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Feasibility analysis and optimization of new energy technologies for sustainable development

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by

Hagreaves Kumba

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Supervisor: Dr. O A Olanrewaju _____________ Date: ___________

DECLARATION

By electronically submitting this thesis, I, Hagreaves Kumba, solemnly affirm that the entire content contained within is of my own creation. This dissertation does not incorporate external data, images, charts, or supplementary information except where it is explicitly recognized as being sourced from external contributors. Furthermore, I confirm that this dissertation has not been presented for any degree or examination at any other university.

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ABSTRACT

Energy is essential for crucial development in Africa. The current electricity shortages or load shedding in South Africa show the country faces significant challenges in reaching positive economic growth. For industries to operate sustainably, an innovative mechanism must be tailored to solve the negative impacts of industrial energy use, particularly climate change. Even though fossil fuels generate the majority of produced electricity in South Africa, the country's potential for renewable energy sources is vast. In contrast, solar irradiance and wind offer considerable commercial potential.

New renewable energy resources are widely seen as a means to address the challenges of climate change and energy insecurity. They can be of crucial importance in developing a sustainable economy in the country. The study aims to show how renewable energy technologies can provide new economic opportunities, contribute to higher standards of living, and reduce the impacts of society on ecosystems, among other things. This thesis presents a feasibility analysis and optimization of new energy technologies by designing and simulating a grid-connected PV system for sustainable development.

The PVsyst software was used to simulate and optimize the PV system. The software was used to design and model the PV systems and to calculate the energy production, economic performance, and environmental impact. The researcher utilized simulation data to compare PV system performance in three scenarios and identify the optimal one.

Overall, the findings of this thesis suggest that grid-connected PV systems are a feasible and sustainable option to meet South Africa's energy needs. By implementing

the results and recommendations, the government, investors, and community can work together to develop and deploy a successful PV system that will benefit all.

WORK DONE IN SUPPORT OF THE RESEARCH

The author has published papers and attended a few conferences as part of his research.

1. **H. Kumba and O. A. Olanrewaju, “A REVIEW OF RENEWABLE ENERGY TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT: CASE STUDY-SOUTH AFRICA,” in SAIIE Conference, 2022, pp. 752–762, doi: https://doi.org/10.52202/066390-0052.**

2. **Kumba, H.; Akpan, J.; Twite, B.; Olanrewaju, O. Renewable energy adoption and integration in South Africa: An overview. In Proceedings of the 12th International Conference on Clean and Green Energy(ICCGE 2023), Xiamen, China, 25-27 May 2023; Institution of Engineering and Technology: Stevenage, UK,2023; pp. 74–87. https://doi.org/10.1049/icp.2023.1607**

CHAPTER 1 : INTRODUCTION

1.0 Introduction

A theoretical issue that has dominated the engineering field proves that energy is the lifeblood of any economy globally. Recent developments validate that energy is essential in any country because energy powers the nation from all economic sectors, including transport, manufacturing, tourism, and mining [1]. Energy is, therefore, an enabler of economic growth and stability. In South Africa, the Department of Mineral and Energy ensures the availability, affordability, reliability, and sustainability of energy resources while reducing environmental impacts, aligned with the target of Sustainable Development Goal number 7 [2]. South Africa's shift towards a sustainable green energy future will address the nation's energy crisis while simultaneously mitigating climate change by providing clean energy.

To address the topic of energy in 2015, the United Nations General Assembly adopted the Sustainable Development Goals (SDGs), a global blueprint to alleviate poverty, protect the environment, and ensure peace and prosperity. [3]. The idea consists of 17 goals and 169 targets, among which one of the targets for sustainable development is for everyone to have access to and supply reliable, affordable, and sustainable energy. Strengthening the linkages between green economy and sustainable development is crucial for achieving the ambitious targets of the Paris Agreement and the SDGs. A green economy in South Africa paves the way for achieving the SDGs and Paris Agreement goals, fostering sustainable development and climate action for a thriving future [4].

The available evidence suggests that globally, such as in emerging economies and developing countries like South Africa, there is a pressing necessity to accelerate progress towards achieving the Sustainable Development Goals (SDGs) while still meeting international climate change mitigation agreements [5]. Further evidence supports that more than 180 UN Framework Convention on Climate Change parties signed the Paris Agreement, committing the world to a transition to clean energy sources. Green economy initiatives aim to produce renewable energy resources, encourage local economies, create sustainable green jobs, and transition to a more pristine region with more reliable energy [6]. The concept of a green economy is multifaceted and encompasses a deep respect for nature, a focus on sustainable technological change, and a commitment to the careful and rational use of natural resources. This is also linked to eco-friendly industrial approaches, such as industrial symbiosis and circularity, which are crucial for achieving sustainability.The transition to a green economy is a complex and challenging process, but it is essential for achieving a sustainable future for all.

The policy promotes introducing and adopting renewable energy technology and meeting Sustainable Development Goal number 7, which supports environmentally sustainable development and resource usage. The use of renewable energy in South Africa will help eliminate the country's energy difficulties. As a result of the increasing global concern for environmental sustainability, particularly in South Africa, this research will focus on the green economy and sustainable development. Renewable energy is one of Africa's fastest-growing energy sources [7]. South Africa will have an energy sector that promotes economic growth and development by 2030, and the country's national energy sector development plan prioritizes investing in renewable energy infrastructure to promote economic growth and development by 2030 [8].

1.1 Background of the Problem

The current South African president Cyril Ramaphosa, recognized energy as the lifeblood of the economy. This vital sector creates jobs and generates value by extracting, transforming, and distributing energy goods and services [9]. It is now the stamina of every modern economy around the globe. Recently, there has been a power shortage in South Africa due to load shedding, poor energy usage, or lack of effective energy management, resulting in a rise in electricity tariffs and blackouts.

Therefore, for industries to thrive sustainably, creative procedures must be adapted to mitigate the negative repercussions of industrial energy use, including climate change.

The South African economy is affected by power supply uncertainties, which also have significant economic consequences for its potential to accomplish its industrial targets. South Africa's economic slump and falling economic growth are directly related to deteriorating power sustainability, as the industrial sector is the leading financial contributor to South Africa's GDP (Gross Domestic Product) [10].

Eskom (Electricity Supply Commission), the utility that distributes and supplies electricity in South Africa, is facing significant challenges in meeting the power supply demand in the country. This company controls power generation, transmission, and electricity distribution in South Africa, which is very tough, as supplies have also dropped due to poor generation [11]. Eskom faces many severe technical and financial challenges in tackling the electrical scenario. All productive economic sectors have suffered a significant decline in growth [12]. An unsustainable electricity supply in the country significantly limits the South African economic environment. Even though the electricity supply remained relatively consistent in 2015 and part of 2016, there is no guarantee that Eskom would be able to meet the ever-increasing power supply problems.

Eskom faces challenges with declining supply and reserves, implementing increased rationing to balance supply and consumption, and threatening the economy. The South African business environment is volatile due to an unsustainable electricity supply.

According to Eskom, the country's population is still growing, so electricity demand is increasing at 4% per year [13]. South Africa is experiencing a tremendous industrial and economic expansion, which, according to the Department of Energy [2], demands a large-scale and sustainable electrification program that meets energy demand. Eskom has now started steps to escalate power supply regulation to reduce the gap between power supply and consumption, triggering a power grid disruption. Jaglin et al. [14] claim that the energy deficit is due to a significant loss of critical skills, poorly maintained infrastructure or power stations, and an inadequate workforce.

It is believed that South Africa's electrical energy demands are expected to multiply as load shedding continues to impact all South Africans' lives significantly, interrupting business and putting further strain on families and communities [13]. The country has a 4,000 MW electricity deficit because of old power facilities, poor maintenance, policy stumbles, and the catastrophic implications of a state takeover [15]. Table 1.0 below shows the energy demand in South Africa forecasted for 2050.

Table 1: Energy demand in South Africa, extracted from [16]

		Demand in MW per year			
Sector		**2020**	**2030**	**2040**	**2050**
Industry	**Electric and Other non-thermal**	423 MW	560 MW	674 MW	752 MW
	Thermal	358 MW	433 MW	495 MW	532 MW
	Feedstock	179 MW	214 MW	237 MW	257 MW
Residential and Commercial	**Electric and Other non-thermal**	228 MW	392 MW	601 MW	839 MW
	Thermal	144 MW	122 MW	89 MW	72 MW
	Non-Commercial	49 MW	55 MW	61 MW	63 MW
Transport	**Public and Private**	819 MW	1 087 MW	1 383 MW	1 683 MW
TOTAL		**2 300 MW**	**2 863 MW**	**3 540 MW**	**4 198 MW**

South Africa heavily depends on fossil fuels, leading to concerns about its electricity supply system and energy policies. The energy share in the country is illustrated in Figure 1

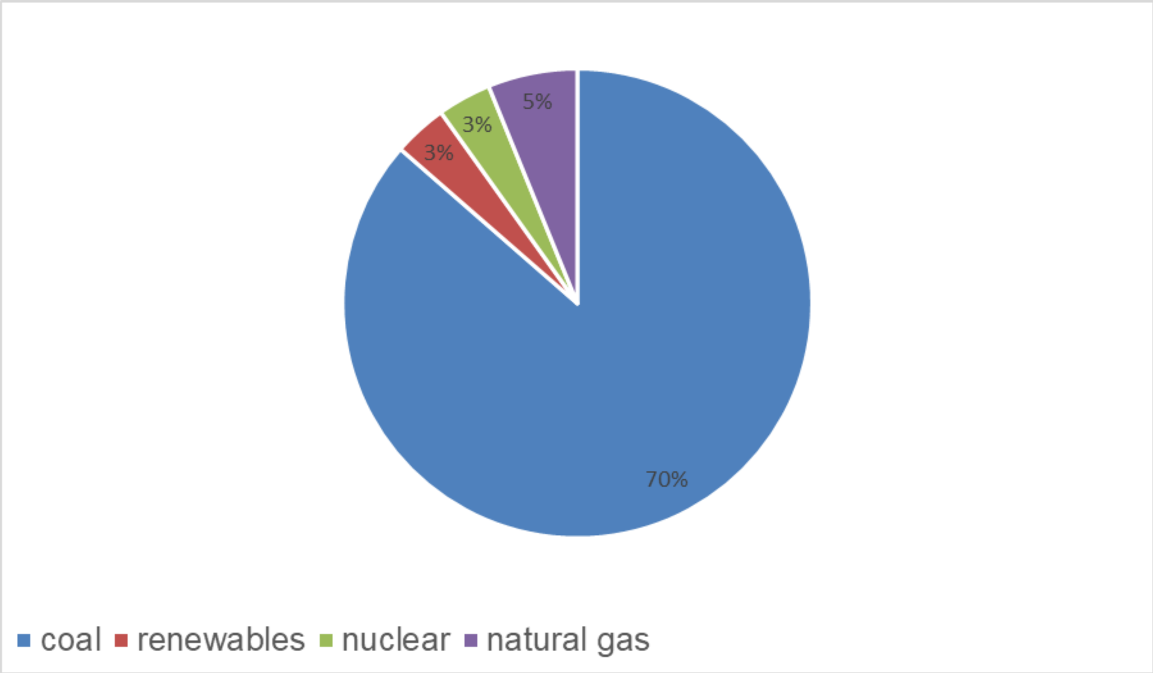


Figure 1: Energy share in South Africa extracted from [17]

Due to its availability and relatively inexpensive nature, coal is South Africa's primary energy source and is considered one of the cheapest in energy expenses [18]. However, according to Wagh and Kulkarni [19], the energy sector accounts for nearly 80% of total emissions. Total emissions refer to releasing pollutants or substances into the atmosphere, typically due to human activities, natural processes, or industrial operations such as carbon dioxide, sulphur dioxide, carbon monoxide, methane particulate matter, and many more. Of this, 50% stems from electricity generation in power stations, presenting a significant environmental challenge

This highlights several concerns for South Africa :

1. High Reliance on Fossil Fuels: The energy sector, primarily coal-fired power plants, is responsible for a significant portion of the nation's total emissions.
2. Environmental Impact: Burning fossil fuels releases greenhouse gases, contributing to climate change and associated problems like extreme weather events.

3. Sustainability: Fossil fuel resources are finite, and their continued reliance raises long-term energy security and sustainability concerns.

South Africa is the seventh-largest producer of coal and the fifth-largest coal exporter. For South Africa to play an essential role in mitigating global climate change, there needs to be a reduction in the use of coal from coal-fired power stations, thus resulting in the introduction of renewable energy [20]. A key determinant in the type of renewable energy in which Eskom will invest is its strong emphasis on ensuring people have access to affordable electricity.

Murray et al. [21] concluded that replacing fossil fuels with renewable energy minimizes greenhouse gas emissions contributing to climate change. The development and use of renewable energy technologies not only tackle climate crisis but also provide energy security and employment to the people [18]. The potential renewable energy sources in South Africa are sun, wind, biomass, geothermal, hydropower, waste-to-energy, and tidal (wave) energy, and their potential varies from province to province [22].

South Africa developed a feasible regulatory framework to increase the amount of renewable energy in the national energy mix. South Africa established and managed the Renewable Energy Independent Power Producer Procurement Initiative (REIPPP) to ensure the effective development and application of renewable energy for electricity generation [23] [24]. This resulted in more electricity being added to the grid through renewable energy, making renewable energy a reality in the country, though at a small percentage. The procurement scheme cannot only promote a whole new industry for South Africa and cut greenhouse gas emissions by greening grid electricity, but it also aims to address economic development on the local level.

The current South African policy encourages the growth of renewable energy technologies. However, renewable energy development is still small, as shown in Figure 2 below. It can be noted that renewable energy consumption has increased over the period from 2013 from 467 MW to 5735 MW in 2021. This means that from 1 November 2013 to 31 December 2021, 3 023 MW of wind, 2 212 MW of solar PV, and 500 MW of Concentrated Solar Power (CSP) become operational in South Africa

Due to the adoption of new energy policies in South Africa, Eskom's increased electricity prices have made renewable energy a more cost-effective alternative.

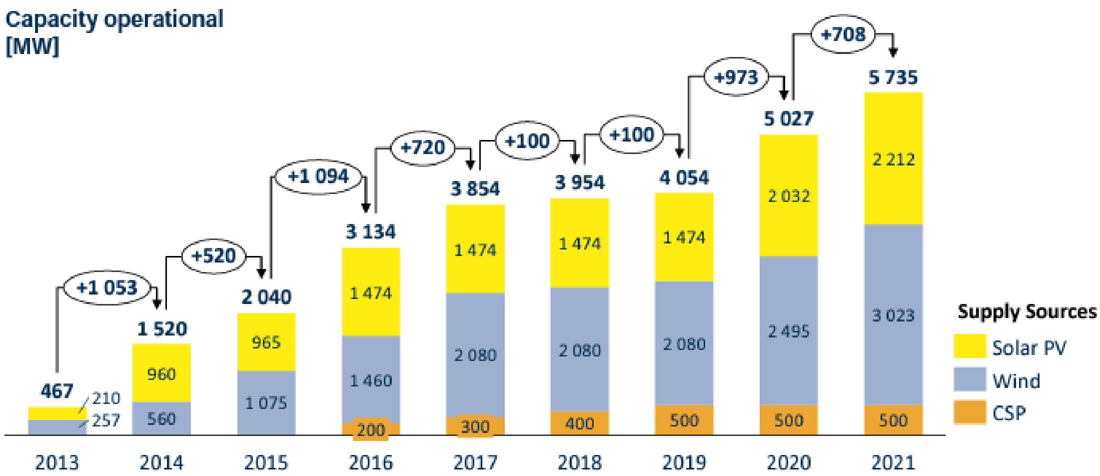


Figure 2: Renewable Energy in South Africa 2013-2021, extracted from [25]

Eskom's generation division comprises 36,441 MW of coal-fired stations, 1,860 MW of nuclear power, 2,409 MW of gas-fired stations, 600 MW of hydro, and 2,724 MW of pumped storage, including the recently commissioned solar plants [26]. The current energy statistics in South Africa state that coal-fired power stations dominate the industry; as of 2021, South Africa energy statistics list that coal still dominates about 70 percent, or 42,000MW, of the nation's electricity generated via coal-fired power stations.

South African Government, with determination and pursuing some hard work to contribute to sustainable development in the future, issued a White Paper on renewable energy, which set a target aim of 10,000 GWh of renewable energy production by 2013 [27]. The White Paper on Energy Policy was designed to clarify government policy for the future decade regarding sustainable energy supply and use. The Renewable Energy Independent Power Producer Procurement Programme has delivered an inspirational investment platform from the private sector into the renewable energy market. However, this target was not reached, and the latest version of the IRP 2019 outlines the country's energy mix targets, including the goals for renewable energy [28]. According to the Eskom report, only 6 280MW is installed in South Africa [29].

Table 1.2 illustrates the total renewable energy currently installed as of 2022, highlighting the South African reality concerning renewable energy utilization.

Table 2:Renewable energy capacity installed in 2022, extracted from [29].

