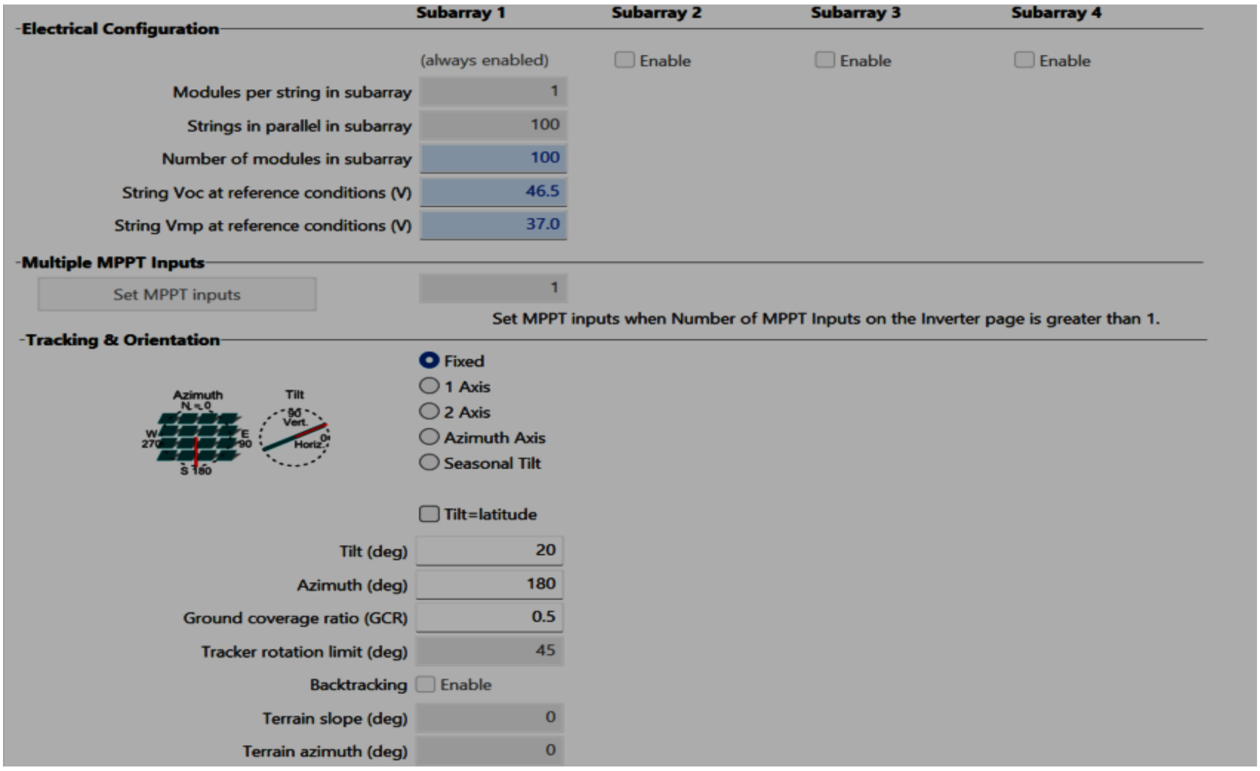
According to conventional testing conditions, these goods have all the required technical features. Users are free to choose any inverter that suits our own system requirements. Still, these things determine how big the inverter has to be:

- **Inverter cost:** Inverters are often optimized to have a DC-AC ratio near to one. However, in certain situations, it may be more cost-effective to utilize a standard size inverter instead of one that precisely matches the requirements of our system. In such instances, designers must establish a harmonious equilibrium between the efficacy of the system and the financial concerns.
- **Efficiency curve:** This is crucial for very tiny systems. The efficiency of the inverter fluctuates depending on the percentage of rated output power. It is important to guarantee that the inverter functions at its highest level of effectiveness.

5.3. PV Orientation and Tracking

5.3.1. Arrangement of strings

To change the number of strings in an array, users may go to SAM's system layout section and click on the Monitoring and Orientation section. Then, we may go on to systems with up to four subarrays for simulation. This is specifically used for developing large-scale photovoltaic systems with a capacity of many megawatts. Each sub array has an own options page that provides designers the freedom to independently configure each sub array. The subarrays may be interconnected either in parallel to a single inverter or with microinverters assigned to each subarray as shown in figure 5.4.



Electrical Configuration

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Modules per string in subarray	1			
Strings in parallel in subarray	100			
Number of modules in subarray	100			
String Voc at reference conditions (V)	46.5			
String Vmp at reference conditions (V)	37.0			

Multiple MPPT Inputs

Set MPPT inputs: 1

Set MPPT inputs when Number of MPPT Inputs on the Inverter page is greater than 1.

Tracking & Orientation

● Fixed
○ 1 Axis
○ 2 Axis
○ Azimuth Axis
○ Seasonal Tilt

☐ Tilt=latitude

Tilt (deg): 20
Azimuth (deg): 180
Ground coverage ratio (GCR): 0.5
Tracker rotation limit (deg): 45
Backtracking: ☐ Enable
Terrain slope (deg): 0
Terrain azimuth (deg): 0

Figure 5.4: Orientation and Tracking configurations

5.3.2.Tracking and Tilt

Different tracking setups are used by each subarray, as shown in Figure 5.5. The most common method for domestic roof- top solar energy installations is the stationary panel tracking. Azimuth axis tracking, 1-axis tracking, and 2-axis tracking are some of the other tracking options. For the purpose of trying to observe the sun's passage from dawn to dark, a uniaxial tracking device spins around a single axis. To compensate for seasonal changes, a dual axis tracking system accurately observes the sun's motion in both the eastward and westward and from northern to southern directions. To keep a close eye on the sun's motion, a tracking device with an azimuth axis spin on a plane that is horizontal. Large photovoltaic farms with several rows of PV panels often use tracking PV. One distinctive characteristic of single axis tracking systems is backtracking. At certain angles of sun incidence, neighbouring rows in closely spaced photovoltaic arrays will be shaded. The shading effect of these systems may be reduced by using backtracking. Figure 5.5 shows how the shadowy impact is reduced in closely spaced rows when backtracking is used.

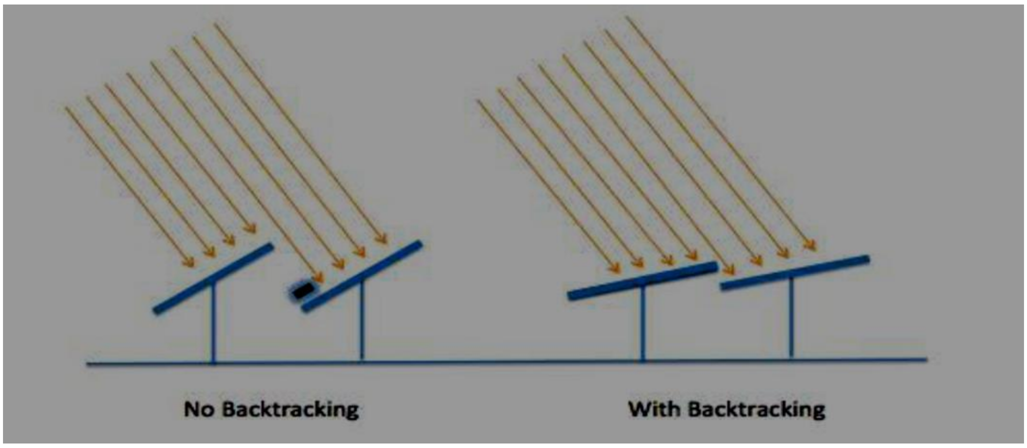


Figure 5.5: Backtracking within densely packed subarrays

In addition, SAM lets customers choose the angle at which solar panels are mounted. Stationary and one-axis tracking mechanisms are the only ones that matter when it comes to the tilt, which is measured in degrees. In a residential photovoltaic system, the tilt is the angle at which the panels mounted on the roof are inclined. The typical tilt range is fifteen to twenty degrees. Stationary tracking systems are the only ones that can make use of azimuth. The degree is the standard unit of measurement for azimuth. An azimuth of 180 degrees would be appropriate for a system pointed to the southern horizon.

5.4. Snowfall and Shadows

Then we have now entered the part of the process when several factors may be involved in the losses. Shading may arise from any item in close proximity to the PV panels that obstructs direct sunlight from reaching the panels. The presence of shadowing may also result from the dense arrangement of PV panels, which obstructs sunlight and casts shadows on adjacent panels. SAM offers many methods to include shading losses into your calculations. SAM retrieves data from:

- PVsyst
- SunEye hourly shading
- SolarPathFinder month-by-hour shading

An additional functionality of SAM is the use of the 3D shade calculator tool, which enables the creation of a three-dimensional representation of the objects responsible for shading. This allows for a more precise estimation of the shading losses incurred by the photovoltaic arrays at a given position.