Renewable Indicator	Current Installed Capacity (MW)
Wind (Eskom + IPP)	3 442
PV	2 287
CSP	500
TOTAL	**6 280**

Renewable energy is gaining traction as a compelling power source in South Africa, offering a reliable, affordable, and sustainable solution for the country's energy needs. The figure above illustrates the current installed capacity of renewable energies from 2021-2023. The current installed capacity is approximately 6280 MW, which includes wind, solar, and other sources such as biomass. This figure is expected to increase from this year to 2030, with more adoption and expansion of the renewable energy sector. For 2022, much of the renewable energy was integrated into the feed mix to provide power since Eskom's coal-fired power is experiencing downtime.

It is not only power cuts or load shedding that threaten the South African economy, but also the escalating electricity prices. A review by Aliyu et al. [18] states that implementing new energy technologies and researching the feasibility of renewable energy patterns in South Africa is essential for sustainable development and economic growth. This project also examines the nature of energy management strategies, energy efficiency, and feasibility of new energy technologies in the study area, as well as the challenges and reasons for their adoption and implementation in the South African power sector.

1.2 Problem Statement

Regionally in SADC, according to the SADC power pool, electricity demand in Southern Africa could increase 8–14 times by 2070 [30]. The electricity power sector aims to transition from fossil fuels to renewable energy technologies, and South Africa is trying to adopt this transition and catch up with world innovation trends.

Several authors have recognized that an economy that lacks energy, particularly electricity, cannot serve the interests of any nation and is doomed to fail [18]. South Africa's economy is growing; hence, energy uptake is also in demand. According to the World Bank report [7], the South African economy is energy-intensive, and the demand is increasing since the country is also industrializing. In South Africa, population growth has outpaced energy production, overwhelming existing energy resources and leading to poor energy supplies, consequently hindering sustainable development. This has also been explored in prior studies by a few researchers, who state that by 2030, we anticipate a rise in energy demand by 30% because the population is also increasing [31]. However, conventional energy sources are currently used to power the industry and contribute to greenhouse gas emissions, which affect climate change. South Africa faces challenges in meeting its energy needs while ensuring sustainable development. The government must explore and optimize new energy technologies that can provide reliable and affordable energy while minimizing the environmental impact.

In light of the challenges faced by South Africa in achieving sustainable and reliable energy sources, there is a need to conduct a feasibility analysis. This analysis aims to fill existing gaps in our understanding of the viability of different renewable energy options and identify the most suitable ones for South Africa's unique context. Key challenges include government policies, technological infrastructure, and financial constraints, and addressing these gaps is crucial for successfully implementing a sustainable and efficient renewable energy strategy.

The potential for solar energy production in South Africa is significant, but several barriers exist, including weak institutional arrangements, strict regulations, and a lack of skills and policy certainty.

To address these challenges, there is a growing interest in optimized battery energy storage systems for solar PV applications, particularly in the context of load shedding.

Additionally, the economic viability of PV hybrid power systems in different climatic zones in South Africa has been explored, with promising results [32]. These studies collectively highlight the need for a comprehensive approach to overcoming the barriers to solar energy production in South Africa, including addressing policy challenges, investing in energy storage solutions, and exploring hybrid power systems.

1.3 Aim

This study analyses the feasibility and optimization of renewable energy technologies, focusing on their applicability and potential sustainable development in South Africa.

1.4 Objectives

- To conduct a comprehensive feasibility analysis of new energy technologies in South Africa for sustainable development.
- To optimize the selected renewable energy technology using PV Syst software.

1.5 Alignment of research objectives and research activities

Research Objective	Research activities

• To conduct a comprehensive feasibility analysis of new energy technologies in South Africa for sustainable development.	• This objective evaluates the practicality and viability of implementing new energy technologies in South Africa to promote sustainable development. • Feasibility analysis of different renewable energy options and identifying the most suitable ones for South Africa's unique context. • Review and evaluate their feasibility based on cost, implementation policies, and barriers. • Providing an in-depth understanding of the feasibility of different energy technologies and their potential contributions to sustainable development in South Africa
• To optimize the selected renewable energy technology using PV syst software.	• Identifying opportunities to optimize the implementation of new energy technology in South Africa to maximize their positive impact on sustainable development • Designing and Improving the performance of renewable energy technologies, using different strategies such as energy storage, innovative grid technologies, and digitalization, and developing a

	roadmap for their implementation

1.6 Methodology

The author conducted a comprehensive review of existing literature and research by other scholars on the feasibility and optimization of renewable energy. This review included an analysis of achievements and outcomes reported by other authors. Additionally, the researcher examined methodologies employed by previous researchers in addressing feasibility issues and identified challenges they encountered. The evaluation and identification of gaps in the current energy scenario in South Africa were based on a thorough review of relevant literature and the author's published research.

After reviewing the gaps in the current energy scenario, the author designed a grid-connected PV system using the PV Syst software. The system was designed, simulated, evaluated, and optimized under the desired working conditions. Economic and environmental evaluations were also conducted to make informed decisions about the system's design, installation, and operation.

1.7 Rationale

This study is motivated by the extreme power shortage, in which demand exceeded availability, leading to continuous electricity disruptions. The project aims to generate awareness and knowledge about renewable energy adoption and help improve the issue. The choice of PV Syst software in designing grid-connected systems in South Africa is driven by various factors. Yadav et al. [33] underscore the significance of performance analysis, focusing on system production, output power losses, and performance ratio, highlighting limited research on these factors. Additionally, few authors emphasized the importance of optimal design and sizing, considering techno-economic factors such as net present cost and cost of energy; therefore, this research will try to bridge the gap and put on the factors.

Load shedding in South Africa shows significant challenges in reaching positive economic growth. Therefore, energy optimization is needed to tackle the energy crisis and advise how to proceed. For industries to function sustainably, it is essential to develop innovative mechanisms specifically designed to address the adverse consequences of industrial energy consumption, focusing on mitigating the impacts of climate change. Enhancing industrial energy efficiency and management is a highly effective approach to reducing the adverse effects of industrial energy use and bolstering these industries' overall productivity and competitiveness. This study focuses on green economy and sustainable development.

1.8 Organization of the Thesis

The study is structured into five chapters, as illustrated in Table 3 below.

The table shows a flow diagram of the thesis, which is designed to illustrate the flow of knowledge as well as the contributions of each chapter to the research objectives. The following is a description of how the research study developed:

Chapter 1:

The first chapter of the research provides an overview of the thesis. The background of the problem focuses on problem definition, research objectives, and methodology, addressing the procedure for achieving these objectives. This will provide a comprehensive overview of the research to readers, including the significance of the study.

Chapter 2:

The chapter reviews and evaluates recent literature on renewable energy technologies. The chapter also presents literature gaps and links the findings to the study's objectives. The chapter gave the author an overview of past research on the problem and how to solve it appropriately.

Chapter 3:

This chapter presents the methodological approach of the research. The chapter describes how the research was conducted to address the research objectives, as informed by the literature review. The introduction of software is part of the chapter to analyze and solve the problem.

Chapter 4:

This chapter presents and analyses the results and findings. The results are analysed in this chapter. Economic and Environmental analysis is also presented, evaluating the viability of the study. In this section, the results are thoroughly scrutinized and interpreted to provide insights into the study's objectives. The findings of this study are significant, and their implications are discussed in detail.

Chapter 5:

In this chapter, the study's findings are summarized and concisely presented. The conclusions drawn from the results are then discussed, highlighting the study's implications and significance in the field of research. Recommendations for future research are provided based on the limitations and gaps identified in this study. These recommendations aim to guide researchers in future studies and contribute to advancing knowledge in the field.

Table 3: Summary of the study

List of chapters	Information covered
CHAPTER 1	• *Introduction* • *Problem Statement* • *Aim and Objectives* • *Rationale of the study*
CHAPTER 2	• *Literature Review* • *Evaluating Literature gaps*
CHAPTER 3	• *Methodological approach* • *PV Syst-Software*
CHAPTER 4	• *Results* • *Evaluation and Analysis of Findings*
CHAPTER 5	• *Conclusion and Recommendations*

1.9 Conclusion

This chapter offers a comprehensive overview of the study, encompassing pertinent background information, its objectives, and the rationale for conducting this research. Subsequently, the following chapter will delve into a literature review that explores energy-related concerns in South Africa while also highlighting the potential of the emerging renewable energy sector to foster empowerment and job opportunities.

CHAPTER 2 : LITERATURE REVIEW

2.0 Introduction

In recent years, the urgency to achieve sustainable development has intensified as the world grapples with mounting environmental and economic challenges, and sustainable development has gained growing significance worldwide. An essential component of sustainable development is developing and implementing innovative energy technologies that may effectively reduce carbon emissions and boost energy efficiency. Nevertheless, before new energy technologies can be widely used, they must undergo feasibility studies and optimization to ensure they are economically, ecologically, and socially feasible.

This chapter will review and aim to offer a comprehensive overview of the current state of knowledge on the topic under study, gathering and integrating relevant empirical information from previous studies. Reviewing the existing literature, this chapter will give an in-depth overview of the potential for renewable energy development in South Africa, including current infrastructure, policies and regulations, technological advancements, and economic feasibility.

2.1 South Africa Energy Situation Overview

According to the World Bank, South Africa has the highest energy demand in Africa and is one of the largest electricity producers in the world [34]. Despite its vast natural resources, South Africa faces severe challenges to sustainable development in the energy sector. According to Solomon et al. [35], South Africa faces an erratic power supply, resulting in persistent load shedding owing to ageing in most coal-fired power plants. The demand for electricity in South Africa is increasing by 4% annually, driven by industrial and economic growth [17]. The South African government requires a stable electrification program to meet this demand. As illustrated below, coal has maintained its status as a primary energy source owing to its widespread availability and cost-effectiveness.

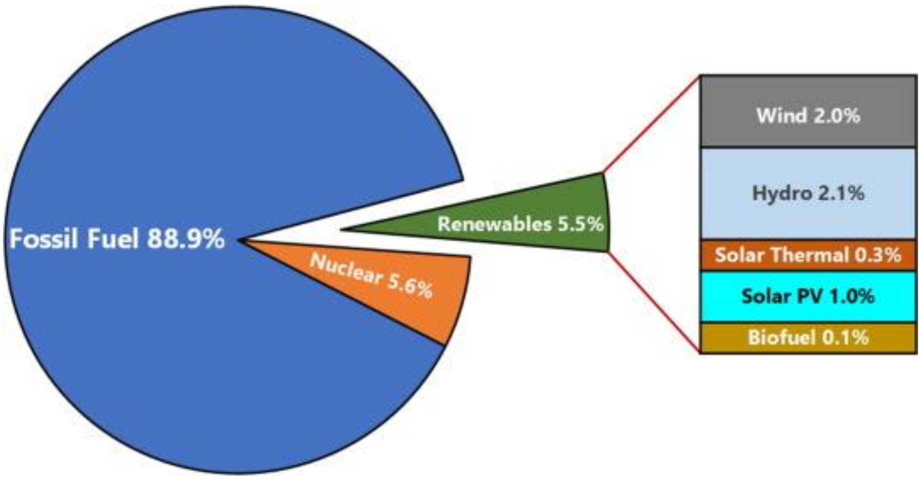


Figure 3: The Energy Mix in South Africa, extracted from [31]

About 70% of electricity in South Africa is generated from coal-fired power plants. As previously mentioned, in 2016, coal, serving as the primary energy source, was complemented by various other sources, such as nuclear, crude oil, natural gas, renewables, and waste energy, which contributed significantly to the country's energy mix. South Africa's population growth has led to an increased demand for energy. Therefore, the Department of Energy is implementing policies to ensure energy security by maintaining a steady supply. Additionally, the department is working towards providing universal access to energy by supplying power to everyone in the country, regardless of their geography or economic condition.

The South African energy landscape is dominated by coal-fired power stations owned and run by Eskom, the state-owned power provider [14]. These power plants use coal of various grade requirements to create and distribute power to different parts of the country. Eskom's production mix comprises 14 coal-fired power units, providing over 70% of the country's electrical output.

Apart from coal-fired power generation, South Africa also operates the only nuclear power plant on the African continent, which is owned and operated by Eskom. According to Van Wyk [36], South Africa is one of the few countries with a nuclear research reactor and has Africa's most advanced nuclear energy and technology. The Koeberg nuclear power plant, located in the Western Cape region, has a capacity of about 1,860 MW. The dominance of coal-fired electricity production and the severe environmental consequences of its operation have prompted the South African government to seek alternative energy sources, such as renewable energy, to diversify the country's energy mix and minimize its carbon footprint [37]. The government has established ambitious targets to augment the proportion of renewable energy in the overall energy mix. Consequently, various renewable energy initiatives, including wind and solar power projects, are underway nationwide.

Furthermore, various African studies have suggested using cleaner, sustainable, and environmentally friendly energy sources, such as renewables, to reduce the environmental impact of energy production and modernize the energy industry [38]. In South Africa, several studies have investigated the relationship between energy consumption and economic growth [12, 17]. In this context, feasibility analysis and optimization of new energy technologies for sustainable development in South Africa are crucial, thus analyzing the potential of integrating renewable energy sources into South Africa's electricity grid. Renewable energy projects must be evaluated for feasibility and optimized to maximize their potential performance while reducing costs and minimizing environmental impacts.

2.2 Environmental and health impacts of coal-fired power generation

Coal plays a vital role in South Africa's energy sector. Coal is one of the primary raw materials fed in the power stations to produce electricity. According to the IEA report, they forecasted that in 2040 coal will still have about 40% of the electricity nexus. To comprehensively review the effects of coal mining and coal-fired power plants in developing countries, Habib et al. [32] studied the effects of coal-fired plants on the environment, including pollution dispersion, eco-toxicological impacts, human health risks, and socioeconomic factors. The aim was to provide a comprehensive overview of the situation within the power stations. A growing body of research has examined how people adopt and address concerns about climate change, energy security, and sustainable development [39] [40].

Coal-fired power stations are one of the significant sources of greenhouse gas emissions, including carbon dioxide, contributing to climate change. Current research proves that coal-fired power stations can emit other harmful pollutants such as sulphur dioxide, nitrogen oxides, particulate matter, and mercury. These pollutants can significantly negatively affect the environment and human health [41].

Coal-fired power station emissions in South Africa cause respiratory, cardiovascular, and cardiopulmonary diseases and, tragically, lead to premature deaths. Globally, fossil fuel pollution is responsible for one in five deaths, and the annual cost of the health impacts of fossil fuel-generated electricity in the United States is estimated to reach $886.5 billion [41]. The future use of fossil fuels for electricity generation and transport is expected to exacerbate these issues, with an estimated 48,000 avoidable deaths by 2030, primarily in South Africa [42].

In recent years, many countries like Turkey have taken steps to reduce their reliance on coal-fired power stations and transition to cleaner energy sources such as renewable energy [43]. Detailed examination by Vardar et al. [44] discusses the need for policies to support renewables and reduce emissions and the research and development of clean coal technologies. It also highlights the negative environmental impacts of coal-fired power plants in Turkey and their potential health effects.

Few authors have also suggested that coal-fired power stations significantly contribute to environmental emissions, but transitioning to alternative new energy technologies should have economic and practical implications [39, 45]. To elucidate, while renewable energy sources produce fewer emissions, they are not yet economically feasible to entirely replace coal. Overall, developing countries such as South Africa rely heavily on coal for economic growth; therefore, reducing emissions from coal-fired power plants should be balanced to ensure access to reliable and affordable electricity.

Numerous studies have been undertaken in the same sector of coal-fired power stations and their environmental consequences. Coal-fired power plants have been the subject of innumerable studies exploring their ecological impact in various countries, including India and China. The available evidence from the research done in India and China seems to conclude that coal-fired power plants constitute a substantial source of air pollution and greenhouse gas emissions in the country [46, 47]. However, some studies have also taken a broader view of the issue, indicating that the economic benefits of coal-fired power outweigh the negative impacts [48] [49] [50]. The findings from these studies demonstrate the urgent need for cleaner, alternative energy sources. It is essential to take proactive measures and shift towards cleaner energy alternatives to address the negative environmental impacts of coal combustion.

Although coal-fired generators have significant environmental implications, they remain vital in many countries and areas. The move to renewable energy sources may be challenging and costly and may not be feasible for many regions. Moreover, renewable energy sources such as wind and solar power can be unpredictable and may not provide a consistent energy supply, particularly in places with fluctuating weather patterns. Consequently, it is vital to establish a balanced strategy that considers communities' environmental and economic demands when examining the role of coal-fired power plants and renewable energy sources. Ultimately, the goal should be to balance the need for energy with environmental responsibility and to work towards a more sustainable future for all.