5.4.1.Ground Coverage Ratio

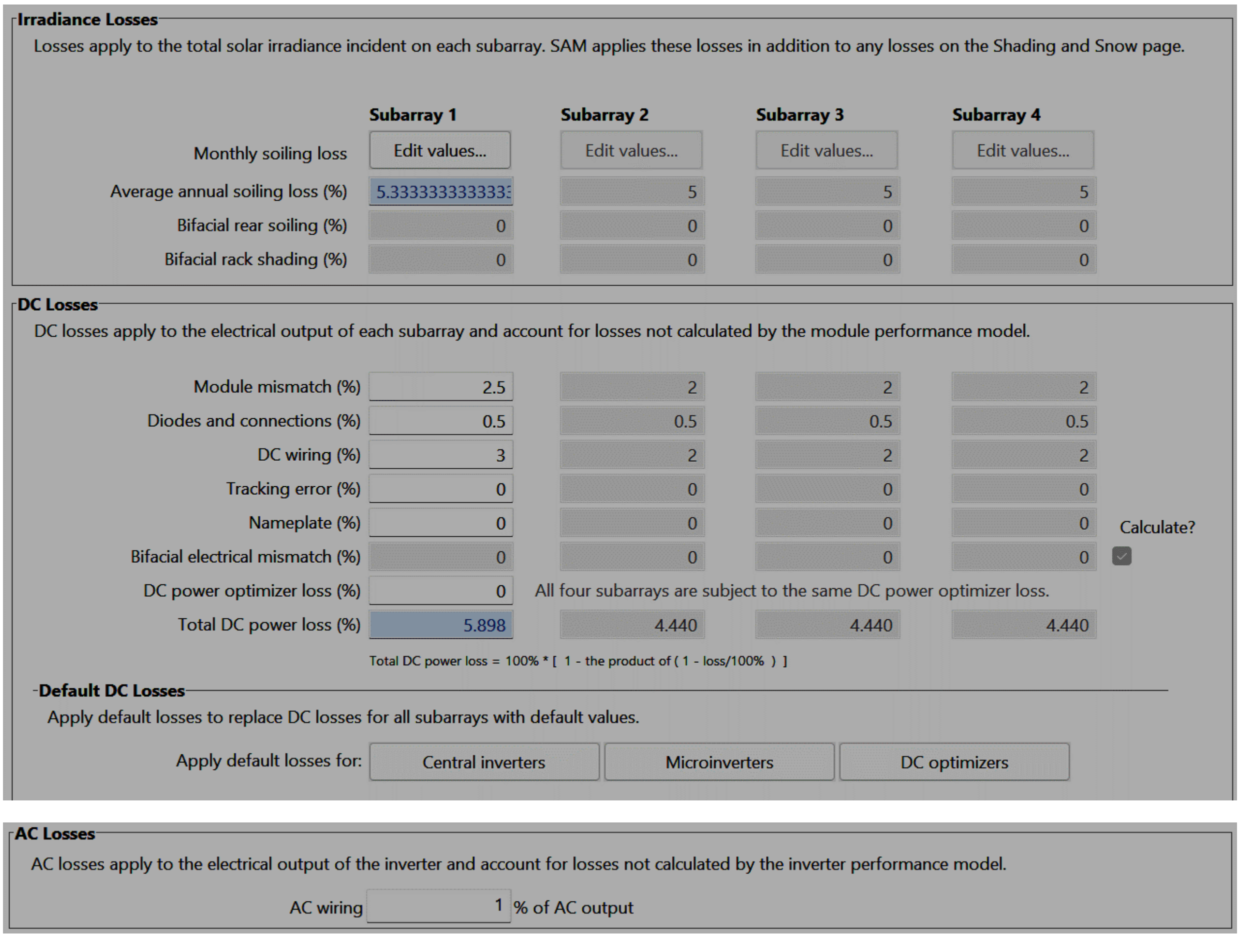
Ground Coverage Ratio (GCR) is a measurement that quantifies the proportion of land area occupied by a PV array in relation to the total land area. The GRC provides a comprehensive assessment of land availability and the required proximity between arrays. SAM utilizes the GCR technique to calculate the reduction in power output caused by shading losses resulting from the overlapping of numerous arrays.

5.4.2.Snow

When snow accumulates on the solar surfaces, SAM can account for the losses that result. It automates the process by using the precipitation data retrieved from the meteorological dataset. If the weather file does not include any snowy information, SAM simply disregards this step.

5.5. Losses

Users may estimate the various loses they expect a solar system to encounter on the loss entry section in SAM. There aren't any detailed formulas for loss calculation in this module. In contrast, SAM puts more weight on users to provide appropriate data, which depends on the exact system that is being built.



Irradiance Losses

Losses apply to the total solar irradiance incident on each subarray. SAM applies these losses in addition to any losses on the Shading and Snow page.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Monthly soiling loss	Edit values...	Edit values...	Edit values...	Edit values...
Average annual soiling loss (%)	5.3333333333333	5	5	5
Bifacial rear soiling (%)	0	0	0	0
Bifacial rack shading (%)	0	0	0	0

DC Losses

DC losses apply to the electrical output of each subarray and account for losses not calculated by the module performance model.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Module mismatch (%)	2.5	2	2	2
Diodes and connections (%)	0.5	0.5	0.5	0.5
DC wiring (%)	3	2	2	2
Tracking error (%)	0	0	0	0
Nameplate (%)	0	0	0	0
Bifacial electrical mismatch (%)	0	0	0	0
DC power optimizer loss (%)	0			
Total DC power loss (%)	5.898	4.440	4.440	4.440

Calculate? ☑

All four subarrays are subject to the same DC power optimizer loss.

Total DC power loss = 100% * [1 - the product of (1 - loss/100%)]

Default DC Losses

Apply default losses to replace DC losses for all subarrays with default values.

AC Losses

AC losses apply to the electrical output of the inverter and account for losses not calculated by the inverter performance model.

AC wiring 1 % of AC output

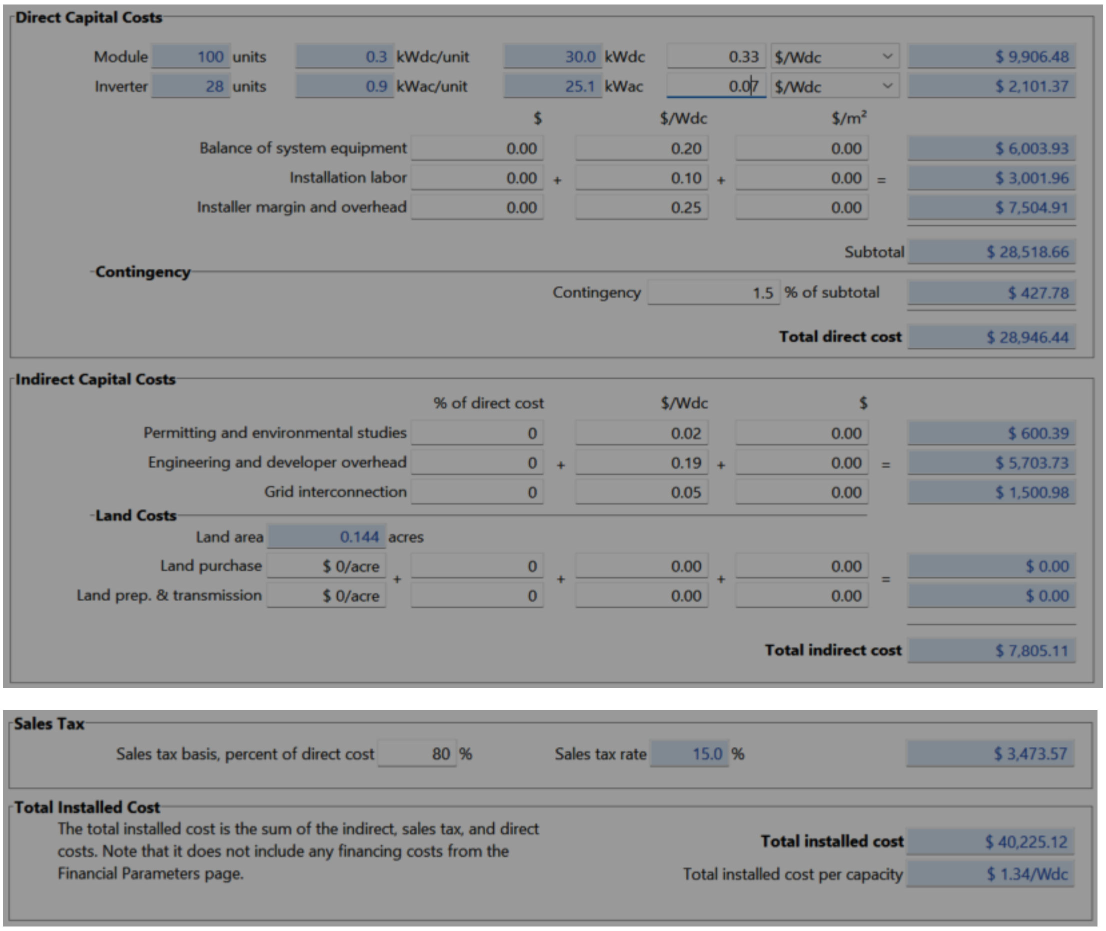
Figure 5.6: PV Losses

SAM classifies losses into the following categories:

i. **Irradiance losses:** such as when particles and filth settle on the panels that produce electricity, reducing their ability to absorb solar energy. Soiling loss may be rather large depending on the amount of precipitation that falls in a particular location. For SAM, the standard soiling loss is 5%.
ii. **DC losses**: may be categorized as module mismatch loss, tracking error, DC optimizer loss, or DC wiring loss. These values are again input by the user.
iii. **AC losses**: refer to losses that occur in the AC wire and are relevant to the inverter's output.

5.6. Costs of System

The SAM website has all the information you need to calculate the costs of solar systems. One way to classify this is as immediate and another as intermediate. Project investments in photovoltaic panels, inverters, and storage systems for batteries (if applicable) make up the real expenses. Expenses including setup labour, earnings margin, and overhead go under this category. Acquisition of land, environmental evaluations, regulatory permits, and grid connection charges are all examples of indirect costs.



Direct Capital Costs

Module	100 units	0.3 kWdc/unit	30.0 kWdc	0.33 $/Wdc	$ 9,906.48
Inverter	28 units	0.9 kWac/unit	25.1 kWac	0.07 $/Wdc	$ 2,101.37

	$		$/Wdc		$/m²		
Balance of system equipment	0.00		0.20		0.00		$ 6,003.93
Installation labor	0.00	+	0.10	+	0.00	=	$ 3,001.96
Installer margin and overhead	0.00		0.25		0.00		$ 7,504.91

Subtotal $ 28,518.66

Contingency

Contingency 1.5 % of subtotal $ 427.78

Total direct cost $ 28,946.44

Indirect Capital Costs

	% of direct cost		$/Wdc		$		
Permitting and environmental studies	0		0.02		0.00		$ 600.39
Engineering and developer overhead	0	+	0.19	+	0.00	=	$ 5,703.73
Grid interconnection	0		0.05		0.00		$ 1,500.98

Land Costs

Land area 0.144 acres

Land purchase	$ 0/acre	+	0	+	0.00	+	0.00	=	$ 0.00
Land prep. & transmission	$ 0/acre		0		0.00		0.00		$ 0.00

Total indirect cost $ 7,805.11

Sales Tax

Sales tax basis, percent of direct cost 80 % Sales tax rate 15.0 % $ 3,473.57

Total Installed Cost

The total installed cost is the sum of the indirect, sales tax, and direct costs. Note that it does not include any financing costs from the Financial Parameters page.

Total installed cost $ 40,225.12

Total installed cost per capacity $ 1.34/Wdc

Figure 5.7: System costs

We also have to pay for things like operation and maintenance. We may choose to record these expenditures as a fixed yearly expenditure or assign a particular cost for a certain year. In the event that the precise price of certain variables is uncertain, SAM essentially accounts for baseline loss estimates in its algorithm, allowing for a fairly realistic examination of an actual system.

5.7. Compensation

Multiple techniques exist for entering reward information in SAM. We have:

- Rewards contingent upon the amount of money invested.
- Remuneration contingent upon the ability or potential.
- Rewards contingent upon productivity.

Users are able to enter Tax Credits into SAM. On the other hand, SAM comes with the DSIRE registry pre-installed. A nonprofit called DSIRE compiles information on the several incentive programs offered by utilities around the country. All it takes is entering the zip code, and we could get a comprehensive list of all the incentive programs that may work with the system. Our research focuses on LADWP's incentive tariff. Incentives for residential, commercial, and government/non-profit enterprises are R5.68 per Watt, R7.57 per Watt, and R21.77 per Watt, respectively, under this scheme [5].

5.8. Electricity tariff

Complex utility rate systems may be modelled using SAM. It works with a wide variety of electricity pricing schemes, including demand fees, time-of-use costs, and tiered price schemes. The utility company Cost Information (URDB), which is maintained by NREL, is an inventory that stores power pricing for different utilities throughout the globe. The platform offers a direct link to this database. We pick the appropriate tariff structure (if any) after identifying the consumer-facing utility.

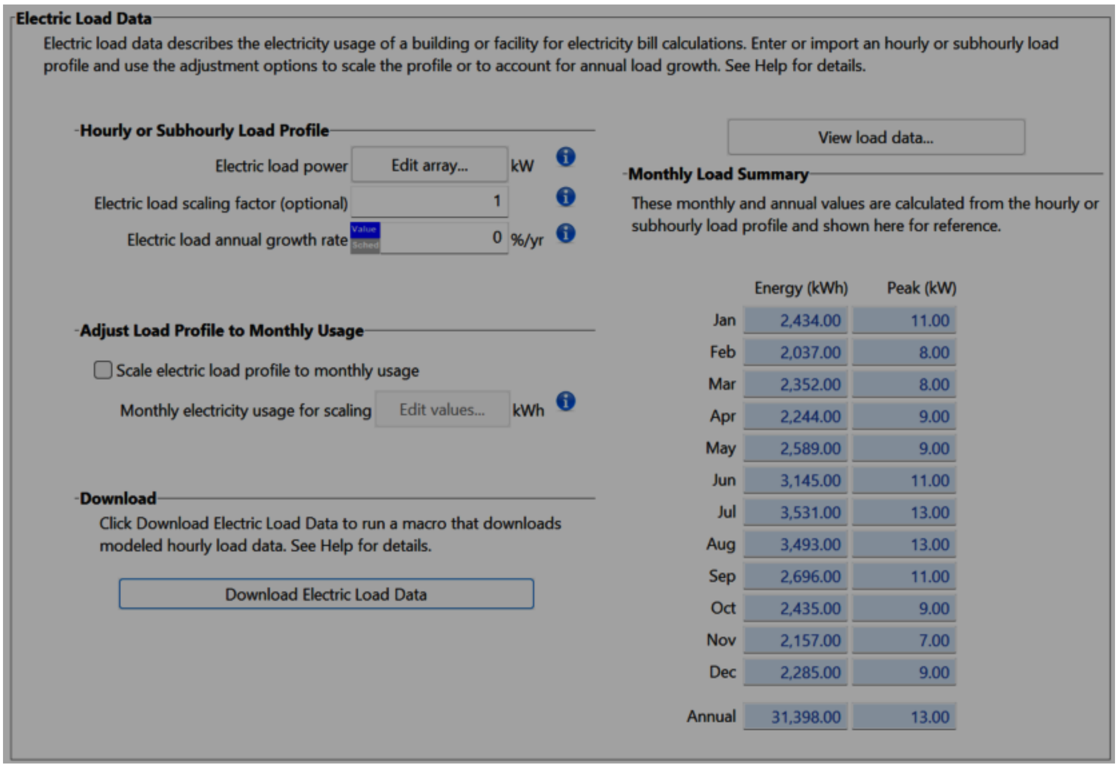
This module further enables users to simulate various metering configurations, such as [5]:

i. Energy may be "rolled over" in kWh via a single meter.
ii. A single metre that accepts rands as an additional credit.
iii. A single meter that does not include rollover.
iv. Two meters, one for sold output and one for bought load.

A more accurate economic evaluation might be obtained by adjusting the SAM inputs according to your electricity tariff structure. In order to determine if a solar energy system is feasible, this is essential. Typically, SAM will run an experiment incorporating the PV system and another without. A more comprehensive analysis of the system's pros and cons may be obtained in this way. That amount of time it takes for your system to save enough money to pay for itself depends on the power pricing. SAM use this function to compute the potential financial advantages if they exist. We used the LADWP tariffs specifically designed for residential properties for this project.

5.9. Load Data

The load data is a crucial characteristic for the economic analysis of PV systems. Accurate determination of load data is essential for achieving the most efficient system size. Additionally, it aids in assessing the economic viability of the project.



Electric Load Data

Electric load data describes the electricity usage of a building or facility for electricity bill calculations. Enter or import an hourly or subhourly load profile and use the adjustment options to scale the profile or to account for annual load growth. See Help for details.

Hourly or Subhourly Load Profile

Electric load power kW

Electric load scaling factor (optional) 1

Electric load annual growth rate 0 %/yr

Adjust Load Profile to Monthly Usage

☐ Scale electric load profile to monthly usage

Monthly electricity usage for scaling kWh

Download

Click Download Electric Load Data to run a macro that downloads modeled hourly load data. See Help for details.

Monthly Load Summary

These monthly and annual values are calculated from the hourly or subhourly load profile and shown here for reference.

	Energy (kWh)	Peak (kW)
Jan	2,434.00	11.00
Feb	2,037.00	8.00
Mar	2,352.00	8.00
Apr	2,244.00	9.00
May	2,589.00	9.00
Jun	3,145.00	11.00
Jul	3,531.00	13.00
Aug	3,493.00	13.00
Sep	2,696.00	11.00
Oct	2,435.00	9.00
Nov	2,157.00	7.00
Dec	2,285.00	9.00
Annual	31,398.00	13.00

Figure 5.8: Load data

SAM provides the capability to input time series load data or compute load data by specifying a set of input parameters. The size of the building, the total quantity of occupants, how many electrical devices, the HVAC applications the ventilation the preferences, and the overall utilization are all variables that affect the monthly load statistics. Additionally, it is possible to input the monthly kilowatt-hour use in order to get a more precise study of the system, as seen in figure 5.8.

5.10. Summary

This chapter presented a methodical approach to railway station building photovoltaic systems using the System Advisor Model , following a step-by-step procedure. We conducted a thorough analysis of all the many factors and constraints that are essential for creating a successful design.

6. CHAPTER 6: RESULTS AND DISCUSSIONS

The project involves a simulation of a 30kW rooftop grid-tied PV system located in the city of East London, Eastern Cape, in order to understand the engineering and financial analytical features of the SAM. A realistic end-user load, accurate weather data, and utility power price were all inputs into the simulation.

6.1. Location and Resource

The NSRDB provides a direct connection to SAM, enabling users to access and retrieve meteorological information corresponding to specified locations and years. A meteorological dataset representing a typical year (TMY) was chosen for the geographical location of East London, situated at coordinates 33°01'02"S 27°54'30"E. The climate information was used to get the amount of radiation as well as dry bulb temps indicated in Figure 6.1.

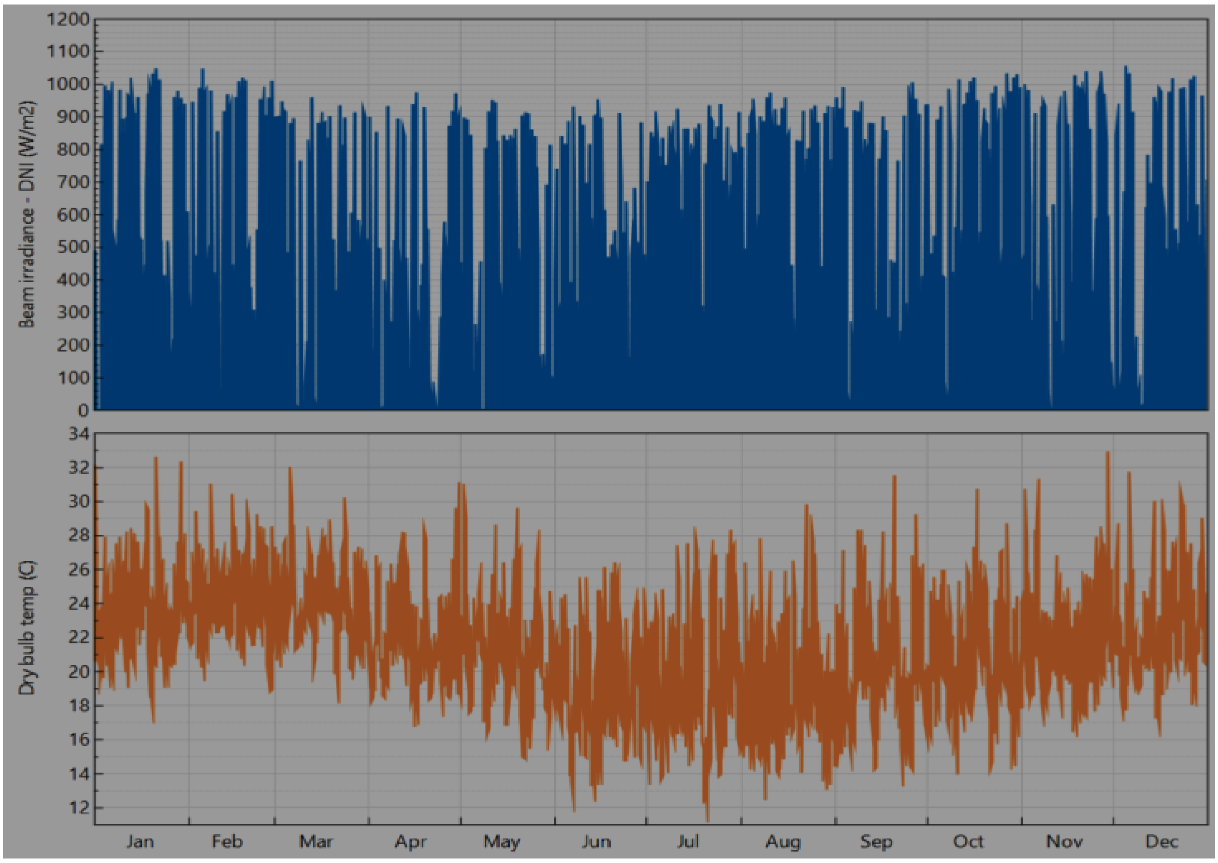
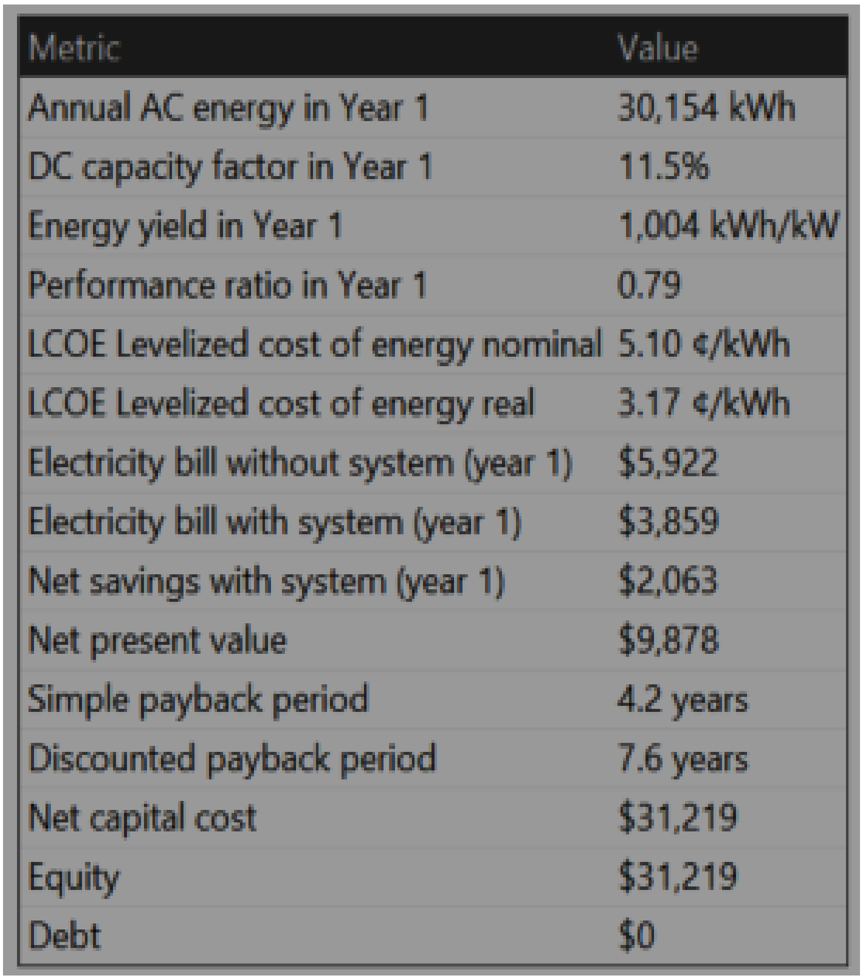