The Republic of South Africa is the globe's seventh biggest manufacturer of coal, and nearly 85% of South Africa’s power is produced from coal, resulting in degradation of the environment and significant carbon emissions. However, South Africa has great potential for renewable energy technologies; therefore, to deal with the energy crisis in the country, the government adopted various policies to enable renewable energy generation in the energy mix. To adequately address and explain the issue of policies, Jain et al. [51] studied the implementation and adoption of sustainable energy sources in South Africa, providing information about potential renewable power supply and development in the nation at large by examining projects and policies established by the government and energy regulators. The authors highlighted the benefits of implementing renewable energy, such as job creation, foreign investment, and improved quality of life for local communities.

While South Africa relies heavily on coal for electricity and faces challenges in distributing centralized power to remote areas, it is crucial to consider the practicality of transitioning to environmentally friendly energy sources, including wind and solar energy. These sources have great potential and require significant investments in infrastructure, including new power grids and storage facilities. In addition, the intermittent nature of solar and wind power means that they may not always be reliable energy sources, particularly during periods of low sunlight or wind. Therefore, it is crucial to carefully weigh the potential benefits and drawbacks of transitioning to renewable energy sources before significantly changing the existing energy infrastructure in South Africa.

2.2.1 Energy Insights-South Africa

The research on energy use in South Africa has highlighted the need for improved efficiency and sustainability. A range of studies have provided insights into the energy sector in South Africa [52]. The country has been experiencing power cuts since 2008 due to insufficient power generation capacity, negatively impacting the economy, as mentioned in the problem statement [53]. Analyzing and examining the electricity demand at the provincial level is important for addressing energy sector issues and improving electricity access [16]. The paper examines the determinants of electricity demand in the nine South African provinces from 1995 to 2019, highlighting regional intervention and policy implementation potential.

The transition to renewable energy sources can help to solve poverty, unemployment, and inequality issues in South Africa. South Africa can potentially turn solar and wind energy into the country's primary power sources, offering a low-cost and decarbonized electricity system that can drive economic growth and create new export opportunities. Victoria et al. [54] underscored the importance of renewable energy consumption in Sub-Saharan Africa, including South Africa, and the need for international collaboration to address developmental challenges. South Africa's future energy mix is transitioning from coal to renewable energy sources such as solar and wind [40]. The integration of renewable energy into the national grid requires increased grid flexibility and strengthening to meet the country's power demand.

Most developing countries, such as South Africa, strive to develop their current energy sources further, and renewable energy sources have been established as a key priority area. Brent [55] argued that energy is critical for long-term development and prosperity; a country must adopt a multi-energy strategy and enhance the share of environmentally friendly and domestic energy sources. Energy efficiency measures are commonly considered a top priority in reducing carbon dioxide emissions and can give businesses a competitive advantage [56]. Despite this, nearly half of the cost-effective energy efficiency improvements proposed by industry are never adopted.

T Mezher and Tsai [57] proposed that developing countries suffer from energy shortages due to supply limitations and insufficient infrastructure, negatively impacting their economies. Moreover, the practice of energy management has the potential to bolster a nation's energy security and serves as a catalyst for fostering a competitive edge for industries. Additionally, the sustainable development model presented by the Department of Energy acquires around 40% of its potential carbon reduction from energy efficiency. Researchers have reviewed various aspects concerning energy management and renewable energy in the past decades for feasibility and sustainable development [58]. Several elements that have attracted attention include.

- Significance of energy management and renewable energy
- Sustainability of energy efficiency and new energy technologies
- Green economy and financial aspects
- Education about new energy technologies
- Environmental and technological development
- Government policies regarding energy development
- Energy consumption review

Industries, governments, and non-governmental organizations are all focusing on energy management since it may be a reasonably quick and cost-effective solution for businesses to save money and cut carbon emissions [59]. As a result, industrial energy management is primarily regarded as a critical component of worldwide efforts to combat climate change. Electricity demand has risen significantly in South Africa due to population growth, and this trend will continue in the future; consequently, industrial energy management is widely recognized as a significant contributor to worldwide efforts.

This aligns with L.Kitzing [60], who finds the same when evaluating that renewable energy can help people and communities escape poverty while reducing greenhouse gas emissions. Goal 1 of the United Nations' Sustainable Development Goals is "no poverty," and Goal 2 is "clean and cheap energy" [3]. The possible implications of renewable energy on poverty reduction are also explored in depth from three perspectives: socioeconomic, environmental, and renewable energy performance. Other studies indicated that renewable energy technologies are increasingly being utilized in South Africa, but there is still a gap since the demand for electricity has increased rapidly [17].

S. Khan et al. [1] highlighted that fossil fuels are being consumed at an alarming rate, and energy from renewable sources is the best possible substitute. The link between renewable energy usage and long-term economic development in emerging and developing economies has been evaluated [61]. The results show a positive correlation effect of renewable energy technologies on economic growth, resulting in a green economy for selected Asian and most African countries; the findings revealed a significant long-run link between renewable energy consumption and economic growth.

South Africa has been continuously impacted by ongoing concerns about the current state of its power systems, structures, and energy policy, which resulted in the 2007–2008 energy crisis and subsequent shortages throughout the next decade. South Africa's electrical "load shedding" in 2007/2008 was poorly prepared. It also points out that South Africa's economy has been harmed by chronic underinvestment in the country's energy industry, which has resulted in growing power prices and a scarcity of capacity during peak demand periods, leading to demand rationing [62] [63].

The relationship between energy management and renewable energy versus unemployment has caused much ongoing debate around the globe, and South Africa is not an exception [64]. Sharma [56] examined the impact of renewable energy on job creation in India using a neo-Keynesian CGEM Three-ME model. The author concluded using Retscreen Software that the transition to renewable energy may create close to 50,000 jobs by 2030, thus contributing to GDP.

Several studies have been conducted to identify the ideal balance between fossil fuels and renewable energy sources when assessing sustainability and feasibility [65]. The feasibility analysis used the RETScreen modelling program [66]. This model compares the energy production of various clean and renewable technologies, considering life-cycle costs and reductions in greenhouse gas emissions (GHG). It also does a standardized and integrated financial, sensitivity, and risk analysis to establish the project's financial feasibility and risk.

According to the literature reviewed, renewable energy is the next promising energy source [67]. Solar energy has been pursued by developed countries such as Germany, the United States, and China. For developing countries, Temene et al. [62] discovered a long-run association between economic growth and renewable energy consumption.

The general goal of the thesis, based on the literature reviewed above, is to align and complement this research by looking at whether and how renewable energy technologies and energy management in the supply mix affect the South African economy. Finally, this research is unique in that it takes a holistic approach to renewable energy feasibility by combining an investigation of links between energy, economy, and technology with energy modelling software.

2.3 Government policies regarding Renewable Energy in South Africa

South Africa has a coal-driven energy sector. The state encounters significant energy-related challenges, primarily from inadequate infrastructure and the absence of suitable technologies to harness available energy resources effectively, particularly emerging renewable sources. The renewable energy sector is still tiny but growing. South Africa has implemented some support frameworks and policies for renewable energy to achieve renewable energy generation.

2.3.1 White Paper on Renewable Energy (1998-2003)

The government's overarching vision of the role of renewable energy within its energy economy entails fostering an environment in which modern renewable energy sources expand their share of the energy consumed. This ensures affordable and widespread access to electricity across South Africa, advancing sustainable development and environmental preservation goals.

According to the South African Constitution, the Renewable Energy Policy of the South African White Paper outlines the country's policy and regulatory framework for renewable energy [68]. The publication of the White Paper on Energy 1998 aimed to provide a coherent and insightful glimpse of the future of energy in South Africa [69]. The document was comprehensive and stated issues regarding using clean energy technologies and implementing renewable energy. The policy document pledged ‘the government support for developing, demonstrating and implementing renewable energy sources for both small and medium industries. However, it did not clearly state the objectives and specific targets. Therefore 2003, the Department of Minerals and Energy released another White Paper on Renewable Energy [70], focusing on long-term targets and specific objectives. The policy highlights about 10 000GWh generation by 2013. The main benefits of the White Paper were targeted at rural communities, those far away from the national grid, and those not connected, such as remote schools, rural clinics, and small factories.

The White Paper emphasized promoting investment in South Africa's renewable energy sector while adhering to sustainable development principles [71]. In evaluating the White Paper, a study by Mukonza et al. [72] explores South Africa's plans to boost wind energy for energy security and sustainable development. It evaluates the existing policies, institutions, and programs to foster onshore wind energy adoption. This analysis demonstrates South Africa's effective establishment of essential policies, institutions, and programs to facilitate the growth of wind energy. Although South Africa has enacted policies and programs to support wind energy, implementation challenges and limitations persist. These hurdles may include funding constraints, community capacity for participation in wind projects, and the political prioritization of traditional fossil fuels over renewable energy sources.

2.3.2 The Integrated Resource Plan (IRP) and Renewable Energy Independent Power Producer Program (REIPPP)

The South African government seeks to improve and strengthen self-sufficient energy sources such as solar generation, self-generation, and co-generation, as outlined in the 2010 Integrated Resource Plan (IRP) [73]. This plan serves as a long-term blueprint for electricity generation and infrastructure in the country.

The initial Integrated Resource Plan (IRP) of South Africa refers to a comprehensive energy blueprint that outlines the country's long-term electricity generation and energy mix strategies [74]. This plan serves as a roadmap for meeting the nation's energy needs while considering factors such as sustainability, affordability, and security of supply. The IRP sets out the South African government's strategy for establishing new generation and transmission capacity for the country from 2010 to 2030.

The listed objectives of the IRP are to make electricity inexpensive, reduce greenhouse gas emissions, and reduce water usage. The government has developed a Renewable Energy Independent Power Producer Program (REIPPPP) to attract more independent power producers (IPPs) to the renewable energy sector [75]. The REIPPP program, part of the energy mix outlined in the National Development Plan, aligns with the current South African policy that promotes renewable electricity generation [75]. The initiation of the REIPPP bidding process has expedited the widespread implementation of renewable energy projects.

The South African government introduced the Renewable Energy Independent Power Producer Procurement Program (REIPPPP) in 2011 to promote renewable energy generation through public-private partnerships. It has attracted significant foreign investment in climate change mitigation in South Africa. The program aimed to accelerate the country's decarbonization process by driving the uptake of renewable energy [76]. The development of the REIPP procurement program has been a positive illustration of successful policy and regulatory learning processes. However the program has also been criticized for its limited impact on socio-economic development in local communities. To add, despite the program's success in stimulating private sector investment, the majority of electricity in South Africa is still generated from coal by state-owned utility Eskom.

2.3.3 Other Energy Policies in South Africa.

2.3.3.1 Renewable Energy Development Zones (REDZ)

Renewable Energy Development Zones in South Africa refer to specific areas identified by the government for the development of renewable energy projects. These zones are strategically chosen based on their potential for renewable energy generation and aim to accelerate the country's deployment of clean energy sources.

- Purpose: The primary goal of Renewable Energy Development Zones is to promote the use of renewable energy to meet South Africa's energy needs
- Identification: The government identifies specific geographic zones with high renewable energy potential, considering factors such as solar irradiance, wind patterns, and other renewable resources. These zones are then designated as Renewable Energy Development Zones.
- Project Development: Once a zone is identified, it becomes an attractive location for developers to establish renewable energy projects, such as solar or wind farms. The government may streamline regulatory processes and offer incentives to facilitate project development in these zones.
- Integration with National Plans: The establishment of REDZ aligns with South Africa's broader energy policies and plans, including commitments to increase the share of renewable energy in the overall energy mix and reduce dependence on traditional fossil fuels.
- Economic and Environmental Benefits: Developing renewable energy projects in these zones contributes to job creation, stimulates economic growth, and helps mitigate the environmental impact of traditional energy sources. It also supports South Africa's efforts to transition to a more sustainable and low-carbon energy system.

2.3.3.2 Renewable Energy Feed-in Tariff (REFIT)

The Renewable Energy Feed-in Tariff (REFIT) in South Africa is a policy mechanism designed to encourage development and investment in renewable energy projects. Here is a summary of how REFIT has been applied to South Africa:

- Tariff Structure: REFIT establishes a predetermined and guaranteed tariff structure for the electricity generated from renewable sources.

- Renewable Energy Sources: REFIT typically covers various renewable energy sources, including solar, wind, biomass, and hydropower.
- Government Involvement: The government plays a central role in implementing REFIT. It sets tariffs, eligibility criteria, and other guidelines to create a supportive environment for renewable energy investment.
- Grid Connection: Projects approved under REFIT typically have guaranteed access to the electricity grid, facilitating the integration of renewable energy into the national power system.

2.4 Feasibility analysis of new energy technologies in South Africa

This section introduces the concept of feasibility analysis in the context of energy technologies. This explains the purpose and significance of conducting feasibility studies to assess the technical, economic, environmental, and social aspects of implementing new energy technologies.

For energy projects, especially renewable energy, such as solar or wind, assessing the availability and reliability of resources is crucial. This involves analyzing factors such as sunlight hours, wind speed, or other relevant natural resources. In addition, choosing the appropriate technology for energy projects is essential. Identifying potential environmental impacts of the project and proposing mitigation measures. This is crucial to regulatory compliance and sustainable development. Feasibility checks, such as thorough community engagement and stakeholder consultations, evaluate social acceptance, address concerns, and ensure community support while assessing the potential for job creation and other social benefits linked to the energy project. Finally, a project timeline is developed, which includes the construction, commissioning, and operation phases. In summary, while feasibility studies across various sectors share some common elements, energy project feasibility studies require a specialized focus on technical, economic, environmental, regulatory, social, market, and project management aspects.

The South African government is trying to promote renewable energy through various initiatives. Mukonza et al. [72] conducted a detailed examination to review policies, institutions, and programs to promote wind energy uptake and feasibility analysis in South Africa. The study concludes that South Africa has implemented critical policies, institutions, and programs for wind energy uptake. The researcher noted the following gaps: insufficient data on the cost-effectiveness and affordability of wind energy in South Africa and limited information on the potential environmental and social impacts of wind energy projects in the country. As applied to the South African context, the limitation is that limited information is available on the effectiveness and impact of policies, institutions, and programs on promoting wind energy uptake.

A comparative study by Jain et al. [51] found that renewable energy projects are feasible in South Africa, and discussed the potential for renewable energy generation in the country, with a focus on solar and wind energy, and suggested that renewable energy implementation, particularly solar and wind energy, is feasible in South Africa. The country has immense potential for renewable energy generation with high levels of solar radiation and wind resources [77]. Government and energy regulators have developed policies and projects to promote renewable energy implementation in the country.

Diverse studies have examined Nigeria, South Africa, and Egypt, the top three largest economies in Africa, and have highlighted their significant renewable energy resources [78] [18]. These studies have analyzed the feasibility and progress of adopting renewable energy in these countries and identified their challenges in developing their renewable energy sectors. According to these studies, South Africa has a high potential for renewable energy because of its abundant natural resources, such as solar, wind, and biomass. A more systematic and theoretical analysis by Ndlovu et al. [79] proved the feasibility of four primary renewable energy sources (hydro, solar, wind, and biomass) for uptake in South Africa. In a randomized controlled trial, the same researchers analyzed these cases. They suggested that with proper technology, awareness, and skills for harnessing resources, South Africa can overcome its persistent energy crisis by utilizing its naturally gifted renewable energy sources.

Many researchers have conducted additional studies to learn more about the fundamental viability of renewable energy in South Africa [80]. Numerous studies have been conducted to reveal and determine the feasibility of renewable energy in the country, and a recent survey by Oyewo et al. [16] proved that renewable energy in the country is possible. The study investigates pathways toward achieving the ambitious goal for South Africa to achieve 100% renewable electricity generation by the year 2050. The research serves as compelling evidence that, in the foreseeable mid-term future, adopting a renewable energy system is not only the most cost-effective choice but also the one with the most minor water requirements, minimal greenhouse gas emissions, and the potential to create a substantial number of jobs within the South African energy system.

According to the Africa Energy Outlook [81], renewable energy technologies can enhance energy security by decreasing dependence on imported and fossil fuels and diversifying power supply in developing countries. In demonstrating the economic feasibility view, a study by Mudziwepasi et al. [82] undertook an investigation into the viability of implementing household-sized renewable energy technologies, such as solar photovoltaic systems and wind generators, to provide electricity in remote rural areas of South Africa. It concluded that wind and solar energy are economically feasible in rural villages and remote regions of South Africa. Thus, the use of renewable energy in rural areas is feasible.

However, several limitations of this study must be considered. For instance, a survey by An et al. [83] reveals several gaps and shortcomings in renewable energy policies and feasibility in South Africa, highlighting the limitations of renewable energy in South Africa, suggesting that imported crude oil is more practical to the needs of the industries of South Africa. The consumption of renewable energy in areas not concerning the sector is insignificant. A systematic review by Batinge et al. [84] argues that there should be more research on renewable energy uptake in the sub-Sahara. The paper argues that the vastly underserved electricity market in sub-Saharan Africa presents a unique opportunity to transition from a fossil-intensive energy system to one centered around renewable resources. Furthermore, this underscores the need for additional research to delve deeper into this potential shift.