Figure 6.1: Climate statistics for East London, Eastern Cape, RSA

6.2. Modelling Outcomes

Utilizing all the provided information and the designated meteorological records, SAM executes an extensive model that aids system developers in undertaking a thorough feasibility evaluation. The simulation overview is shown in Figure 6.2. The total quantity of energy produced during the inaugural year is shown on the summary page of the report. The energy expense is calculated by it. Power bills are computed by the technology using current utility costs, regardless of whether the PV installation is there or not. In the end, it calculates the system's expenditures and examines the period of time needed to recover the capital investment.

The method also offers a profitable arrangement with a return on investment of just 4.2 years. The value of time cannot be adequately measured using a simple repayment time frame. To make up for this, the discounted payback period calculates how long it takes for an investment to earn back the money that was initially invested using discounted cash flows. Consequently, 7.6 years is the discounted payback time. According to the data in figure 6.2, the system's capacity factor is 11.5%. Furthermore, the total expense for the whole system using the SAM approach amounts to R579 322.55.



Metric	Value
Annual AC energy in Year 1	30,154 kWh
DC capacity factor in Year 1	11.5%
Energy yield in Year 1	1,004 kWh/kW
Performance ratio in Year 1	0.79
LCOE Levelized cost of energy nominal	5.10 ¢/kWh
LCOE Levelized cost of energy real	3.17 ¢/kWh
Electricity bill without system (year 1)	$5,922
Electricity bill with system (year 1)	$3,859
Net savings with system (year 1)	$2,063
Net present value	$9,878
Simple payback period	4.2 years
Discounted payback period	7.6 years
Net capital cost	$31,219
Equity	$31,219
Debt	$0

Figure 6.2: The overview of SAM output

The photovoltaic system described in this research is simulated using the System Advisor Model. Figure 6.3 illustrates the monthly generation of energy. It is evident that the monthly energy output is greater during the summer months due to two factors: an increased number of peak solar hours and the use of a tilt angle of 25° instead of 35°, which corresponds to the latitude of East London.

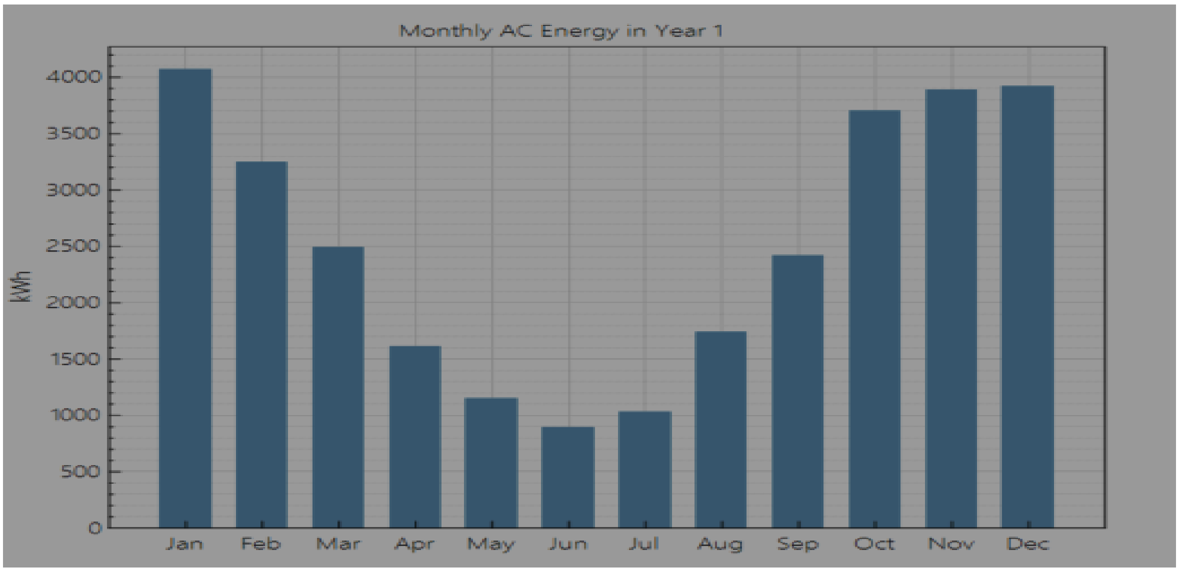


Figure 6.3: Energy output on a monthly basis.

Figure 6.4 shows the information that shows the system's annual power generation over a 25-year period. The system exhibits its peak performance in the first year and has a progressive decline in performance as it approaches the conclusion of its lifespan. The first year yields a total of 30.154 kWh, whereas the last year's production is around 26.85 kWh. The inverters, PV modules, wires, and other parts of the system have all deteriorated, which is causing the power output to fall.

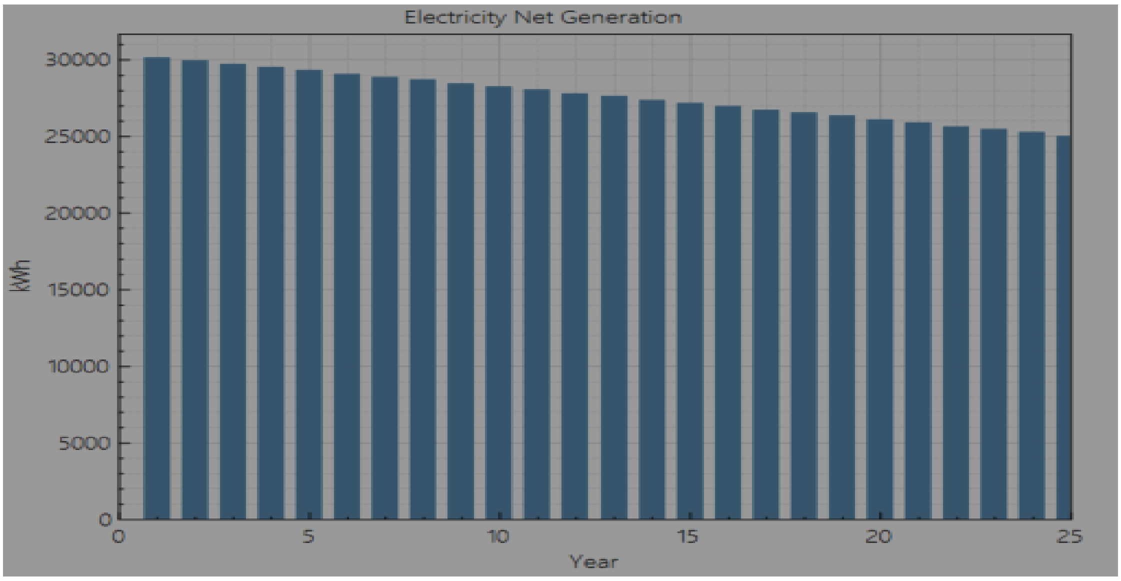


Figure 6.4: Total energy output during a period of 25 years, measured in kWh

Additionally, Figure 6.5 depicts the limited time period between 9 a.m. and 3 p.m. that is accountable for the generation of power throughout the whole year . The window's proportions shrink throughout the winter as a result of the lower duration of maximum sunshine hours in this season.

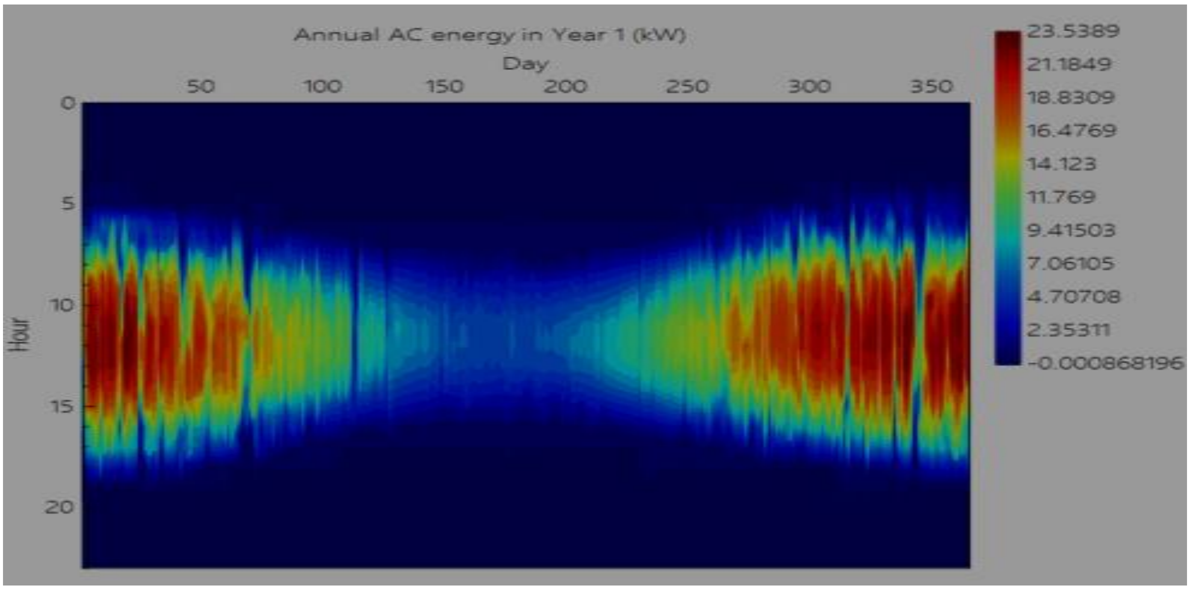


Figure 6.5: Annual electricity generation.

Figure 6.6 is a graph showing the projected monthly energy production for 2022 generated by the SAM program. The graphic clearly shows that the summertime months (November, December, and January) are the most active in terms of energy production, while the winter months (May, June, and July) are the least active. Through the process of net metering, the excess energy is sent back into the utility system.

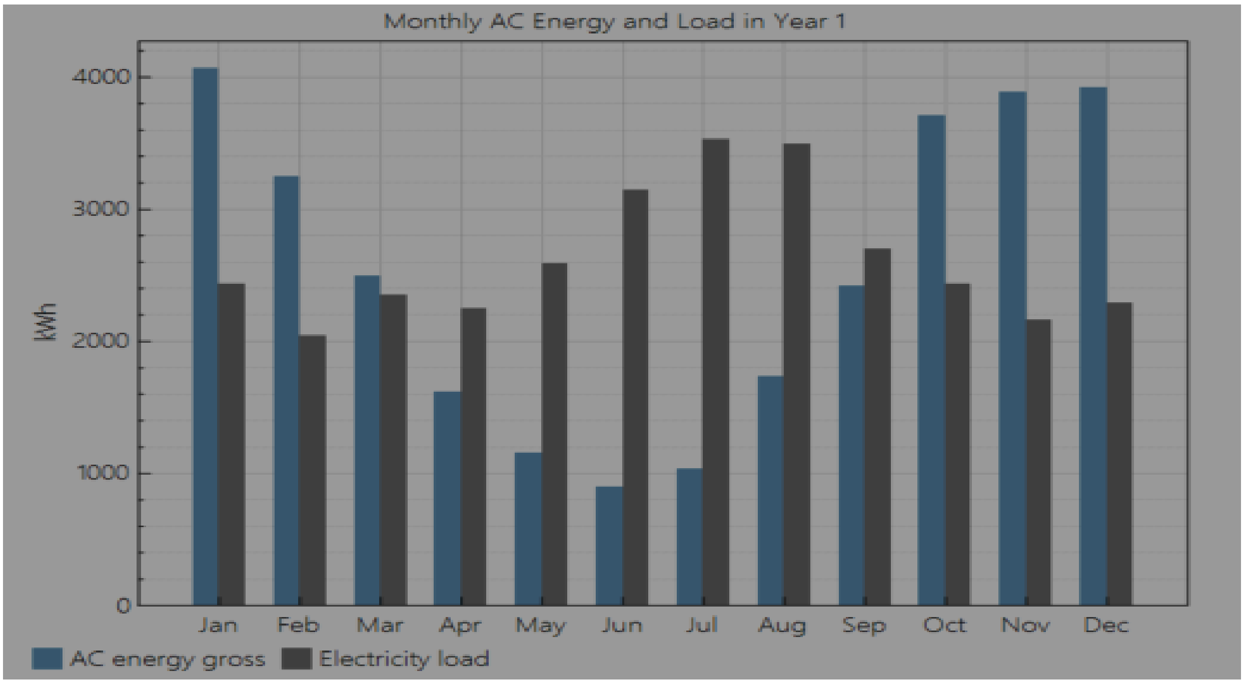


Figure 6.6: Annual energy output and consumption

Figure 6.7 displays the energy loss of the proposed photovoltaic solar power system. Shade, dirt, sides reflection, inverter MPPT trimming, imbalance, tracking, inverter effectiveness, connections, and many other factors contribute to the wasteful performance of grid-connected rooftop solar energy generating systems.

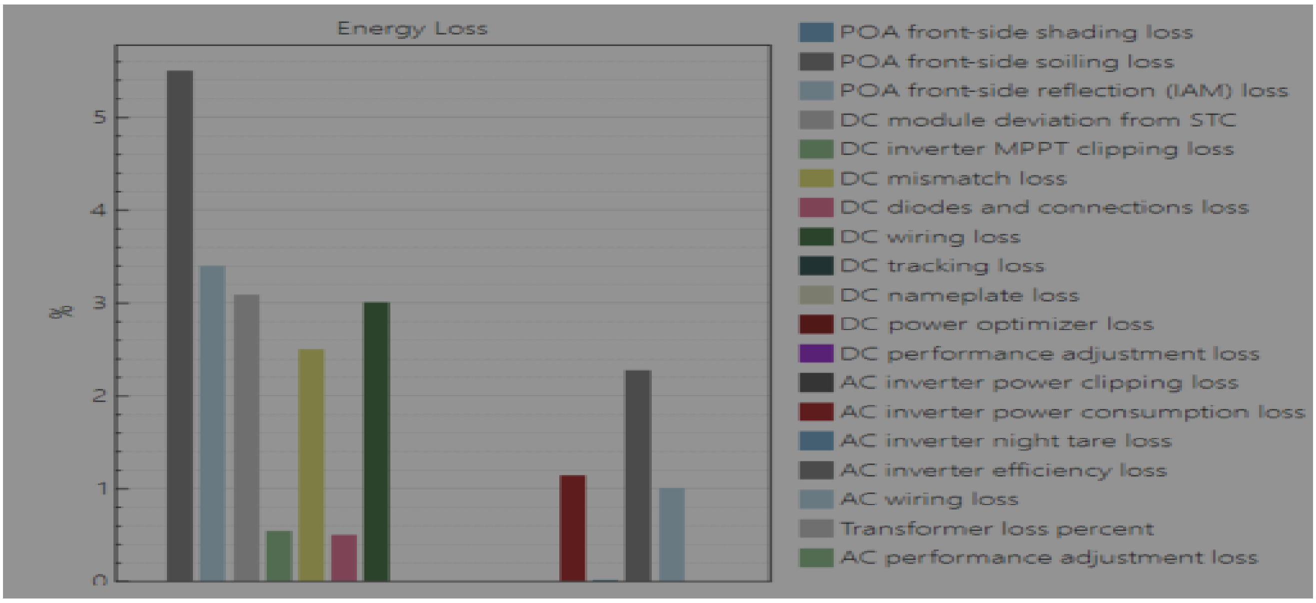
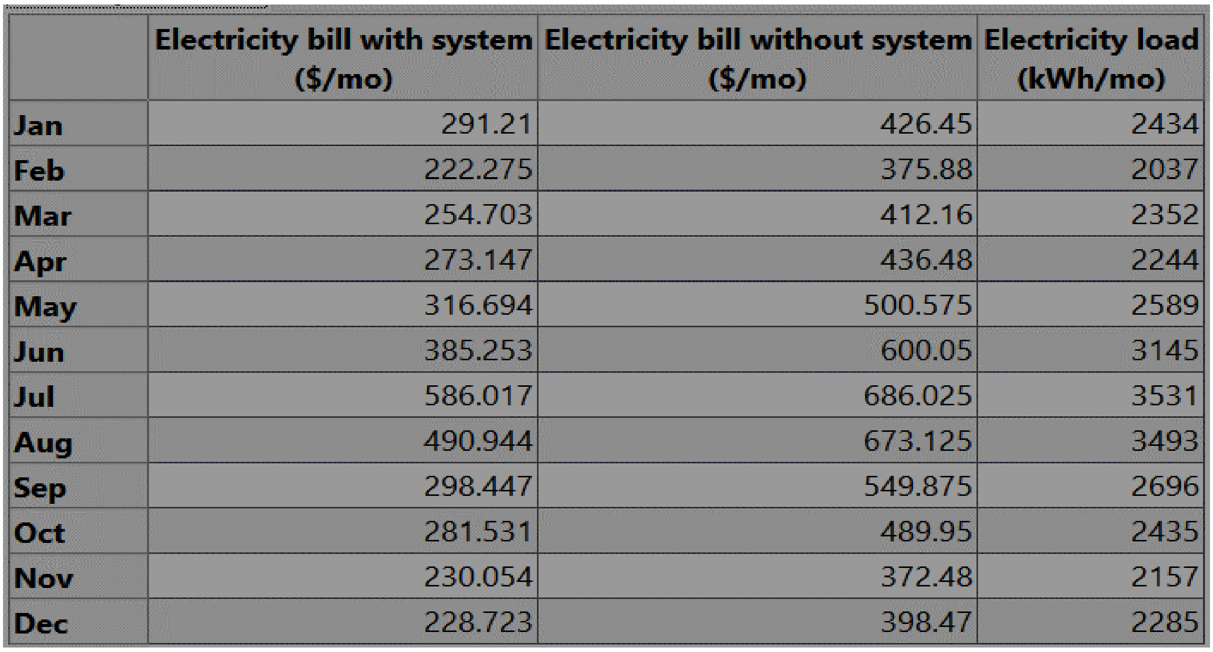


Figure 6.7: Potential energy waste in the suggested design

Figure 6.8 shows a detailed analysis of the electricity costs for a train station in two different scenarios: one with and one without a photovoltaic system. There is evidence that the proposed PV system can drastically cut monthly power bills.



	Electricity bill with system ($/mo)	Electricity bill without system ($/mo)	Electricity load (kWh/mo)
Jan	291.21	426.45	2434
Feb	222.275	375.88	2037
Mar	254.703	412.16	2352
Apr	273.147	436.48	2244
May	316.694	500.575	2589
Jun	385.253	600.05	3145
Jul	586.017	686.025	3531
Aug	490.944	673.125	3493
Sep	298.447	549.875	2696
Oct	281.531	489.95	2435
Nov	230.054	372.48	2157
Dec	228.723	398.47	2285

Figure 6.8: Bills for electricity and load each month

The system has a payback time of 4.2 years, indicating a lucrative arrangement. A significant limitation of a basic payback period is its failure to account for the time worth of money. The discounted payback period is a method that considers the time it takes for an investment to recover the original cash expenditure by using discounted cash flows. The discounted payback time is 7.6 years. The Figure 6.9 displays the payback time produced from the SAM simulation program.