Despite some challenges, renewable energy is a feasible option for solving the energy crisis in South Africa. The primary limitations noted by energy researchers are concerns about poor infrastructure and delays in implementing renewable energy projects, including policy barriers that inhibit the feasibility of energy projects in South Africa, which can be addressed through effective policy-making and implementation [22]. [53] [79]. Finally, it is also important to point out that the argument that the feasibility of renewable energy projects makes it impossible to replace fossil fuels is mainly used by governments and fossil fuel companies to undermine investments in renewables.

2.5 Optimization of new energy technologies in South Africa

South Africa's energy industry is dominated by coal. The use of coal dominates the energy industry. Various coal-fired power plants are at the end of their lifespans and may now be substituted with an energy mix combining and blending with renewable sources. Therefore, there is a need for further research on new energy technologies to solve the power crisis in South Africa. The optimization of new energy technologies in South Africa is an essential area of research and development, aiming to enhance the performance and efficiency of energy systems. According to the World Bank report [7], access to clean, modern energy is still a crisis in the sub-Sahara. There is still a need to optimize and implement new energy technologies to increase energy production for sustainable development. A recent study explored the potential for optimizing renewable energy technologies in South Africa [84]. It was revealed that renewable energy sources could meet approximately 30% of the country's power requirements.

2.5.1 Optimization of Renewable Energy

The optimization and optimal implementation of new energy technologies in South Africa is a critical area of research and development to enhance the performance and efficiency of energy systems. A closer look at the literature review in the South African energy area by scholars highlights the potential of renewable electricity sources to meet the energy needs of mining operations [22]. However, some argue that the previous literature suffers from specific weaknesses in demonstrating the feasibility of incorporating solar and wind power, reducing reliance on fossil fuels, and minimizing environmental impact [5]. Therefore, further research is required to fully understand the benefits of adopting renewable energy in the energy sector.

Optimization techniques and models have been used to optimize the unit commitment of electric power systems with intermittent renewable energy sources. The Southern African Development Community (SADC) region has implemented platforms, energy programs, and plans to address the energy crisis and improve efficiency within its member states [85]. Accordingly, the South African government has targeted generating 18 GW of renewable energy by 2030, focusing on optimizing renewable energy technologies [86].

A recent study by Wagh et al. [19] focused on the solar energy optimization approaches and the problems and disadvantages within the energy area. The study also discusses the most current optimization techniques. The potential of renewable energy capacity has been explored in South Africa, and new energy technologies have provided opportunities to improve the economy.

Optimization models are commonly used in South Africa's electricity grid to determine the optimal deployment of renewable energy sources such as solar and wind energy. Previous studies have emphasized the importance of renewable energy optimization [87] [20]. A considerable body of literature exists on optimization; a good example, Siddaiah et al. [88] explored the feasibility and cost-effectiveness of hybrid renewable energy system-based power generation in off-grid applications, but it also delves into the optimization techniques used in the modelling of these systems. Additionally, the work explores using different research methods, such as reliability-based modelling, economic modelling, and optimization techniques, to investigate hybrid renewable energy systems.

Several studies have attempted to determine and implement an optimal ratio of wind power to solar power by considering different optimization targets [87]. The optimization of stand-alone and winding hybrid systems was reported by Al-Falahi et al. [89]. The review mentioned that classical algorithms, modern techniques, and software tools are among the most popular optimal sizing methodologies for complex optimization problems in renewable energy. The study evaluates standalone solar and wind energy systems, focusing on their economic, reliability, environmental, and social aspects, and provides insights into size optimization methodologies.

Asadi et al. [90] presented a comprehensive overview of biomass use. The article presents a stochastic analysis and proposes an optimized approach using a mixed-integer optimization model, thereby emphasizing the importance of optimizing the network to minimize the environmental impact, maximize economic efficiency, and meet customer demand. This paper discusses optimization methods for renewable and sustainable energy, including biomass supply chain design and strategic decision-making. Techniques such as stochastic programming and fuzzy programming can be used to address the uncertainty in biomass supply chain parameters.

Another optimization review was conducted by Momoh et al. [91] to understand and grasp the concept of optimization techniques applied to the renewable energy resource optimization framework. A detailed examination by Kaufmann et al. [92] proved that optimization techniques are fundamental in planning, optimizing, and projecting sustainable renewable energy systems. This research focused on optimization methods for their application in renewable energy production and consumption.

Nevertheless, the rapid expansion of renewable energy is yet to be coupled with a similar rise in using sustainable energy sources. Regarding the utilization of renewable energy, it is important to note that previous research has primarily focused on optimizing the analysis of power systems that combine wind, hydro, thermal, and hydro-thermal sources. However, these findings might not directly apply to systems incorporating more intricate and diverse power sources. A recent study used the multi-objective optimization strategy of multi-sources power system operation based on fuzzy chance constraint programming and improved analytic hierarchy process [93]. The results from the optimization model proposed in the research enhance the economy, environmental protection, energy savings, and power system stability, leading to better utilization of renewable energy sources.

An ever-increasing body of literature shows that optimizing renewable energy has contributed to the uptake of renewable energy projects in rural areas, especially in Africa [94]. A detailed examination by Klepacka [52] emphasized the importance of renewable energy optimization in economic circumstances, the need to protect the natural environment, continuous education on technological advances, and the aim to strengthen self-reliance and independence in the provision of energy, especially in remote areas. The research highlighted the need for more investments in renewable energy to be extensively advocated, adopted, and endorsed by different countries, particularly in rural areas. This suggests that policy and financial support are crucial for optimizing the adoption and utilization of renewable energy sources.

Another study revealed that increasing economic activities in developing economies raise energy demand, mainly from conventional sources; therefore, more energy is needed by sourcing other energy alternatives. [95]. In addition to these findings, the paper's results demonstrate that optimizing renewable energy increases economic output and reduces carbon dioxide emissions, contributing to the significance of renewable energy use. Optimizing renewable energy consumption contributes positively to economic output, indicating that promoting renewable energy generation and use can support sustainable economic development [13].

In addition to the above literature, researchers have noted that stochastic optimization methods and their applications in renewable energy systems are superior to deterministic methods in terms of social, technical, and economic aspects [96] [97]. Overall, optimization techniques and models have been used to enhance the performance and efficiency of energy technologies. Several case studies and examples have explored the country's potential for various renewable energy technologies and the importance of optimization techniques in improving their performance and reducing costs [37] [98] [66].

2.5.2 Renewable energy technologies

South Africa has been actively pursuing developing and integrating various renewable energy technologies to diversify its energy mix, reduce carbon emissions, and promote sustainability. According to Aliyu et al. [18], renewable energy technologies include solar, wind, geothermal, bioenergy, waste-derived, ocean thermal, tides, waves, and hydraulic energy. These sustainable energy technologies are being explored as alternatives to fossil fuels to stop the risks of climate change and environmental depletion. The most significant renewable energy source is bioenergy, followed by solar and wind energies, which have the most prominent technical potential. Recent research by Mudziwepasi et al. [82] highlighted some of the renewable energy technologies as applied in South Africa:

1. Solar Photovoltaic (PV) Power:
- Utility-Scale Solar Farms: Large solar power plants generate electricity from sunlight, contributing to the national grid and distributing rooftop solar installations on homes, businesses, and other structures.
2. Wind Power:
- Onshore wind farms with wind turbines on land harness wind energy to produce electricity and offshore wind potential, thus exploring the potential for offshore wind farms along the coastline.
3. Hybrid Systems:
- Solar-wind hybrids integrate solar and wind technologies for more reliable and continuous power generation.
4. Concentrated Solar Power (CSP):
- Solar Thermal Power Plants use mirrors or lenses to concentrate sunlight for steam turbine electricity generation.

2.6 Integration of Feasibility Analysis and Optimization:

Feasibility analysis and optimization are essential in deploying and adopting new energy technologies in South Africa. Feasibility analysis assesses the viability and potential of implementing these technologies, while optimization aims to enhance their performance and efficiency. Recent critical research on the feasibility analysis and optimization of an energy-water-heat nexus supplied by an autonomous hybrid renewable power generation system at airport facilities highlights the importance of sustainable energy access and water quality alternatives [99].

A more comprehensive description can be found in a recent study that discussed the state of renewable energy development in South Africa, and few studies have examined the technical feasibility of the large-scale integration of wind energy into the South African grid system [77]. The research discusses South Africa's electricity generation, biomass, wind, and solar energy industries and recommends steps for integrating renewable technologies.

The controversy over the integration and feasibility of new energy technologies has raged for many years. Similarly, Mbav et al. [100] conducted a technical, economic, and environmental assessment of Landfill Gas to Energy generation systems in South Africa, including cost optimization analysis using HOMER software. The view is supported by Baloyi et al. [101]; the authors compare the economic feasibility of wind and biomass-based electricity generation systems for rural electrification in South Africa, including storage and hybridization for hybrid renewable energy systems.

Around the globe, a comprehensive investigation of the economic feasibility and optimization of hybrid renewable energy systems for rural electrification in Peru reveals the sustainable potential of implementing such systems [102]. Finally, a study on Zimbabwe's techno-economic comparative analysis of renewable energy systems presents a proposed system with better economic and technical feasibility than similar renewable energy systems, either standalone PV or wind [103]. The literature suggests that feasibility analysis and optimization are interrelated and synergize strongly in the context of new energy technologies worldwide, including South Africa.

2.7 Optimization of New Energy Technologies

Several research papers have explored the optimization of new energy technologies using different tools in South Africa. Optimization methods and software are crucial for sustainable energy system planning and forecasting, primarily promoting research on renewable energy production and consumption [92]. Goel et al. [104] presented an overview of various software tools available for designing and optimizing solar photovoltaic systems. The authors discussed various software tools for analyzing and optimizing renewable energy systems.

With a closer look at the literature on optimizing new energy technologies, Tozzi Jr et al. [105] provides an overview of the various modelling tools used to simulate and optimize renewable energy projects by categorizing them into different project scales and comparing their similarities and differences. Data from several studies have identified HOMER and RETScreen as two popular software tools used to optimize and analyze renewable energy systems [106]. The researchers have proposed a modelling framework using HOMER and RETScreen to assess renewable energy systems, focusing on electricity generation. Many researchers have conclusively proved that policymakers, academic researchers, and energy planners use optimizing software tools such as HOMER and RETScreen in the techno-economic design of renewable energy technologies for better decision making, to obtain better reliability and efficiency of power generation, and to save on installation costs [101] [19] [107] [62].

Assessment of renewable energy systems combining techno-economic optimization with energy scenario analysis: Case studies have been conducted on optimizing new energy technologies in South Africa. A recent study was conducted in South Africa by Leholo et al. [108]. They proposed a hybrid renewable energy plant methodology comprising a wind turbine, photovoltaic panels, and fuel cell for a remote Global System for Mobile Communications (GSM) base station. The goal is to provide an alternative green energy source. The hybrid system and base station simulation results using the HOMER software revealed renewable energy solutions for air pollution reduction and remote off-grid load alternatives. The study concludes that the proposed hybrid renewable energy plant is feasible, with HOMER simulation results indicating its environmental friendliness and potential for implementation. A critical problem with this argument is that the simulation results produced by HOMER are based on the assumptions and inputs used in the software, which may not accurately reflect real-world conditions. This study suggests a hybrid renewable energy plant for air pollution reduction, and still, despite fewer emissions compared to fossil fuel-based systems, it is essential to assess the overall life cycle impact of the proposed hybrid system.

In South Africa, approximately 55% of rural people lack access to electricity [82]. New energy technologies can be utilized in South Africa to design microgrids by combining wind turbines, photovoltaic panels, and fuel cells for continuous power to off-grid loads. These microgrid designs have been argued to be a solution for rural areas in South Africa that lack access to electricity. This view is supported by Longe et al. [109], who proposed an optimized renewable energy microgrid design using PV with a battery system as a better solution for electricity access in rural areas of South Africa. This study compares the implementation of a renewable energy source microgrid in Umhlabuyalingana Local Municipality, South Africa, providing a better solution to electricity access with grid extension. The system was simulated using HOMER, and the results favoured photovoltaic and battery systems as the optimal combination, offering better electricity access in unelectrified areas. The conclusion is that a standalone microgrid is an optimal solution for providing electricity access to rural areas in South Africa.

In order to elucidate the optimization of renewable energy technologies, Ogunmodede et al. [101] further investigate and demonstrate the use of an integer-programming optimization model to minimize costs and optimize the sizing and dispatch of renewable energy. The study utilizes an integer-programming optimization model to optimize the design and dispatch of a renewable energy system. The paper highlights the potential for millions of dollars in savings and increased renewable energy adoption through optimized system design and dispatch by providing an alternative to rule-of-thumb approaches.

Another study revealed that increasing economic activities in developing economies raise energy demand, mainly from conventional sources; therefore, more energy is needed by sourcing other energy alternatives to curb the demand [95]. In addition to these findings, the paper's results demonstrate that optimizing renewable energy increases economic output and reduces carbon dioxide emissions, contributing to the significance of renewable energy use. Optimizing renewable energy consumption contributes positively to economic output, indicating that promoting renewable energy generation and use can support sustainable economic development.

To date, research has focused on the exploitation of renewable energy, which is vital for the world, since the world's energy use continues to rise because conventional energy sources are no longer adequate to meet energy demands, sparking an energy crisis [110]. The authors met the objectives of optimizing hybrid renewable energy systems, which combine multiple renewable energy sources, as a promising solution to overcome the increasing energy demands.

2.7.1 Solar potential assessment using PVSYST software

PVSYST is a computer software package for assessing, simulating, and analyzing solar photovoltaic systems [111]. The software was designed to assess the solar potential and the system's performance. PVSYST allows users to model various aspects of a solar photovoltaic system, including solar energy production, power losses, and performance ratios. The software is commonly used in the renewable energy industry to assess the feasibility and viability of installing solar photovoltaic power plants.

An important finding of using PVsyst emerged from assessing the solar potential [112]. The paper compares the viability of installing a 1 MW solar photovoltaic power plant in Tamilnadu and the cost of solar energy production and life cycle. The research to date has focused on using the software to do analysis.

Another study proposed a Grid-connected Solar Photovoltaic plant performance evaluation using PVSYST Software [67]. The results present a simulation and evaluation of a grid-connected solar photovoltaic system using the PVSYST software, concluding that the simulation offers valuable performance insights.

In a randomized controlled study design, simulation and performance analysis of a 1 kWp photovoltaic system using PVsyst was performed using data from the location [33]. The paper presents a simulation and performance analysis of a 1 kWp photovoltaic system using PVsyst software, demonstrating the accurate use of onsite data for system design and analysis.

2.8 Analysis and Synthesis of Literature

Objective 1 of this study was met, and solar energy was selected as the renewable energy source for design and optimization, as South Africa is struggling to fight the power crisis in the country [77]. Review articles on energy have highlighted several key findings and arguments. Despite decades of research, this continues to be debated among researchers who have analyzed the context of adopting new renewable technologies per the Paris Agreement. Many studies have found significant growth in the coverage of renewable energy [6] [59, 65]. Several questions regarding South Africa's government's aim to install 17.8 GW of renewable energy capacity by 2030 remain to be addressed. A recent study by Mukonza et al. [72] on policies, planning, and frameworks concluded a need to revise government laws regarding adopting new energy technologies. To fill this gap, the country is gradually developing its renewable energy sector to mitigate carbon dioxide emissions and provide reliable electricity. The reviewed articles offer valuable insights into optimizing new energy technologies using various techniques and software tools. These studies emphasize the importance of selecting an appropriate software tool based on the specific requirements of the system being optimized and highlight the need for further research in this field.

The author will use the PV syst from the literature provided for this research. PV syst includes a built-in optimization tool that allows researchers to automatically vary one or more parameters of a PV system to achieve a desired outcome. This can be used to optimize various objectives, such as maximum energy production, minimum cost, or lowest carbon footprint. After the simulations, the PV syst generated detailed reports on the performance of the PV systems. These reports can be used to identify areas in which improvements are possible.

2.9 Conclusion

In conclusion, the literature review highlights the importance of feasibility analysis and optimization of new energy technologies for sustainable development in South Africa. This review reveals that the adoption of renewable energy technologies is still limited owing to various barriers. The findings indicate that the country faces significant challenges in meeting its growing energy demands while striving to achieve sustainable development goals. It is evident from the literature above that extensive studies have been conducted in the energy industry to inform the world about the transition from fossil fuels to new energy technologies, the feasibility and optimization of these technologies, and how to attain them. There is a global consensus on transitioning to more sustainable and cleaner energy sources and technologies.

This literature review explores the feasibility analysis and optimization of new energy technologies for sustainable development in South Africa. The findings from this review also entail that the energy policy and frameworks in South Africa, particularly the IRP, promote renewable energy integration and expansion to address these challenges and drive sustainable development in South Africa.

Based on the literature examined above, the overall aim of this thesis aligns with and complements the feasibility analysis and optimization of new energy technologies for sustainable development. However, it is vital to acknowledge the challenges that accompany the implementation of new energy technologies in South Africa, so this thesis study intends to fill this gap and make a contribution by conducting the analysis.