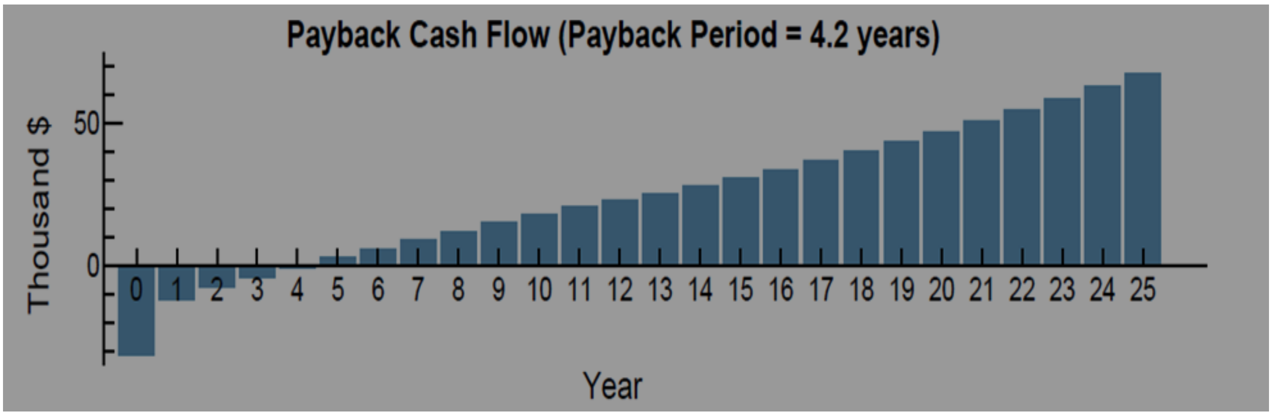


Figure 6.9: Pay Back cash flow

7. CHAPTER 7: CONCLUSION AND SUGGESTIONS

7.1. Conclusion And Recommendation

In a world whereby traditional sources of energy account for roughly 32 percent of global production, one goal of the previously stated future plans is to achieve near-zero energy buildings. To start, one way to accomplish these goals would be to decrease the amount of energy produced by traditional sources, such as fossil fuels. In order to improve the advantages of implanting these alternative technologies, this research is necessary, but it also allows us to state that a future without a profound dependency on fossil fuels is achievable.

This study's main findings suggest that the East London railway station has the technical capability to install distributed PV systems. The annual energy production of these systems is 30.154 kWh, which is sufficient to provide about 65.7% of the power needs of the train station. With a performance ratio of 0.897, the system is 35.10 percent effective. A considerable quantity of CO_2 emissions in the East London area might be mitigated by the solution that was both implemented and simulated. The system design seems to be both technically feasible and promising, according on the findings. A sufficient quantity of energy is generated by the station's rooftops to meet the station's power needs.

7.2. Future work

The work presented here lays the groundwork for future research into the technological viability of integrating more renewable energy generating methods, such as solar thermal and wind. The research's electrical viability would be enhanced by conducting thorough investigations of the area's electrical grid layout. To further widen the study's major significant accomplishments, future research could additionally include the environmental effect of the modelled and simulated systems.

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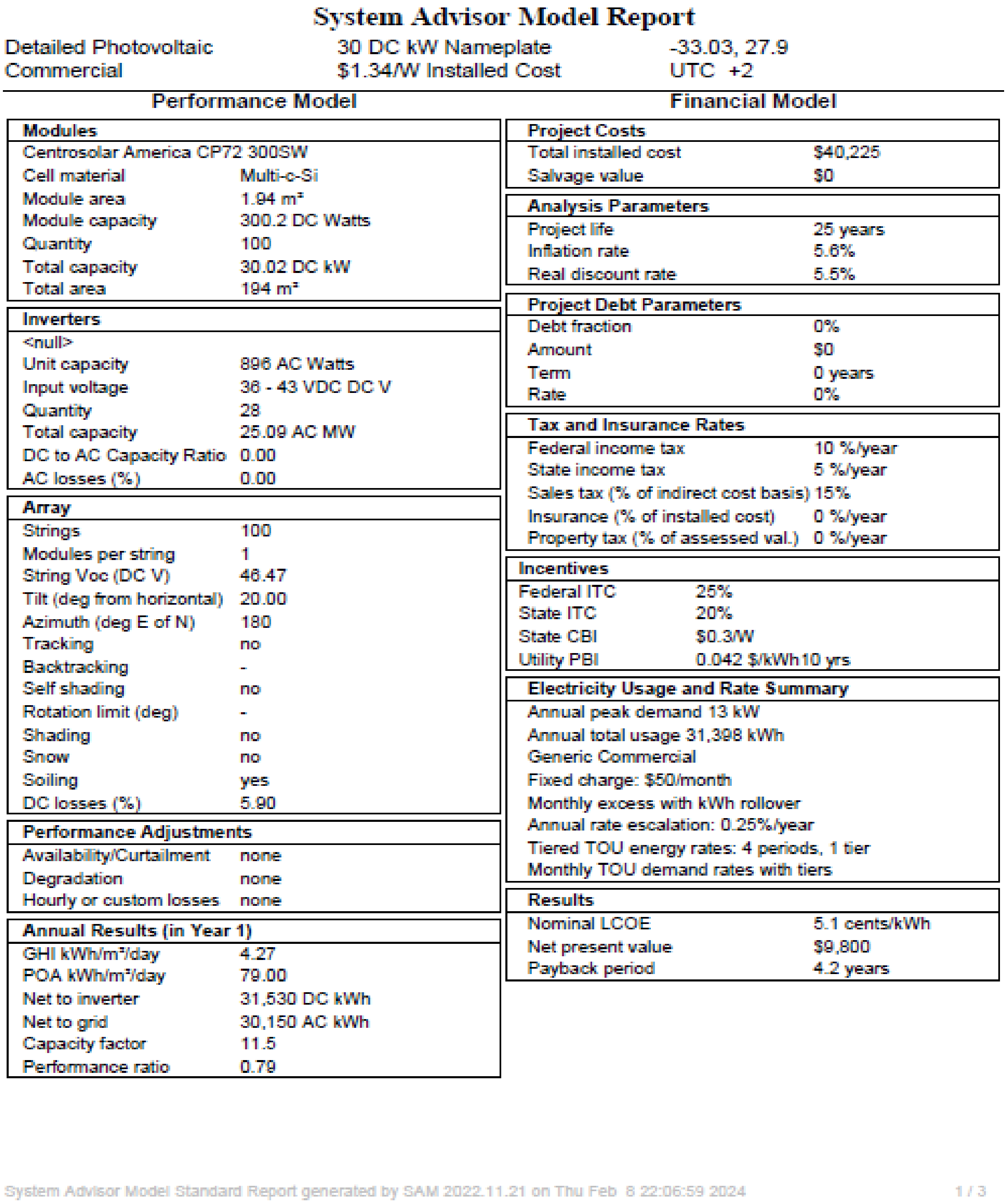
A. APPENDICES

A.1. Design Report



System Advisor Model Report

Detailed Photovoltaic
Commercial

30 DC kW Nameplate
$1.34/W Installed Cost

-33.03, 27.9
UTC +2

Performance Model

Modules	
Centrosolar America CP72 300SW	
Cell material	Multi-c-Si
Module area	1.94 m²
Module capacity	300.2 DC Watts
Quantity	100
Total capacity	30.02 DC kW
Total area	194 m²

Inverters	
<null>	
Unit capacity	896 AC Watts
Input voltage	36 - 43 VDC DC V
Quantity	28
Total capacity	25.09 AC MW
DC to AC Capacity Ratio	0.00
AC losses (%)	0.00

Array	
Strings	100
Modules per string	1
String Voc (DC V)	46.47
Tilt (deg from horizontal)	20.00
Azimuth (deg E of N)	180
Tracking	no
Backtracking	-
Self shading	no
Rotation limit (deg)	-
Shading	no
Snow	no
Soiling	yes
DC losses (%)	5.90

Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.27
POA kWh/m²/day	79.00
Net to inverter	31,530 DC kWh
Net to grid	30,150 AC kWh
Capacity factor	11.5
Performance ratio	0.79

Financial Model

Project Costs	
Total installed cost	$40,225
Salvage value	$0

Analysis Parameters	
Project life	25 years
Inflation rate	5.6%
Real discount rate	5.5%

Project Debt Parameters	
Debt fraction	0%
Amount	$0
Term	0 years
Rate	0%

Tax and Insurance Rates	
Federal income tax	10 %/year
State income tax	5 %/year
Sales tax (% of indirect cost basis)	15%
Insurance (% of installed cost)	0 %/year
Property tax (% of assessed val.)	0 %/year

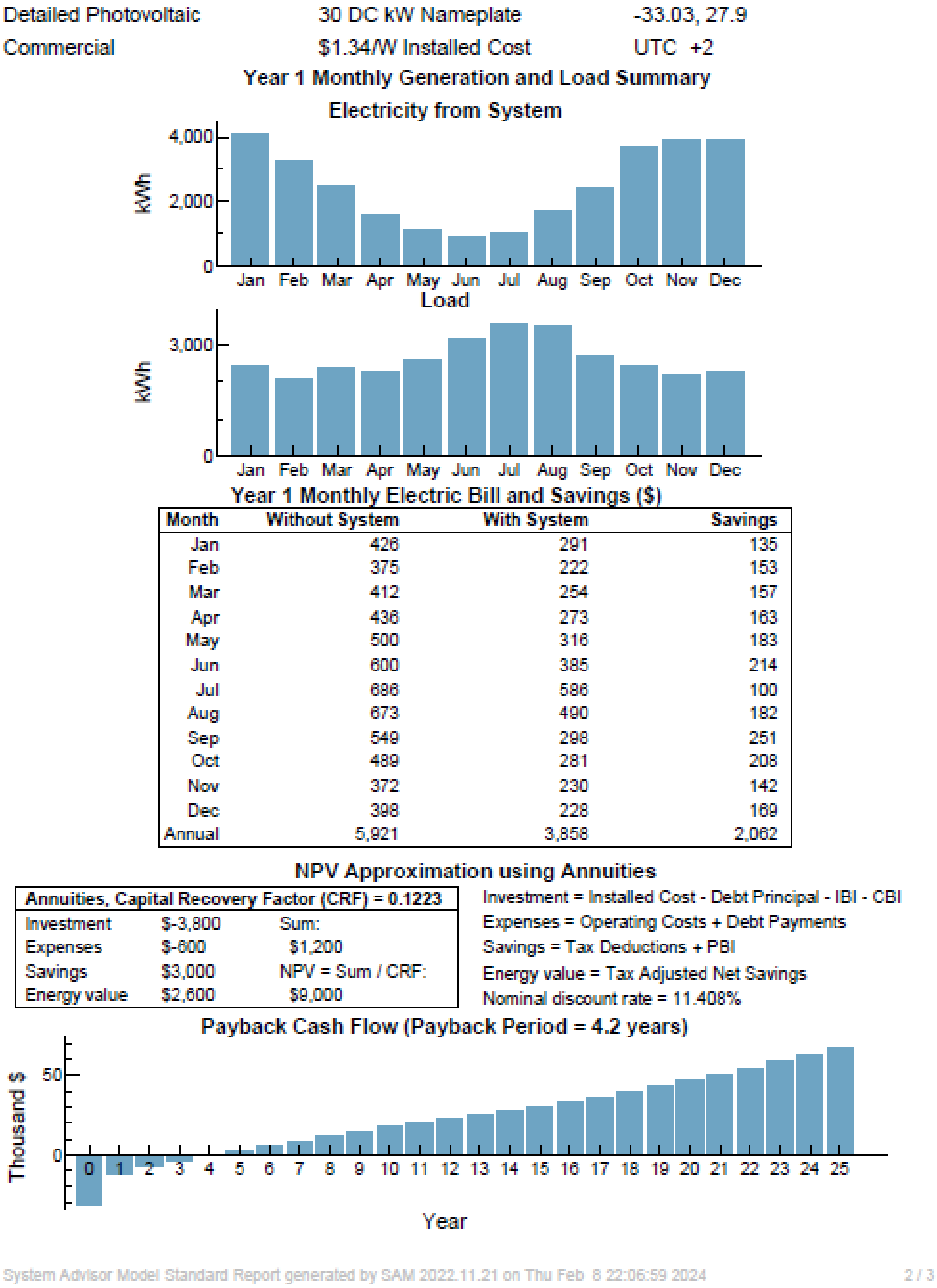
Incentives	
Federal ITC	25%
State ITC	20%
State CBI	$0.3/W
Utility PBI	0.042 $/kWh 10 yrs