The general goal of the thesis, based on the literature reviewed above, is to align and complement this research by looking at whether and how renewable energy technologies and energy management in the supply mix affect the South African economy. Finally, this research is unique in that it takes a holistic approach to renewable energy feasibility by combining an investigation of links between energy, economy, and technology with energy modelling software.

CHAPTER 3 : METHODOLOGY

3.0 Introduction

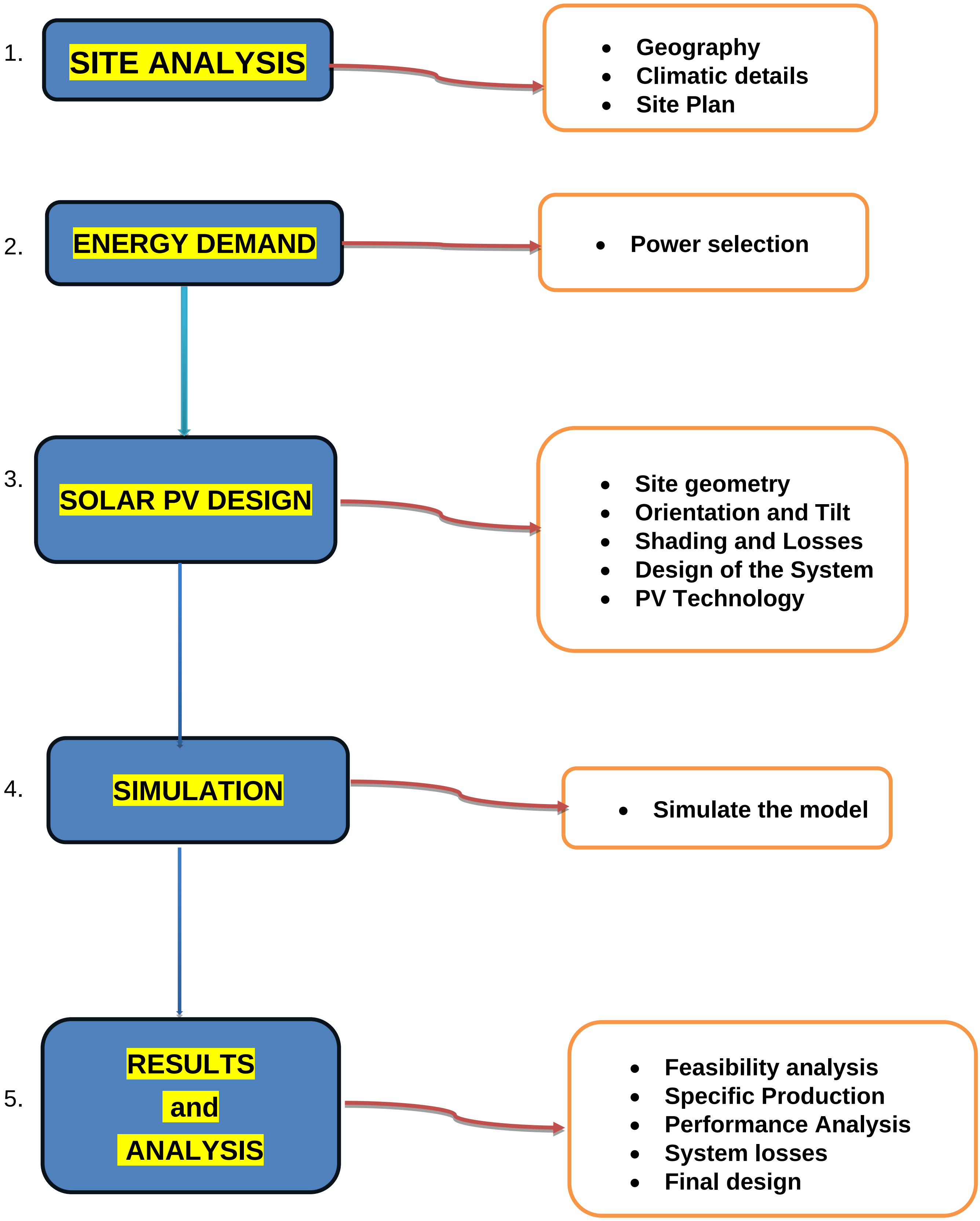
Photovoltaic (PV) power systems are becoming increasingly popular with the increasing energy demand and concern for environmental pollution worldwide. The design and use of solar PV systems have gained significant attention in recent years for harnessing and analyzing the feasibility of renewable energy sources.

The current study identified research related to the literature reviewed to analyze and conduct a comprehensive feasibility review of new energy technologies in South Africa for sustainable development. Secondly, it is observed from the literature study that the design and installation of solar PV systems have been widely studied to achieve sustainable development goals. However, most studies have been conducted on stand-alone PV systems. Nevertheless, grid-connected PV systems supply power to the grid, and their potential solar benefits cannot be overlooked.

Therefore, the novelty of this study lies in exploring the design and feasibility analysis of installing a grid-connected PV system, as reviewed in Chapter 2 of the literature. The author used the PV syst software for the design.

3.1 The Research Design

In order to carry out the design, it is necessary to analyze the research design. This research consists of different stages in order to come up with the final result. All these phases are interconnected.



When designing a research study on the design of a grid-connected PV system using PVsyst, the above listing for the research design should be considered [33].

3.2 Technology Selection and Design

To design, analyze, and simulate the system and assess its performance, the researcher will use the PVsyst software as a valuable tool in this project. PVsyst software, created by Mermoud and Villoz, was designed to facilitate the entire PV system's examination, dimensioning, and comprehensive data analysis.

PV syst software is used to optimize renewable energy systems. Baqir et al. [113] demonstrated the analysis and design of solar PV systems using Pvsyst software for a study in Afghanistan. The paper's results prove that using Pvsyst software for analyzing and designing a solar PV system is viable, providing insights into the system's performance and potential contribution to meeting the country's electricity demand. Data from several studies have identified the use of Pv syst software as an optimization tool for system analysis, visualization, and simulation results, assessing solar energy feasibility and potential for electricity generation, particularly useful for grid-connected and stand-alone photovoltaic systems [114-116].

3.2.1 Design Process

Designing and integrating the system into PVsyst necessitates the input of extensive data and the meticulous definition of numerous parameters to establish an accurate, valid, and comprehensive grid-connected system. In order to conduct a thorough analysis, it is imperative to have access to essential data for the plant, which includes:

- Geographical information
- Site and Climatic conditions
- PV Technology selection
- Simulate the model.

Multiple simulations will be conducted to facilitate meaningful comparisons, enabling refinement of the system design to meet specific conditions. The software offers insights into the total energy output and losses and delivers an economic evaluation encompassing factors such as pricing, energy costs, and profitability.

3.3 Site identification and climatic data

To design a PV system, it is crucial to know where it will be located so that the designer understands various factors affecting system performance [117]. Therefore, site analysis is essential. This methodology presents the Project location, addition, and meteorological data, including temperature variation and annual/monthly solar radiation from reliable sources.

Due to its solar potential and higher irradiation levels, the project will be located in Lephalale, a town in the Limpopo province. The selected area is Onverwacht, with a latitude of -23.72639, a longitude of 27.68833, and an altitude of 848m. The proposed project area is reasonably flat, with a topographic high. The project will be located between Matimba and Medupi power stations, making it easy to connect to the primary grid supplying the municipality or other parts of the country.

The table below shows geographical site parameters for Onverwacht and the exact location of the project. The table highlights average weather parameters for the years 2000 to 2018. PVsyst employs Meteonom 7.2 to access and present the monthly meteorological data for the designated area, as illustrated in Table 3.1 below.

Table 4: geographical site parameters for Onverwacht

Months	Horizontal global irradiation kWh/m^2	Wind velocity m/s	Relative humidity %
January	204.3	3.09	64.1
February	178.5	2.67	65.8
March	182.5	3.14	56.6
April	153.8	2.89	59.0
May	147.0	3.02	61.8
June	128.8	3.00	52.1
July	141.3	2.98	48.1
August	166.2	3.15	51
September	184.3	3.56	53.6
October	202.3	3.23	49.9
November	205.4	3.11	42.9
December	210.7	2.93	51.9

Lephalale is one of the warmest areas in South Africa, with predominantly sunny conditions and prevailing temperatures getting as high as 40°C in summer. The data shown in Table 5 below is the meteorological data for the town and was derived from the latest available information contained in Meteonorm 7.2, which is a comprehensive meteorological database encompassing weather data from across the globe for the period 1991–2020 and also integrated with data from the Photovoltaic Geographical Information System, referred to as PV-GIS, is a specialized tool that has been developed and is currently maintained by the European Commission [118].

Table 5: Average temperature in Lephalale

Months	Monthly Average Temperature (2010-2020) in °C
January	29
February	32.5
March	30.5
April	28.9
May	27.5
June	26
July	26
August	30.5
September	33
October	34.7
November	32.6
December	34

From the data presented, it can be concluded that Lephalale, Onverwacht, is a suitable place to implement a PV plant. The soil of the site is presumed to be highly suitable for this study because of its favorable characteristics, including dryness, resistivity, load-bearing capacity, and chemical properties, and generally, the predominant ground layer at the site consists of sandy soil. Information like floods, rainfalls, snow, and high temperatures was also analyzed, as these can affect the plant's performance. The chosen location is not under extreme weather conditions, so every parameter will not affect the design.

3.4 Designing the system

Several steps are needed to develop the system's model in the software [119].

- Definition of the project
- Definition of the site (already done)
- Selection of metereo file in the PV Syst software
- Defining the orientation of the system
- Defining the system variants
- Definition of the PV system in several "Variants" or "Calculation versions
- Run various simulations

3.4.1 System Orientation

The system orientation is a critical variable as it determines the energy produced by the system, given the sun's changing position throughout the day. Regarding this project, only one orientation will be used: fixed tilt orientation. Using a fixed orientation simplifies the design process. It requires fewer components and reduces the complexity of the installation.In this study, fixed PV modules are employed for both economic considerations and ease of maintenance duties. It is crucial to set these modules' orientation and tilt angle to optimize the energy output, which will be elaborated upon and explained in more detail in subsequent sections. However, the proposal for this project is to optimize and maximize the energy produced. To proceed with the design, it is essential to determine both the collector's tilt and the system's azimuth. In the Southern Hemisphere, the plane azimuth is defined as the angle between the north and the collector planes. It is worth noting that this angle is considered negative when pointing eastward.

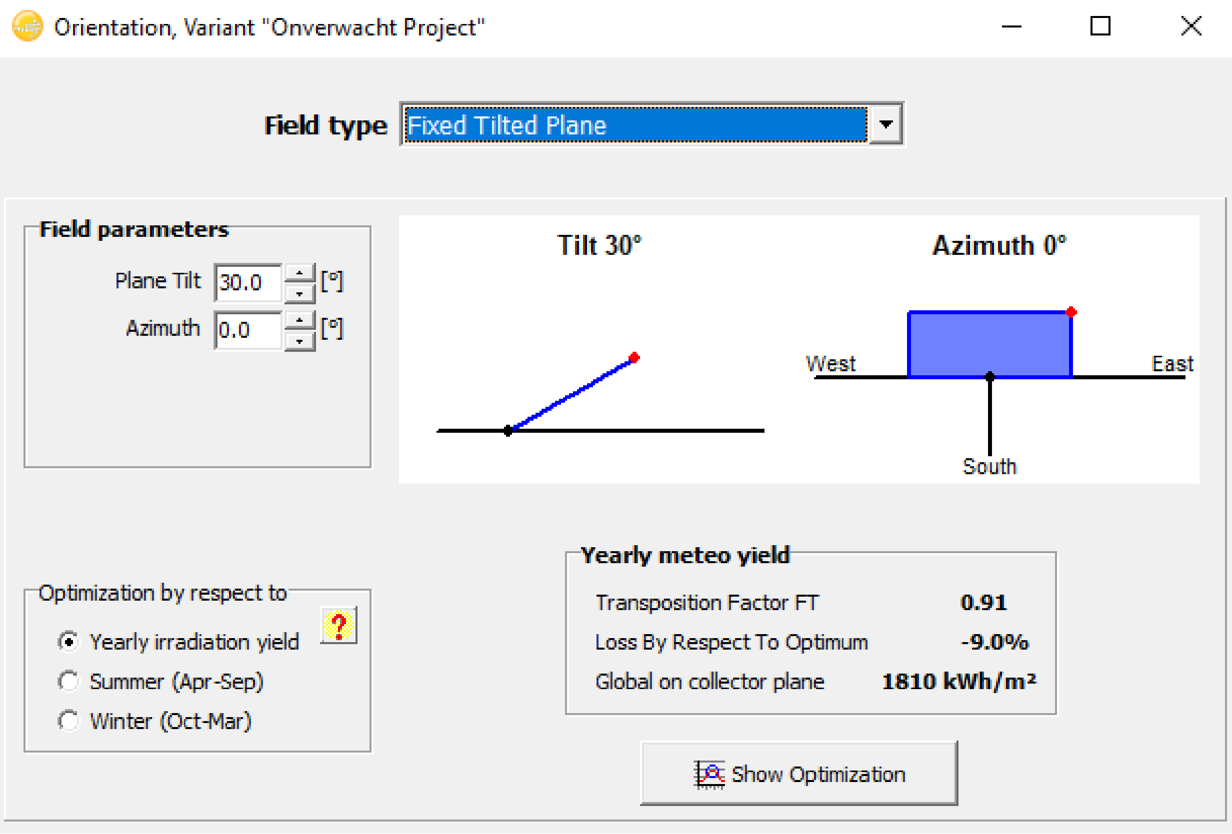


Figure 4: Module orientation and tilt angle settings on PVsyst

3.5 System Design

It is essential to choose the right technology for the system. This also affects the operational efficiency of the system. The system components include a PV module and Solar Inverter.

3.5.1 PV Module:

The photovoltaic module is one of the most important components of the grid-connected PV system as it changes solar radiation energy into electrical energy. The PV module refers to the fundamental building block of the photovoltaic system as it directly converts sunlight into electricity through the photovoltaic effect. So, choosing the correct PV modules is critical in designing the grid-connected system.

In order to enhance the system's output power, a specific number of PV modules are interconnected to create a solar array. The PV array must be accurately sized to ensure an uninterrupted power supply throughout the year without operational issues. The researcher also considers factors like module type (monocrystalline, polycrystalline, or thin-film), efficiency, temperature coefficient, and manufacturer's reputation during the design.

The most important parameters when choosing PV modules are :

- Efficiency: Efficiency refers to how effectively a PV module converts sunlight into electricity. Higher efficiency modules generate more power for a given area, which can be crucial if space is limited.
- Temperature Coefficient: The temperature coefficient measures how a PV module's efficiency is affected by temperature changes. Solar panels tend to produce less electricity as they get hotter. A lower temperature coefficient signifies reduced sensitivity to temperature fluctuations, resulting in improved performance under hot weather conditions. Consequently, the durability of the PV module is extended when the temperature coefficient is less sensitive.
- Manufacturer's Reputation: The reputation of the PV module manufacturer is essential for ensuring the quality and long-term reliability of the panels. Reputable and established manufacturers are more likely to produce reliable modules.
- Durability: This refers to the ability of the selected PV modules to withstand various environmental and operational conditions over an extended period without significant deterioration in performance. Durability is crucial in ensuring a solar PV system's long-term reliability and cost-effectiveness.

In summary, when considering PV module selection for a grid-connected PV system, it is important to weigh factors like module type, efficiency, temperature coefficient, and the manufacturer's reputation. These factors will help you choose PV modules that align with your budget, available space, and performance requirements, ultimately optimizing the performance and longevity of the solar energy system.

For this study, the researcher chose a Q.PLUS L-G4.1 340 panel manufactured by Hanwha Q Cells. This monocrystalline solar panel is known in the industry for its high efficiency and space-efficient design. It is a high-efficiency module that converts more sunlight into electricity, resulting in a higher energy yield.