Electricity Usage and Rate Summary

Annual peak demand 13 kW
Annual total usage 31,398 kWh
Generic Commercial
Fixed charge: $50/month
Monthly excess with kWh rollover
Annual rate escalation: 0.25%/year
Tiered TOU energy rates: 4 periods, 1 tier
Monthly TOU demand rates with tiers

Results	
Nominal LCOE	5.1 cents/kWh
Net present value	$9,800
Payback period	4.2 years

System Advisor Model Standard Report generated by SAM 2022.11.21 on Thu Feb 8 22:06:59 2024 1 / 3



Detailed Photovoltaic	30 DC kW Nameplate	-33.03, 27.9
Commercial	$1.34/W Installed Cost	UTC +2

Year 1 Monthly Generation and Load Summary

Electricity from System

Load

Year 1 Monthly Electric Bill and Savings ($)

Month	Without System	With System	Savings
Jan	426	291	135
Feb	375	222	153
Mar	412	254	157
Apr	436	273	163
May	500	316	183
Jun	600	385	214
Jul	686	586	100
Aug	673	490	182
Sep	549	298	251
Oct	489	281	208
Nov	372	230	142
Dec	398	228	169
Annual	5,921	3,858	2,062

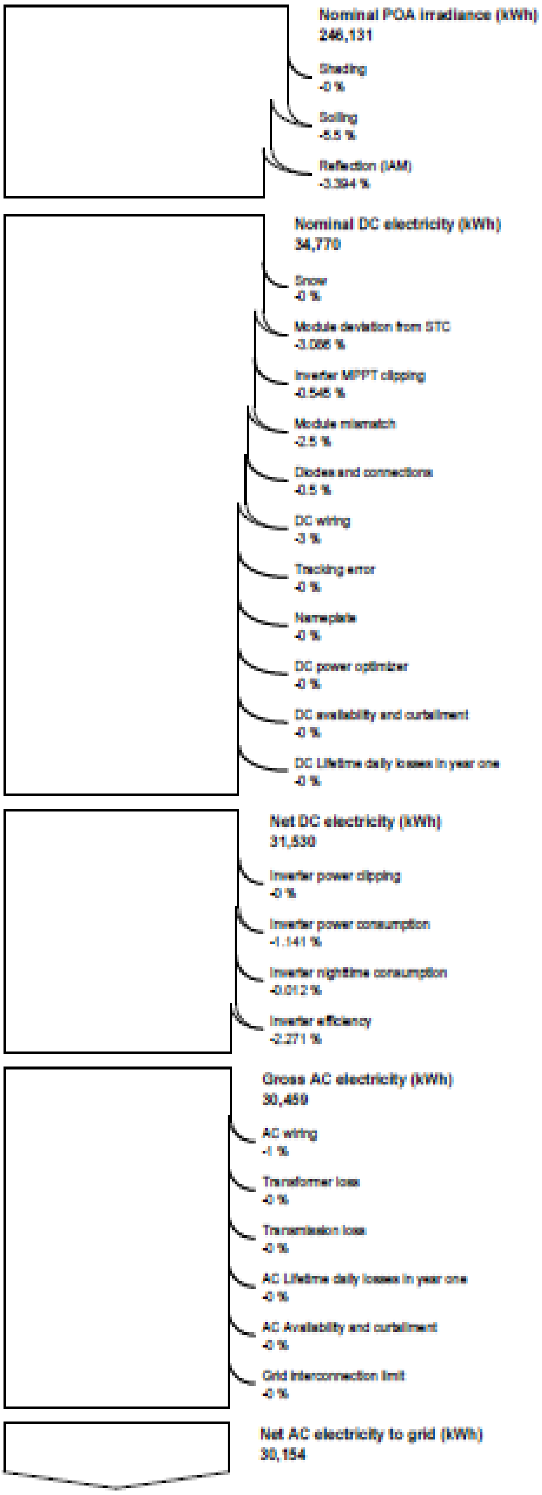
NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.1223		
Investment	$-3,800	Sum:
Expenses	$-600	$1,200
Savings	$3,000	NPV = Sum / CRF:
Energy value	$2,600	$9,000

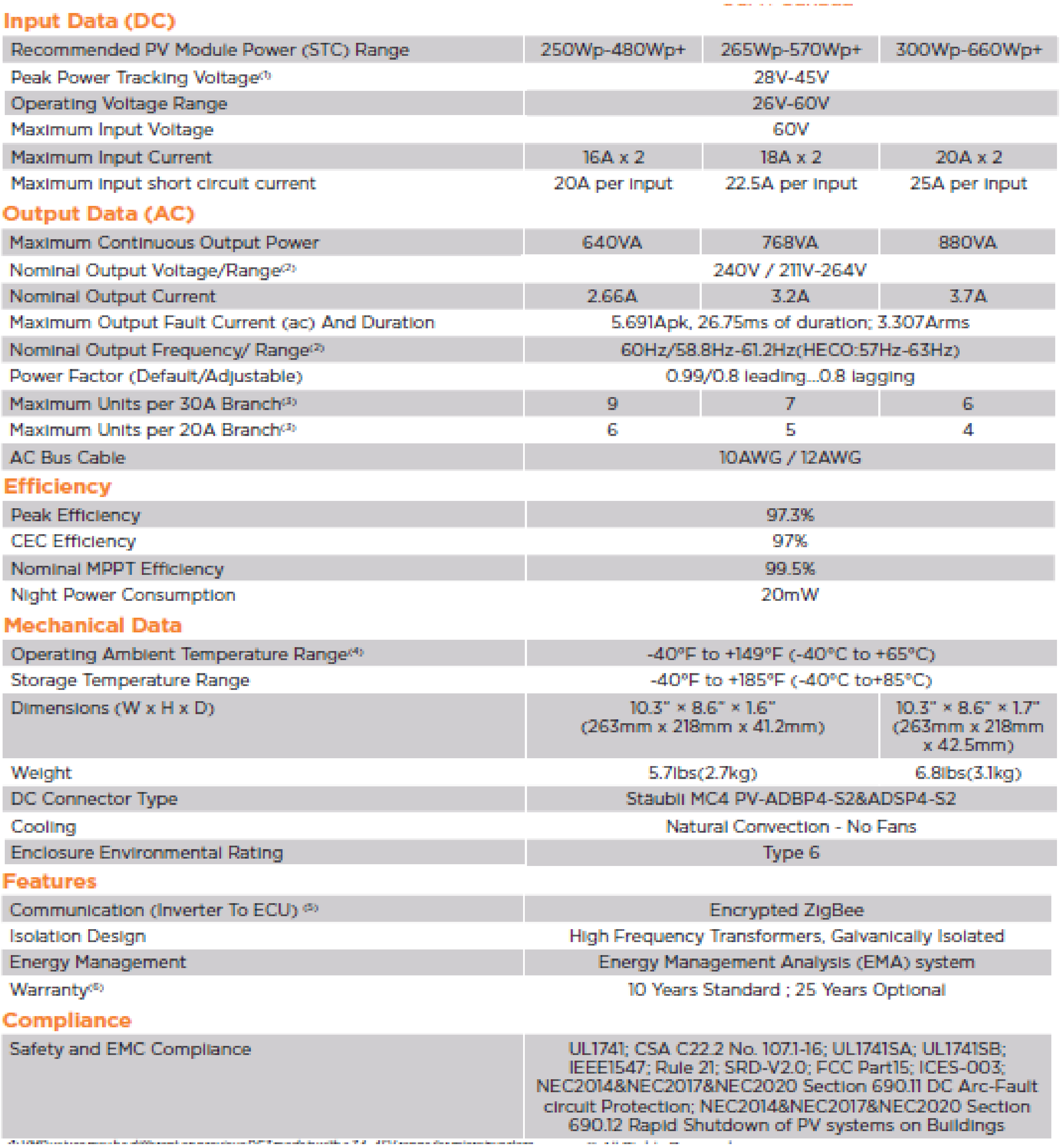
Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 11.408%

Payback Cash Flow (Payback Period = 4.2 years)

Detailed Photovoltaic	30 DC kW Nameplate	-33.03, 27.9
Commercial	$1.34/W Installed Cost	UTC +2



A.2. Data sheet for Inverter



Input Data (DC)

Recommended PV Module Power (STC) Range	250Wp-480Wp+	265Wp-570Wp+	300Wp-660Wp+
Peak Power Tracking Voltage(1)	28V-45V		
Operating Voltage Range	26V-60V		
Maximum Input Voltage	60V		
Maximum Input Current	16A x 2	18A x 2	20A x 2
Maximum input short circuit current	20A per input	22.5A per input	25A per input

Output Data (AC)

Maximum Continuous Output Power	640VA	768VA	880VA
Nominal Output Voltage/Range(2)	240V / 211V-264V		
Nominal Output Current	2.66A	3.2A	3.7A
Maximum Output Fault Current (ac) And Duration	5.691Apk, 26.75ms of duration; 3.307Arms		
Nominal Output Frequency/ Range(2)	60Hz/58.8Hz-61.2Hz(HECO:57Hz-63Hz)		
Power Factor (Default/Adjustable)	0.99/0.8 leading...0.8 lagging		
Maximum Units per 30A Branch(3)	9	7	6
Maximum Units per 20A Branch(3)	6	5	4
AC Bus Cable	10AWG / 12AWG		

Efficiency

Peak Efficiency	97.3%
CEC Efficiency	97%
Nominal MPPT Efficiency	99.5%
Night Power Consumption	20mW

Mechanical Data

Operating Ambient Temperature Range(4)	-40°F to +149°F (-40°C to +65°C)	
Storage Temperature Range	-40°F to +185°F (-40°C to+85°C)	
Dimensions (W x H x D)	10.3" × 8.6" × 1.6" (263mm x 218mm x 41.2mm)	10.3" × 8.6" × 1.7" (263mm x 218mm x 42.5mm)
Weight	5.7lbs(2.7kg)	6.8lbs(3.1kg)
DC Connector Type	Staubli MC4 PV-ADBP4-S2&ADSP4-S2	
Cooling	Natural Convection - No Fans	
Enclosure Environmental Rating	Type 6	

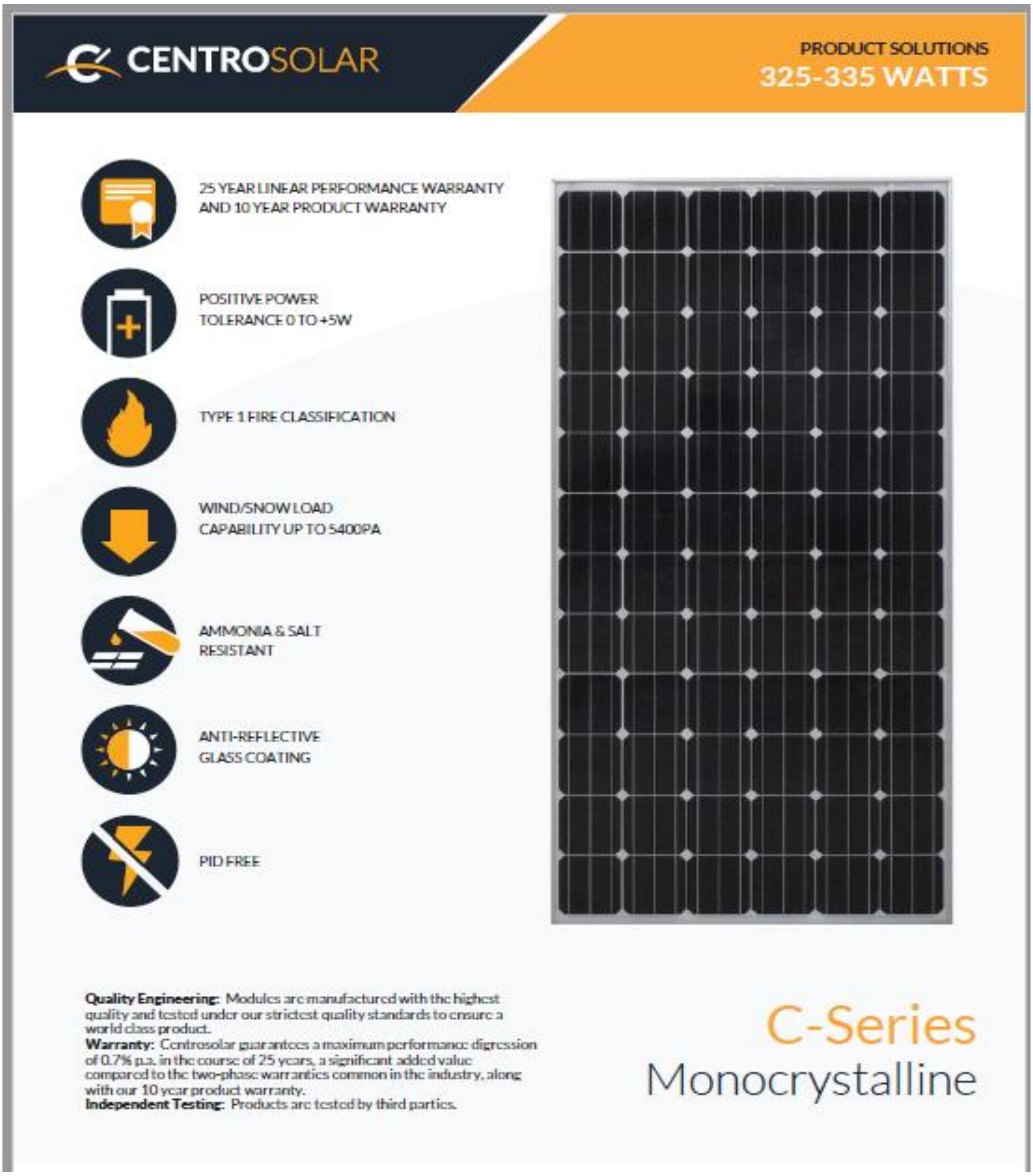
Features

Communication (Inverter To ECU) (5)	Encrypted ZigBee
Isolation Design	High Frequency Transformers, Galvanically Isolated
Energy Management	Energy Management Analysis (EMA) system
Warranty(6)	10 Years Standard ; 25 Years Optional

Compliance

Safety and EMC Compliance	UL1741; CSA C22.2 No. 107.1-16; UL1741SA; UL1741SB; IEEE1547; Rule 21; SRD-V2.0; FCC Part15; ICES-003; NEC2014&NEC2017&NEC2020 Section 690.11 DC Arc-Fault circuit Protection; NEC2014&NEC2017&NEC2020 Section 690.12 Rapid Shutdown of PV systems on Buildings

A.3. Data sheet for PV module



CENTROSOLAR

PRODUCT SOLUTIONS
325-335 WATTS

25 YEAR LINEAR PERFORMANCE WARRANTY AND 10 YEAR PRODUCT WARRANTY

POSITIVE POWER TOLERANCE 0 TO +5W

TYPE 1 FIRE CLASSIFICATION

WIND/SNOW LOAD CAPABILITY UP TO 5400PA

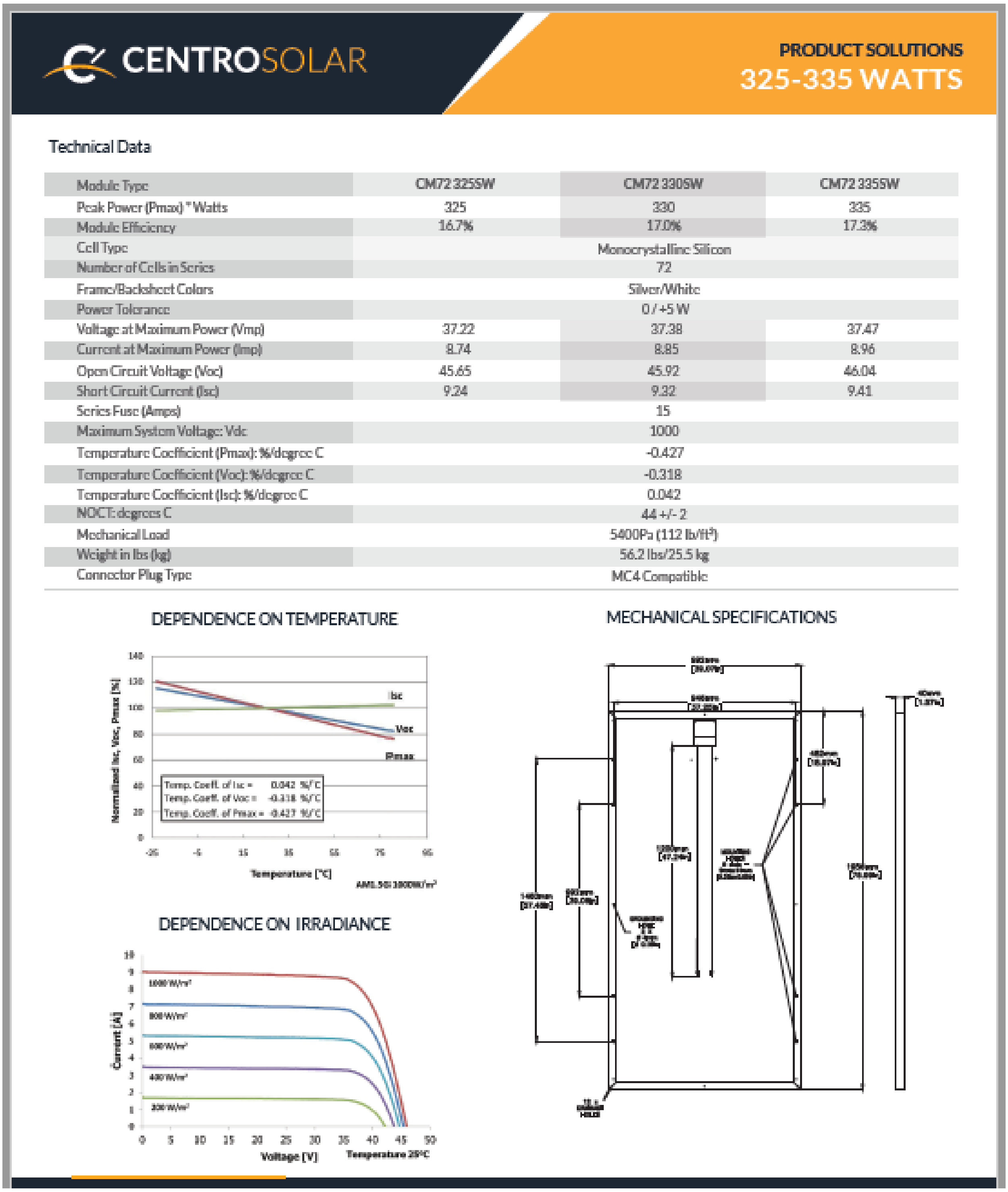
AMMONIA & SALT RESISTANT

ANTI-REFLECTIVE GLASS COATING

PID FREE

Quality Engineering: Modules are manufactured with the highest quality and tested under our strictest quality standards to ensure a world class product.
Warranty: Centrosolar guarantees a maximum performance digression of 0.7% p.a. in the course of 25 years, a significant added value compared to the two-phase warranties common in the industry, along with our 10 year product warranty.
Independent Testing: Products are tested by third parties.

C-Series
Monocrystalline



CENTROSOLAR

PRODUCT SOLUTIONS

325-335 WATTS

Technical Data

Module Type	CM72 325SW	CM72 330SW	CM72 335SW
Peak Power (Pmax) *Watts	325	330	335
Module Efficiency	16.7%	17.0%	17.3%
Cell Type		Monocrystalline Silicon	
Number of Cells in Series		72	
Frame/Backsheet Colors		Silver/White	
Power Tolerance		0 / +5 W	
Voltage at Maximum Power (Vmp)	37.22	37.38	37.47
Current at Maximum Power (Imp)	8.74	8.85	8.96
Open Circuit Voltage (Voc)	45.65	45.92	46.04
Short Circuit Current (Isc)	9.24	9.32	9.41
Series Fuse (Amps)		15	
Maximum System Voltage: Vdc		1000	
Temperature Coefficient (Pmax): %/degree C		-0.427	
Temperature Coefficient (Voc): %/degree C		-0.318	
Temperature Coefficient (Isc): %/degree C		0.042	
NOCT: degrees C		44 +/- 2	
Mechanical Load		5400Pa (112 lb/ft²)	
Weight in lbs (kg)		56.2 lbs/25.5 kg	
Connector Plug Type		MC4 Compatible	

DEPENDENCE ON TEMPERATURE

DEPENDENCE ON IRRADIANCE

MECHANICAL SPECIFICATIONS