Key Features and Specifications:

- Type: This monocrystalline solar panel is known for its high efficiency and space-efficient design.
- Power Output: The "340" in the product name suggests that this panel has a power output of approximately 340 watts under standard test conditions (STC). The actual power output can vary based on sunlight intensity and temperature.
- Efficiency: Monocrystalline panels like the Q.PLUS L-G4.1 are more efficient than other solar panel types. The efficiency indicates how effectively the panel converts sunlight into electricity.
- Durability: Hanwha Q Cells typically produces high-quality solar panels with a focus on durability. These panels are designed to withstand various environmental conditions and have a long lifespan.
- Applications: Solar panels like the Q.PLUS L-G4.1 340 are commonly used in grid-connected solar PV systems for residential, commercial, and industrial applications

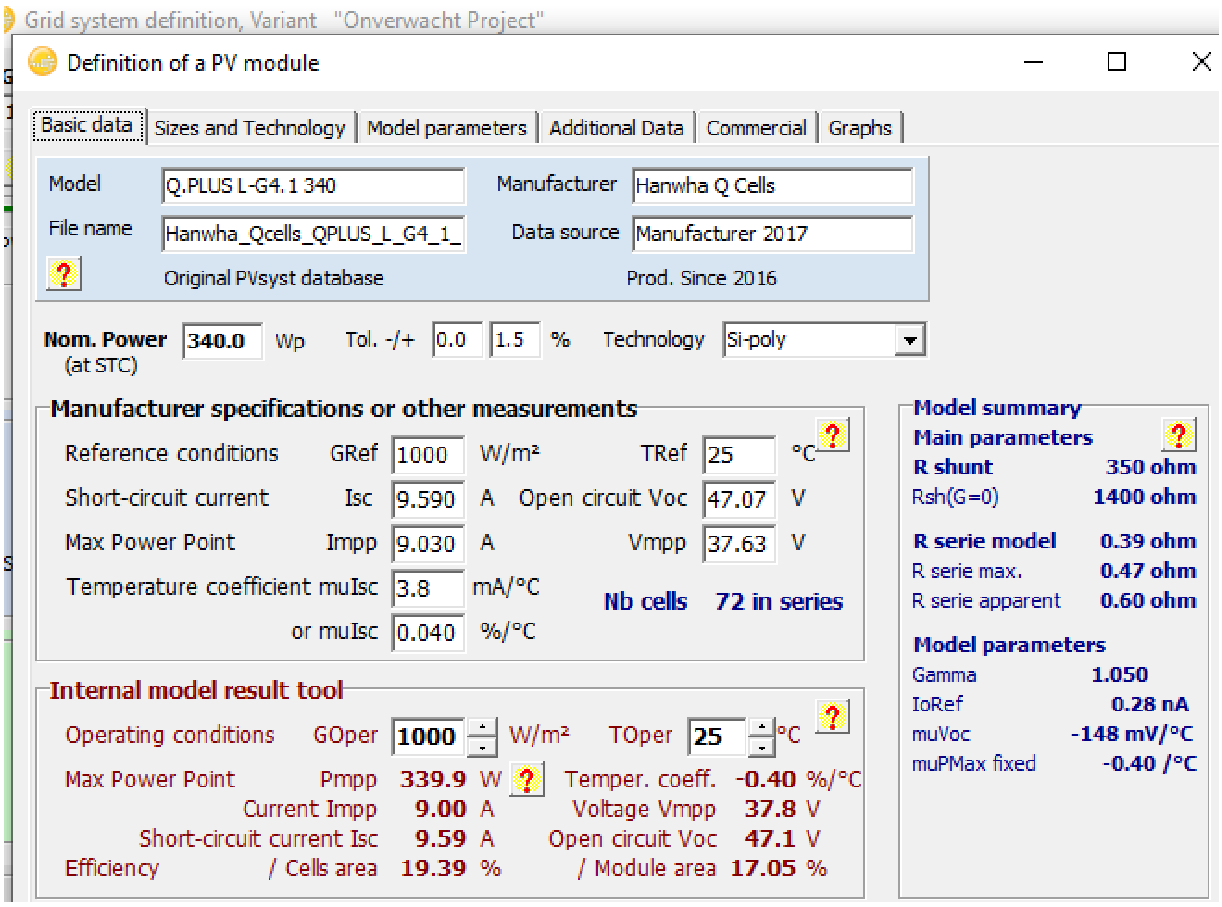


Figure 5: Data set for the PV module selected

3.5.2 Inverter

The inverter holds significant importance within grid-connected PV systems because it plays a pivotal role in converting the DC power generated by the PV modules into the AC power necessary for integration with the grid. It is an important electric component to meet the inverter specification with the PV specification to run the system properly. In a grid-connected system, the electricity produced by the solar panels must be synchronized with the utility grid's frequency and voltage. Inverters are designed to match the grid's electrical characteristics to ensure a seamless connection. This synchronization is crucial to safely inject excess electricity into the grid or draw electricity from the grid when needed.

For this research, we use The "Ingecon Sun 50", a solar inverter manufactured by Ingeteam, a well-known company in the renewable energy industry.

Key Features and Specifications;

- Capacity: The "50" in the product name indicates the inverter's capacity, often expressed in kilowatts (kW). In this case, the inverter has a capacity of 50 kW.
- Efficiency: Solar inverters like the Ingecon Sun 50 have efficiency ratings that indicate how effectively they convert DC power into AC power. Higher-efficiency inverters are desirable as they minimize energy losses during conversion.

The figure below shows the selected inverter and its specifications for the system.

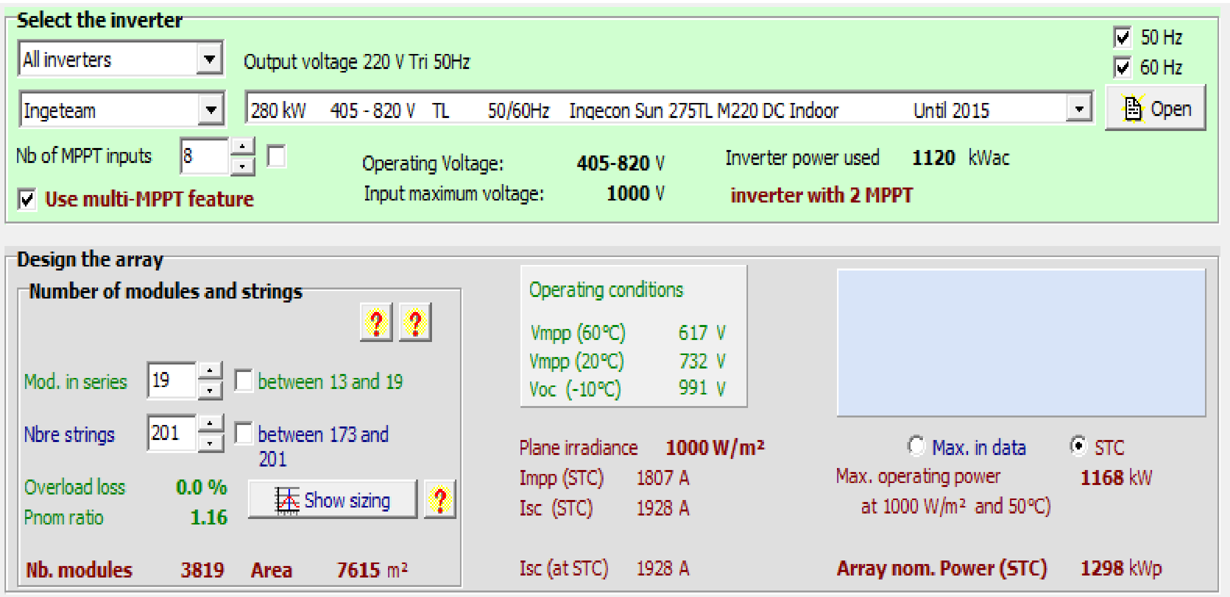


Figure 6: Selected inverter and its specifications

<u>Data of the selected inverter: Input (DC)</u>

The tables below state the operating characteristics values for the inverter

Table 6:Operating characteristics for the inverter (input)

Minimum Voltage	405 V
Maximum Current	22A
Absolute Maximum Voltage	1000V
Nominal Power	N/A
Power Threshold	150W
Input short-circuit current	15A
Full load DC voltage range	400V-925V
Maximum input current	12A

<u>Data of the selected inverter: Output(AC)</u>

Table 7: Operating characteristics for the inverter(output)

Rated power	**280KW**
Maximum AC Power	**736A**
Maximum AC Current	**736A**
Efficiency	**98.10%**

3.5.3 Horizon

In this study, it was assumed that the proximity or vicinity of the PV system remains unobstructed by objects or buildings that can cast direct shadows on the panels, thereby obstructing their performance. Without such obstacles, sunlight should have an unobstructed path and pass to the ground.

System overview.

- Orientation parameters
  Field type: Fixed Tilted Plane
  Plane tilt/azimuth = 30° / 0°

- Compatibility between System defintions
  System orientation tilt/azim = 30° / 0°
  1 sub-array
  No Shading field defined
  Power = 1298 kWp, modules area = 7615 m²

- System parameters
  PV modules:
  201 strings of 19 modules in series, 3819 total
  Power = 340 Wp Power array = 1298 kWp, Area = 7615 m²
  Inverters (280 kWac) 8 MPPT inputs, Total 1120 k

It is important to note that the decision to connect solar panels in series is part of the overall system design process. Additionally, the inverter technology and system design impacted this consideration.

The figure below shows the designed Grid-connected PV system with all its components. Once all the steps outlined in the preceding sections have been carried out and every detail has been thoroughly established and finalized, the resulting grid-connected system is illustrated below.

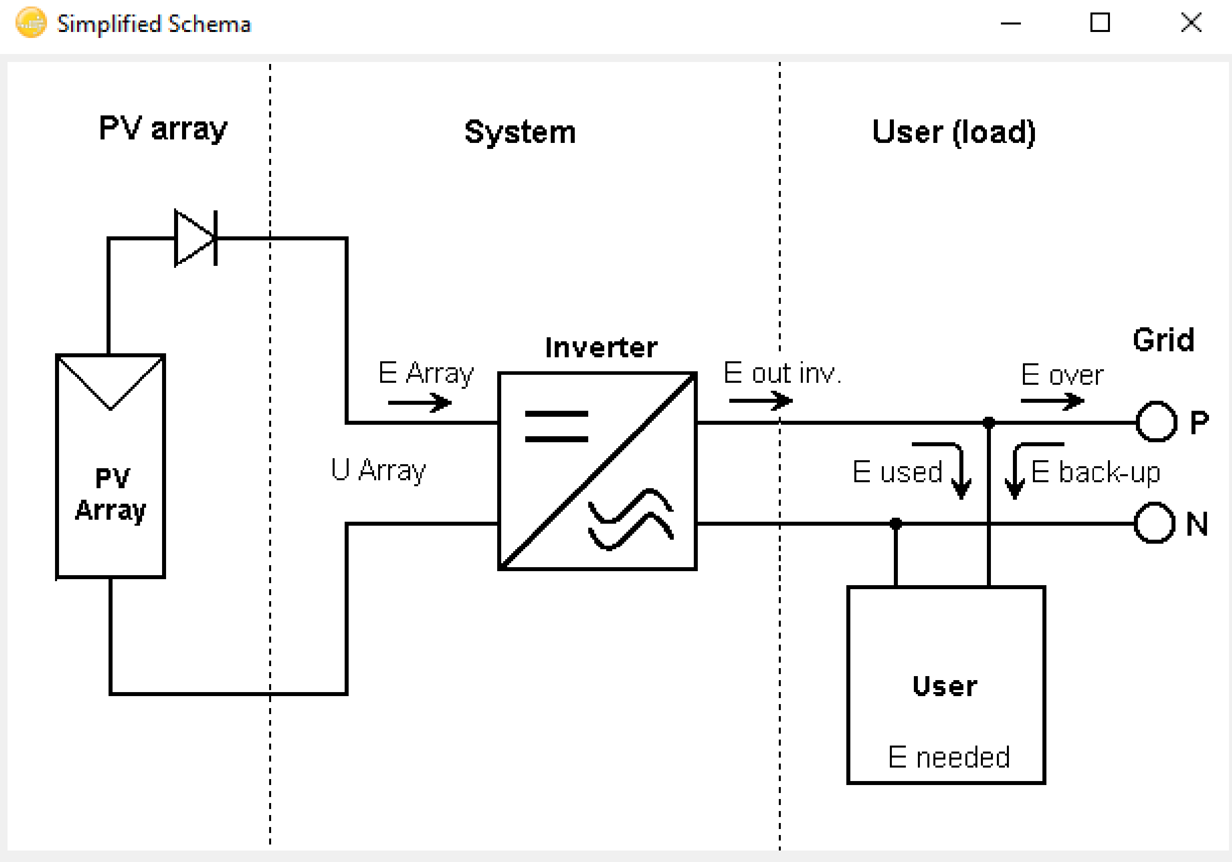


Figure 7: A simplified representation of the grid-connected photovoltaic (PV) system

3.6 Simulation scenarios

This chapter provides a comprehensive listing and a detailed explanation of all the essential steps required for designing the system, which enables the definition of various simulation scenarios. Consequently, alterations to the layout of the system can be explored. Investigating additional layouts beyond those previously described could be of particular interest, especially if the software results indicate specific trends or reveal new insights. Subsequently, the identified optimal scenario will undergo further enhancement by incorporating a storage system, which will be elaborated upon in a subsequent section.

3.7 Conclusion

In conclusion, this chapter presents a comprehensive methodology for designing a PV system using PV syst software. This section explains the methodological approach for designing a PV system in detail. The methodology for designing a PV system using PV syst software involves a systematic and data-driven approach. A better understanding of how the data used in this research were obtained is illustrated through a research design diagram. The research design provided the research flow, and the data were explained in detail. A grid-connected photovoltaic system was designed and simulated using PV syst software. The system's output depends on the received solar radiation, as the simulation results show in the next chapter. This methodology ensures that the system is appropriately sized, configured, and optimized for maximum energy production and cost-effectiveness.

CHAPTER 4 : RESULTS AND DISCUSSIONS

4.0 Introduction

In this section, we present the results of our simulations and provide an overview of the methodology employed to identify the optimal solution for a PV system. This section explains the significance of the research and draws meaningful conclusions. This includes the System Performance Analysis, thus presenting data on the actual performance of the grid-connected PV system, including energy generation, system efficiency, and any relevant metrics, and comparing the actual performance with the expected or simulated results.

The key parameters to be analyzed are as follows:

- The performance ratio (PR) is a crucial metric for assessing the efficiency of photovoltaic systems. This metric is precisely defined as the ratio between the actual energy output or utilization and the energy that would have been produced if the system consistently operated at its nominal capacity.
- Energy Yield: This energy yield represents the total amount of energy generated by the PV system throughout a specified duration. It is usually expressed in kilowatt-hours (kWh) per year or month, depending on simulation expectations. Energy yield can be used to evaluate the overall performance of a grid system.
- Normalized Production: Normalized production is the ratio of actual energy production to the installed capacity of the PV system. This is usually expressed as kilowatt-hours per kilowatt-peak (kWh/kWp) per year or month. The normalized production parameter helps evaluate the system's performance relative to its installed capacity.
- Loss: This is a factor that reduces the efficiency of the PV system. They can be caused by shading, soiling, module quality, and other factors during design.

From the PV syst's loss diagram, one can identify the primary sources of losses in the system and evaluate their impact on its performance.

- Sensitivity Analysis: Sensitivity analysis was performed to identify the key parameters significantly affecting system performance. This aids in understanding the robustness of the system under varying conditions.

4.1 Optimal Configuration of the System

All the simulation scenarios and their respective parameters are detailed in Table 8. Notably, the remaining parameters, including losses and technology configuration, remained consistent across all scenarios. Why is it essential to form different scenarios? It is vital to create different scenarios because they allow researchers to model the performance and efficiency of a PV system under different conditions [120]. This will enable them to identify the scenario that best meets their needs, taking into account all relevant factors in the design.

The three scenarios for the PV system in the software were formed by varying the tilt angle of the PV modules. The tilt angle, also known as the inclination angle, pertains to the angle at which the PV modules are positioned relative to the horizontal ground surface [33]. The tilt angle affects the amount of sunlight the PV modules receive and the amount of energy they produce.

1. Scenario A assumes a tilt angle of 30 degrees. This is the standard tilt angle for PV systems in several parts of the world.
2. Scenario B assumes a tilt angle of 45 degrees. This tilt angle is often used in PV systems in areas of high solar radiation.
3. Scenario C assumes a tilt angle of 15 degrees. This tilt angle is often used in PV systems in areas with low solar radiation levels.

The software calculated the energy production of the PV system for each scenario based on the tilt angle of the PV modules and the amount of solar radiation available at the site. The three scenarios were formed to provide a range of possible outcomes for the PV system and to optimize or choose the best system. The researcher utilized simulation data to compare PV system performance in three scenarios and identify the optimal one.

Table 8: Configuration of the system

Scenario	Tilt	Number of PV modules
A	30	3819
B	45	5880
C	15	4832

The specific energy production, derived from a PVsyst simulation, quantifies the energy generated by a photovoltaic (PV) system per unit of installed capacity. This metric is typically expressed in kilowatt-hours per kilowatt-peak per year (kWh/kWp/year). The specific energy production is an essential metric for evaluating the performance of a PV system and comparing it to other systems. It considers factors such as the efficiency of the PV modules, orientation and tilt angle of the modules, shading, and other losses.

From the simulation scenarios, the specific energy production values for scenarios A, B, and C are 1325, 1147, and 1438 kWh/kWp/year, respectively. These values indicate each system's energy per unit of the installed capacity. Higher specific energy production indicates a more efficient PV system. Scenario C has a higher specific energy production than Scenarios A and B. This is because Scenario C has a tilt angle of 15 °, which is closer to the optimal tilt angle for solar panels in the southern hemisphere. Based on the specific energy production, scenario C had the highest specific energy production value of 1438 kWh/kWp/year. This indicates that scenario c has the highest potential for energy production per unit of installed capacity, and the optimal tilt angle is the angle at which the solar panels will receive the most sunlight throughout the year.

Scenario A has a Specific Energy Production of 1325 kWh/kWp/year, which falls between Scenario C (higher) and Scenario B (lower), with Scenario B having the lowest Specific Energy Production at 1147 kWh/kWp/year.

4.2 Energy Production

Energy production is a PV system's total energy over a given period. It is typically measured in kilowatts (kWh). Higher energy production indicates that a PV system can produce more power. The table shows that the energy production values for scenarios A, B, and C were 1720, 1720, and 2259 MWh/year, respectively. Scenario C produced the highest total energy output at 2259 MWh/year, significantly higher than scenarios A and B.

Table 9: The System performance

Scenario	Tilt	Specific Energy Production	Energy Production	Performance Ratio (%)	System Efficiency (%)
A	30	1325 kWh/kWp/year	1720MWh/year	73.6	17.05
B	45	1147 kWh/kWp/year	1720 MWh/year	73.0	16.5
C	15	1438 kWh/kWp/year	2259 MWh/year	75.0	15.5

However, it is essential to note that specific energy production values alone do not provide a complete picture of the performance of PV systems. Other factors such as cost, maintenance requirements, and environmental impact should also be considered when evaluating different scenarios for optimizing a system.

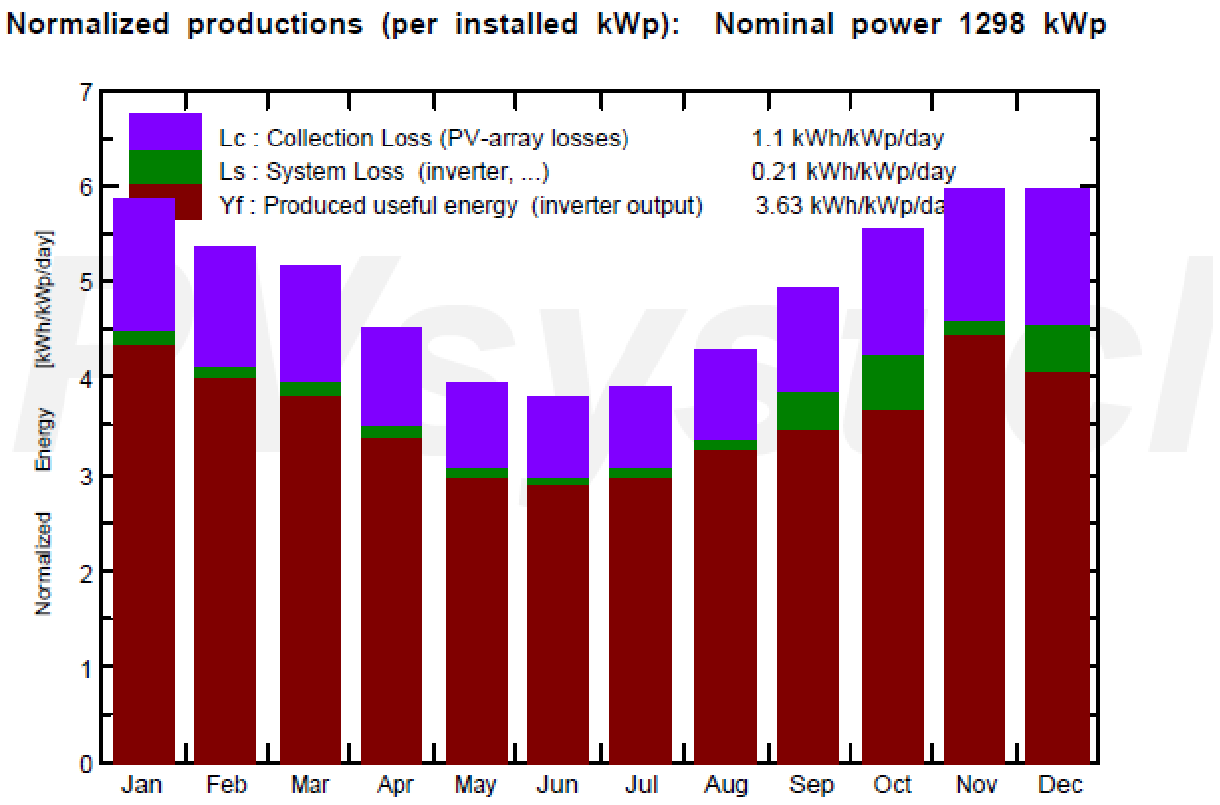


Figure 8: Energy production for Scenario A

From the figure above, which shows the energy production for Scenario A, the x-axis represents the months of the year, and the y-axis represents the normalized energy production in kWh/kWp/day. The graph shows the normalized production of energy per installed kilowatt peak (kWp) for a PV system with a specific energy production of 1325 kWh/kWp/year. This means that the PV system for Scenario A will produce 1325 kWh of energy per kilowatt peak of installed capacity over the course of a year, or the system will generate 1325 kWh of energy per kWp annually. The graph illustrates and offers a visual representation of how energy production changes over the year for Scenario A, which is highest in summer with more sunlight and lowest in winter with less sunlight—the winter months also had the highest system loss.

It is evident from the graph that energy production is at its peak during the summer months when there is ample sunlight but drops during the winter months with reduced sunlight. The presence of losses within the system, visually depicted by the green and purple bars on the graph, is noteworthy. These losses are most pronounced during winter, aligning with reduced energy production. The red bars represent the valuable energy produced by the inverter output, whereas the green bars indicate system losses, including losses from the inverter. Finally, the purple bars represent collection losses encompassing PV array-related losses.

The total energy production for the PV system in Scenario A can be calculated by multiplying the normalized energy production by the system's installed capacity. In this case, the installed capacity of the system is 1298 kWp, so the total energy production is calculated as follows:

Energy production = Normalized production of energy * Installed capacity

Energy production = 1.1 kWh/kWp/day * 1298 kWp * 365 days/year

Energy production = 1720 MWh/year

Figure 4.0 has already been evaluated from the software.

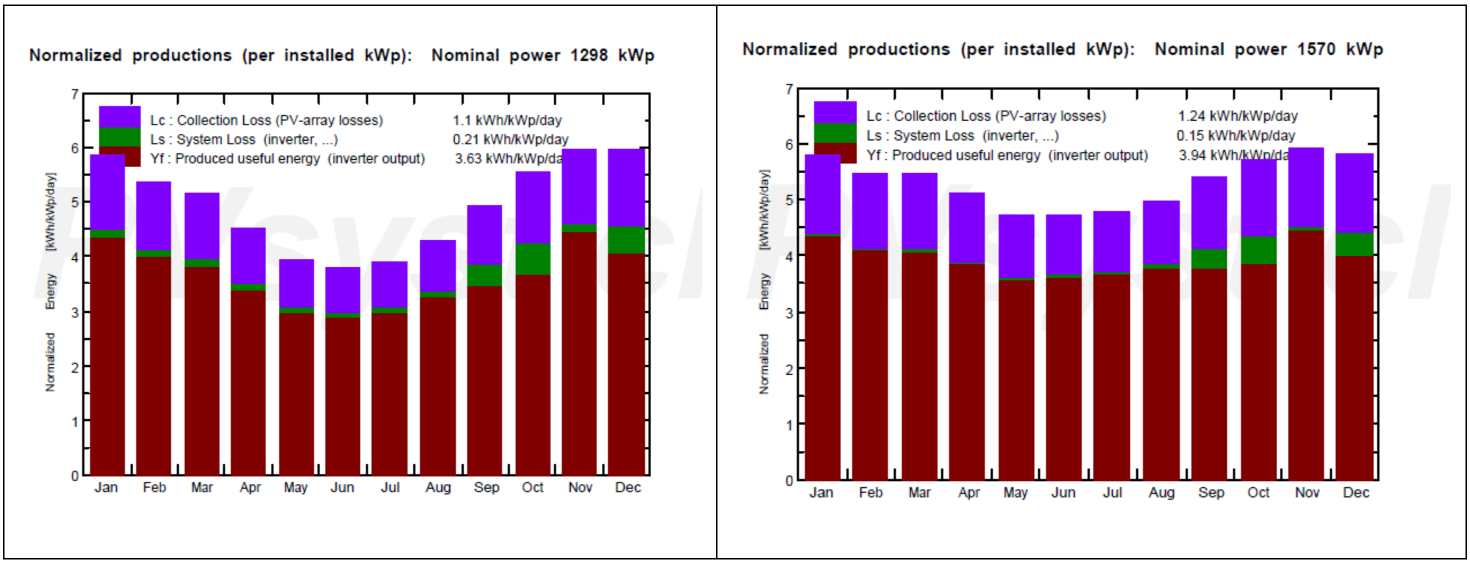


Figure 9: Energy production for Scenarios B and C

The graphs above provide a visual representation of how energy production varies throughout the year for scenarios B and C. Scenario C has a specific energy production of 1438 kWh/kWp/year, which is higher than Scenario A (1325 kWh/kWp/year) and Scenario B (1147 kWh/kWp/year). This means that Scenario C will produce more energy per kilowatt peak of installed capacity over the course of a year than Scenario A and Scenario B. The graphs show that in Scenario C, energy production is highest during summer and lowest in winter, just like in Scenarios A and B. However, Scenario C consistently outperforms Scenarios A and B throughout the year. This proves that energy production is highest during the summer when there is more sunlight and lower during winter when there is less sunlight.

For example, in June, the normalized production of energy for Scenario C was 1.438 kWh/kWp/day, while the normalized production of energy for Scenario A was 1.325 kWh/kWp/day, and the normalized production of energy for Scenario B was 1.147 kWh/kWp/day. This means that Scenario C produces 8.5% more energy than Scenario A and 25.7% more energy than Scenario B in June.

Therefore, the total energy production for Scenario C was calculated as follows:

Energy production = Normalized production of energy * Installed capacity
Energy production = 1.438 kWh/kWp/day * 1570 kWp * 365 days/year
Energy production = 2259 MWh/year

Table 10: comparison of the outputs from the PV Syst simulation

Scenario	Specific energy production (kWh/kWp/year)	Energy production (MWh/year)	Performance ratio (%)
A	1325	1720	73.6
B	1147	1720	73
C	1438	2259	75

- Specific energy production: Scenario C has the highest specific energy production, meaning it will produce the highest energy per kilowatt peak of installed capacity. This is because Scenario C has a tilt angle of 15 °, which is closer to the optimal tilt angle for solar panels in the Northern Hemisphere.
- Energy production: Scenario C has the highest energy production, producing the most energy overall. This is because Scenario C has the highest specific energy production and the same installed capacity as Scenarios A and B.
- Performance ratio: Scenario C has the highest performance ratio, which means it is more efficient than Scenario B but less efficient than Scenario A. The higher performance ratio is likely because Scenario C has a higher tilt angle than Scenario A. Solar panels tend to have lower performance ratios at higher tilt angles. After all, they are more susceptible to shading and dust buildup.

Scenario C is the best PV system from this analysis because it has the highest specific energy production and the highest performance ratio.

4.2.1 Additional Considerations

In addition to the above factors, other factors need to be considered when selecting the best PV system for a particular application. These factors include:

- Cost: The cost of the PV system is an important consideration. Scenario C may be the best PV system based on the above-mentioned factors but may also be the most expensive.
- Space: The amount of space available for a PV system is another critical consideration. A PV system with higher specific energy production may be the best option if limited space is available.
- Aesthetics: The appearance of the PV system may also be a consideration

4.3 Performance Ratio

The performance ratio (PR) measures the efficiency of a PV system in converting sunlight into electrical energy [113]. It is explicitly defined as the ratio of the energy that is effectively produced to the energy that would be generated if the system operated continuously under its standard operational conditions. The PR is expressed as a percentage and is calculated by dividing the actual energy production by the expected energy production.

The PR of the three simulated scenarios are:

- Scenario A: 73.6%
- Scenario B: 73%
- Scenario C: 75%

Scenario C had the highest PR, indicating it was the most efficient of the three systems. This is likely due to the fact that Scenario C has a tilt angle of 15 degrees, which is closer to the optimal tilt angle for solar panels. The higher the PR, the more efficient the PV system.

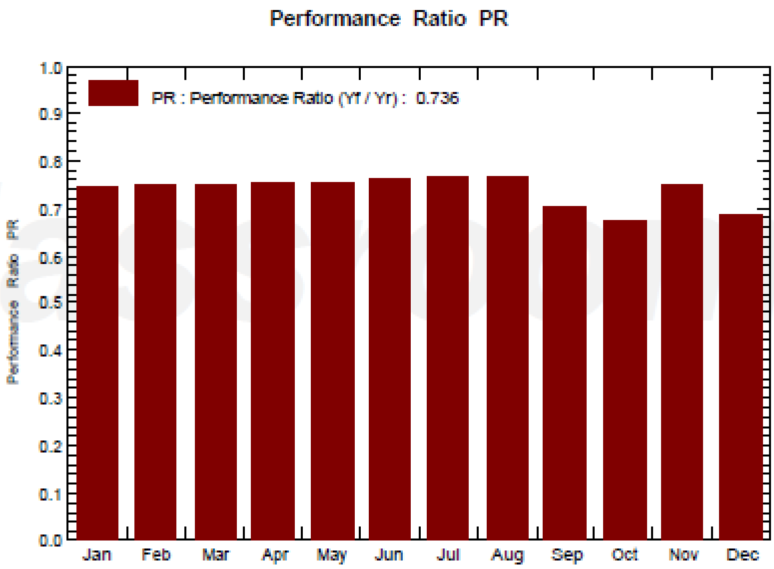


Figure 10: Normalised energy production for A

The above graph illustrates the energy production per kilowatt-peak (kWp) of installed capacity, normalized for Scenario A, with a specific energy production of 1325 kWh/kWp/year and a PR of 73.6%. This means that the PV system will produce 1325 kilowatt-hours of energy per kilowatt peak of installed capacity over the course of a year. A PV system's performance ratio (PR) measures its efficiency; therefore, the PV System for Scenario A has higher efficiency, which means that the system has a higher output. The higher the PR, the better the system performance.

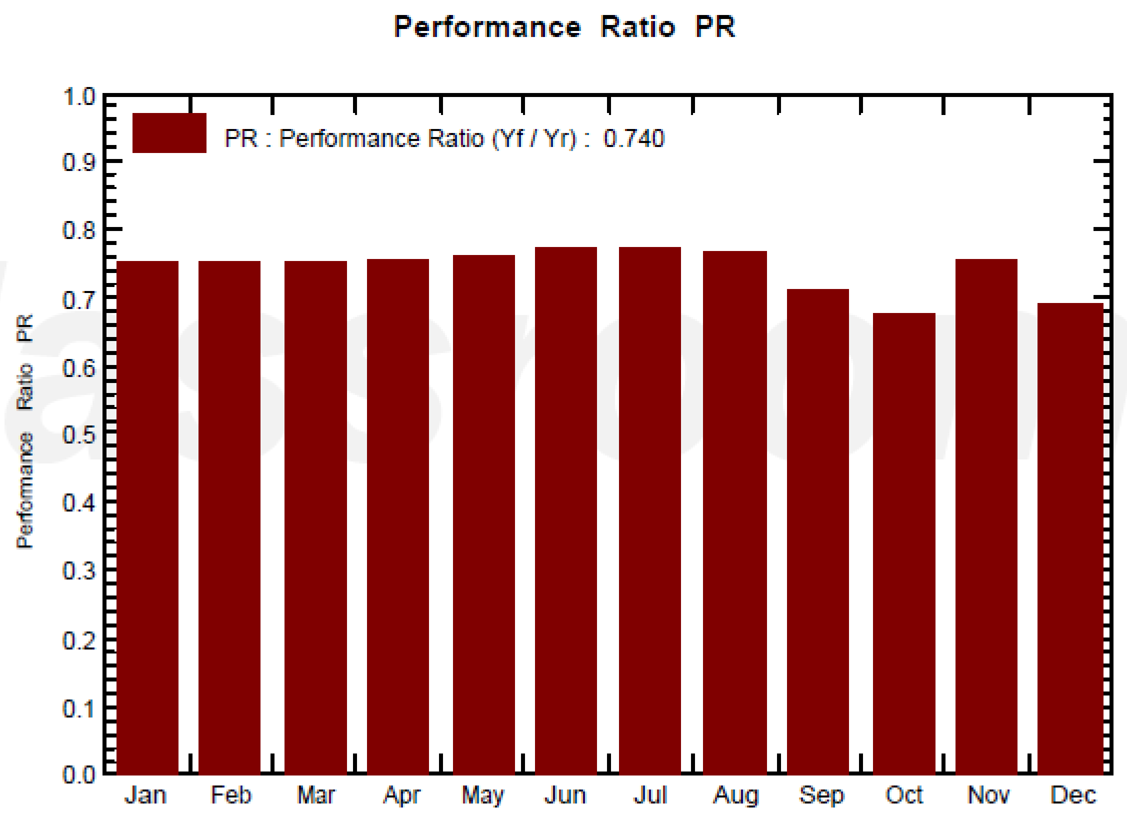


Figure 11: PR for Scenario C

As shown above, Scenario C had the highest PR, followed by scenarios A and B. This indicates that Scenario C is the most efficient of the three systems. Scenario C's high PR suggests an efficient PV system, likely due to its 15-degree tilt angle, which is close to the Northern Hemisphere's optimal angle for solar panels. A quality inverter furthers system efficiency.

The PR of a PV system is affected by several factors, including:

- Tilt angle: The tilt angle of the solar panels is an essential factor in determining the PR. The optimal tilt angle for solar panels in the Northern Hemisphere is typically between 30 and 45 degrees. Solar panels tilted at the optimal angle will receive the most sunlight throughout the year, leading to a higher PR.

- Shading: If trees or other objects shade the solar panels, the sunlight reduces and leads to a lower PR.
- Dust buildup: If the solar panels are covered in dust, this will reduce their sunlight and lead to a lower PR.
- Type of solar panels: The type used will also affect the PR. Some types of solar panels are more efficient than others.
- The efficiency of the inverter: The inverter, which serves as the key device, is responsible for converting the DC electricity produced by solar panels into AC electricity, thereby making it compatible with household appliances and electronic devices for practical usage. The efficiency of the inverter will also affect the PR

Generally, a higher PR indicates a more efficient PV system. Nevertheless, it is essential to understand that PR is only one factor when selecting a PV system. Other aspects, such as cost, space requirements, and aesthetics, should also be considered in your decision.

4.4 System losses

The loss diagram, an integral feature within PVsyst, offers a convenient and illuminating view of the quality of PV system design by pinpointing the primary sources of losses. It is always present in the simulation report for the entire year and is available for each month.

This can be used to improve the PV system's performance, identify the sources of loss that are most significant, and then take steps to address them. A good example is that if soiling losses are a significant source of loss, you can take steps to keep your panels clean. Similarly, if thermal losses are a significant source of loss, steps can be taken to improve the system’s cooling. The loss diagram of a PV system shows the different types of losses that occur between the sun's energy and electricity generated by the PV system. Losses are typically expressed as a percentage of the energy available in the previous stage.

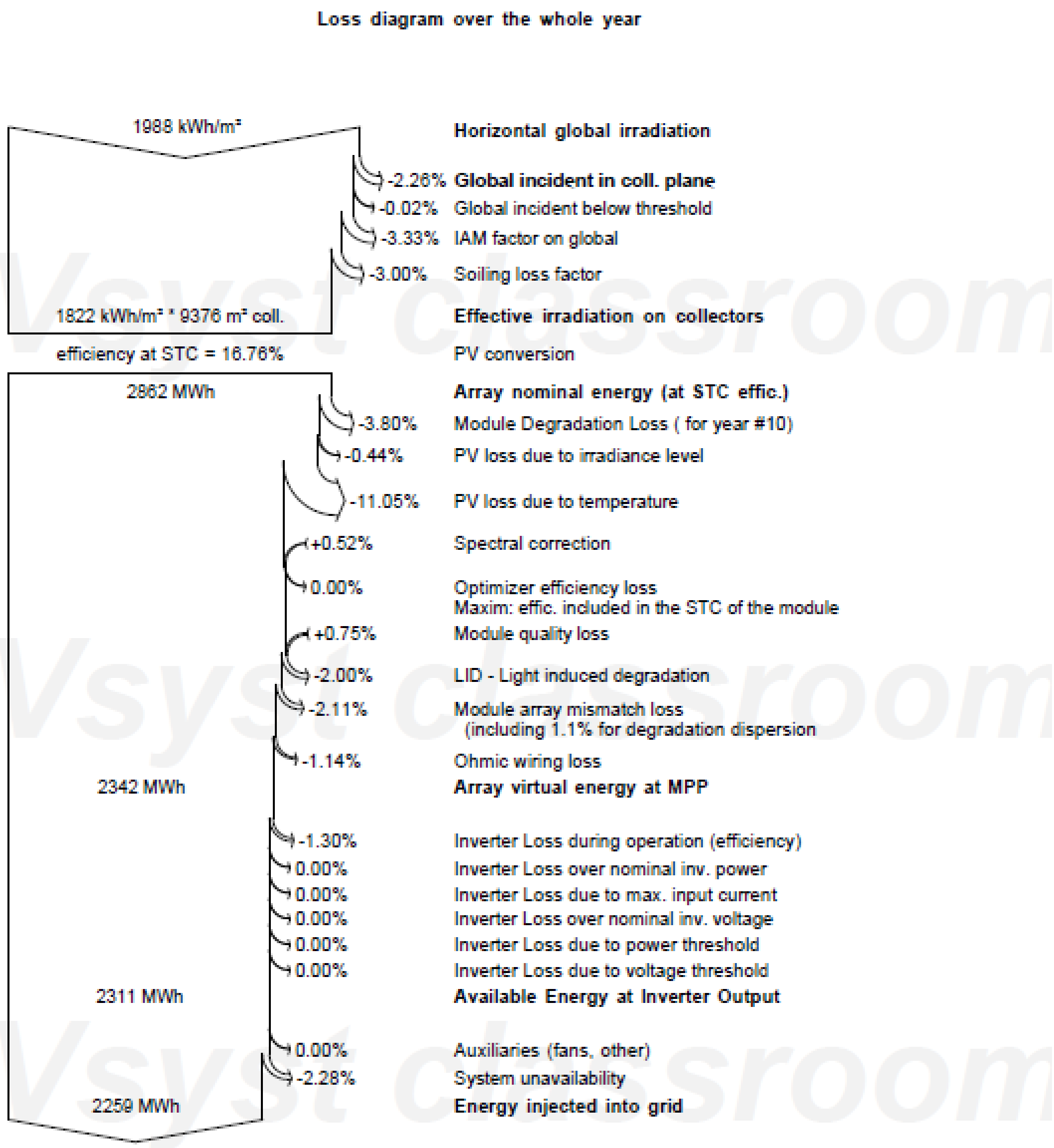


Figure 12: Loss diagram for Scenario A

The loss diagram for Scenario A provided above shows the following losses:

- Horizontal global irradiation: This is the total amount of solar energy that is incident on a horizontal surface that is about 1988kWh/m^2

- Global incident in collector plane: This is the amount of solar energy that is incident on the solar panels, taking into account the tilt angle and orientation of the panels.
- IAM factor on global: This factor accounts for the reduced incident solar energy due to the angle of incidence of the sunlight.
- Soiling loss factor: This factor accounts for the reduced incident solar energy due to the soiling of the solar panels.
- Module efficiency at STC: This is the efficiency of the solar panels under standard test conditions (STC). The efficiency for Scenario A is about 17%
- Array nominal energy (at STC efficiency.): This is the total energy the PV system could generate if operating at STC efficiency.
- Module Degradation Loss (for year 10): This is the solar panels' efficiency loss due to degradation over time, thus over 10 years.
- PV loss due to irradiance level: This is the solar panels' efficiency loss due to operating at a lower level than STC.
- PV loss due to temperature: This is the solar panels' efficiency loss due to operating at a higher temperature than STC.
- Spectral correction: This is a small correction factor that accounts for the different spectral distribution of sunlight in different parts of the world.
- Optimizer efficiency loss: This is a small loss factor that accounts for the energy loss in the optimizer.
- Module quality loss: This is a small loss factor that accounts for the manufacturing tolerances of the solar panels.
- Array virtual energy at MPP: This is the total energy the PV system can generate at its maximum power point (MPP).
- Inverter Loss during operation (efficiency): This is the loss of efficiency of the inverter due to its operating efficiency.
- Inverter Loss over nominal inv. Power: This is a small loss factor that accounts for the energy loss in the inverter due to its nominal power rating.
- Inverter Loss due to max. Input current: This is a small loss factor that accounts for the energy loss in the inverter due to its maximum input current rating.

- Inverter Loss over nominal inv. Voltage: This is a small loss factor that accounts for the energy loss in the inverter due to its nominal voltage rating.
- Inverter Loss due to voltage threshold: This is a small loss factor that accounts for the energy loss in the inverter due to its voltage threshold.
- Available Energy at Inverter Output: This is the total amount of energy available at the output of the inverter.
- Auxiliaries (fans, other): This is a small loss factor that accounts for the energy loss in the auxiliaries of the PV system, such as fans.
- System unavailability: This is a small loss factor that accounts for the unavailability of the PV system due to maintenance or other factors.
- Energy injected into grid: This is the total amount of energy injected into the grid by the PV system.

As shown in the loss diagram, a number of different types of losses can occur in a PV system. However, the overall efficiency of PV systems is still relatively high, with typical efficiencies of approximately 15-20%. This loss diagram is a simplified representation of the losses in the designed PV system. In reality, the losses vary depending on a number of factors, such as the type of solar panel used, the efficiency of the inverter, and environmental conditions.

4.5 Evaluation and Choosing the Best PV System

To answer objective 2: To design and optimize the selected renewable energy technology, after performing the simulation for the scenarios, we had to choose the best system for the grid, from which the energy output, performance, energy production, and efficiency were analyzed, showing that the three systems had different outputs.

Scenario C is the best PV system among the three scenarios. It has the highest specific energy production, total energy production, and performance ratio. Combining a lower tilt angle (15 °) and efficient energy conversion led to superior performance.

Scenario B has the lowest specific energy production and performance ratio, suggesting that a 45-degree tilt angle may not be optimal for this location. Scenario C, with a 15-degree tilt angle, is the best PV system among the three scenarios, as it maximizes energy production and system efficiency.

Scenario A falls in the middle regarding the specific energy production and performance ratio. However, it is essential to consider other factors, such as cost, local climate conditions, and maintenance requirements, when making a final decision for real-world applications.

Table 11: Number of PV modules for the systems

Scenario	Number of PV modules
A	3819
B	5880
C	4832

In Table 11, displayed above, you can find a detailed listing of the necessary quantity of PV modules needed for each respective system. In terms of cost, Scenario B is the most expensive, as it requires the most PV modules. Scenario A was the least expensive because it required the fewest PV modules. Scenario C was between these two scenarios. Considering energy production, efficiency, number of modules required, performance ratio, and maintenance, Scenario A chose the best PV system. It requires fewer PV modules than other systems; thus, cutting costs as capital is the most critical issue, but it still produces the same amount of energy. The installation cost is a significant concern; hence, Scenario A will be installed.

So, based on the analysis, Scenario A emerges as the optimal PV system. Its cost-effective design delivers equivalent energy output while meeting critical budget constraints.

4.6 Economical And Environmental Analysis

The design of PV systems heavily relies on economic and environmental analyses. These analyses form a framework that helps assess and evaluate the feasibility and effectiveness of installing such systems by considering several key factors. Economic and environmental analyses are crucial in designing PV systems as they provide the necessary insights and information to make informed decisions about whether the goal is to save money, decrease the environmental impact, or satisfy sustainability objectives [45]. Following the successful completion of the design, thorough simulation, and confirmation of the viability, the next crucial step involved conducting an in-depth assessment of the economic feasibility of the installation.

Economic and environmental analyses are vital for the design of photovoltaic (PV) systems for multiple reasons. Cost–benefit Analysis: An economic analysis helps determine the financial feasibility of installing a PV system. It considers initial setup costs, operational expenses, and potential revenue or savings from the system. This analysis allows individuals and organizations to make informed decisions about whether to invest in a PV system that is financially viable.

- Return on Investment (ROI): By assessing the economic viability of a PV system, stakeholders can calculate the expected ROI. This helps us understand how long it will take to recoup the initial investment and generate profits or savings. A positive ROI is a key driver for the adoption of PV systems.
- Environmental Impact Assessment: Environmental analysis assesses the ecological footprint of a photovoltaic (PV) system. It evaluates factors such as carbon emissions reduction, reduced dependence on fossil fuels, and overall environmental benefits. This information is important for individuals and organizations interested in reducing their environmental impact and contributing to sustainability goals.

- Life Cycle Assessment: Environmental analysis can include the PV system's life-cycle assessment (LCA). This assessed the ecological consequences of PV panel production on disposal, considering resource extraction, manufacturing, transportation, and end-of-life disposal. This holistic view helps us understand these systems' long-term environmental implications.

4.7 Financial analysis

The primary factor that plays a pivotal role in establishing the value of power generated by PV systems is the upfront cost associated with both hardware and installation. This directly influences the capital required for project implementation. The objective of cost analysis is to determine a project's financial viability from a project developer's perspective to arrive at a suitable investment decision.

The researcher used the OPEX and CAPEX models for the economic analysis, with taxes and energy production in the mix. In the economic evaluation of a PV system, "CAPEX" refers to the "capital expenditure." CAPEX is a crucial financial analysis component representing the upfront investment required for the PV system's design, purchase, installation, and commissioning. This typically includes the following.

1. PV Panels: The cost of purchasing solar panels, which are the primary components for converting sunlight into electricity,
2. Inverters: The cost of inverters that convert direct current (DC) electricity generated by PV panels into alternating (AC) electricity suitable for the project.
3. Mounting and Racking Systems: Expenses related to mounting and racking systems that secure PV panels in place, ensuring optimal exposure to sunlight.
4. Wiring and Electrical Components: Costs associated with wiring, electrical components, and connectors necessary to connect the PV system to the electrical grid.

5. Labour costs: labour expenses, including installation and commissioning by skilled technicians or contractors.
6. Permits and Inspections: Fees for obtaining the necessary permits, inspections, and approvals from relevant authorities, which can vary by location.
7. Land preparation: Costs of preparing the installation site, which may include site clearing, levelling, and foundation work.
8. Balance of System (BoS): Additional costs for components such as surge protectors, meters, and monitoring systems.
9. Project Management and Engineering Costs: Project management, design, and engineering services expenses.
10. Miscellaneous Costs: Any miscellaneous cost specific to the project, such as shipping, insurance, or contingency.

It is imperative to emphasize that OPEX, an acronym for operational expenses, encompasses ongoing costs associated with system maintenance and management. These expenses are associated with running, maintaining, and managing a PV system throughout its lifetime. These costs are incurred after the PV system is installed and operational. OPEX includes various expenses such as:

1. Routine Maintenance: The Costs of inspecting, cleaning, and maintaining PV panels, inverters, and other system components regularly to ensure optimal performance.
2. Repairs and Replacements: Funds set aside for repairing or replacing components that degrade or malfunction over time, such as damaged solar panels or inverters.
3. Monitoring and Management: Expenses for remote monitoring, system management, and data analysis to ensure that the PV system operates efficiently and that any issues are addressed immediately.
4. Insurance: Premiums for insurance coverage to protect against damage, theft, or other unforeseen events that may affect the PV system.
5. Administrative and Regulatory Fees: Fees for administrative tasks, regulatory compliance, and any reporting or documentation required by authorities.

6. Inverter Replacement: Because inverters have a shorter lifespan than PV panels, they may need to be replaced during the system's operational life.
7. Site Security: Costs related to security measures to prevent theft or vandalism of the PV system, such as fencing, alarms, or surveillance.
8. Land Lease or Space Rental: If a PV system is installed on land or in a facility that the PV system owner does not own, lease or rental fees may be associated with using the space.
9. Utilities: Electricity costs for powering equipment related to the PV system, such as monitoring systems and administrative facilities.
10. Wages and salaries for personnel in charge of monitoring, maintenance, and administrative tasks related to the PV system

The capital expenditure for the PV syst is shown in the table below.

The quoted sources are from the current market price as of 20 October 2023. In the table, quantity is defined as units; for example, on the PV modules, there are 3,819 units. This indicates the quantity of the Q.PLUS L-G4.1 340 modules being procured for the PV system; in this case, it is 3819 units. 1'200.00 ZAR/unit: This is the cost per unit of the Q.PLUS L-G4.1 340 module, expressed in South African Rand (ZAR). Each module costs 1200 ZAR. 4'582'800.00 ZAR: This is the total cost for all the modules. It is calculated by multiplying the quantity of units (3819) by the cost per unit (1200 ZAR). This gives a total of 4,582,800 ZAR.

Table 12: Capital expenditure of the system

Description	Price per unit (ZAR)	Number of units required (quantity)	Total Costs (ZAR)
PV modules	1200	3819	4 582 000
Inverters	4600	4	18 000
Support for Modules	60	3819	210 045
Loan and bank charges		1	2 500 000
Installations and land preparations			1 937 500
Transport	50	650	32 500
Accessories, Fasteners	1.25	200 000	6 500
Settings of the system			250 000
Land and labour taxes			670 000
Studies and analysis			32 600
Gross Investment		**9 371 595.00 (ZAR)**	

Removing taxes and subsidies of about 35 000 ZAR, the Net Investment (CAPEX) is 9 336 500.00 ZAR.

This means that approximately 10 million rands are required for this investment. The table below outlines the sources of funds allocated to finance this project. The investment will be funded through a combination of equity investment, a bank loan, and government incentives, with the total investment amounting to 10 million rands, as shown below.

Table 13: Financing of the PV system

Source of funds	Amount ZAR
Equity Investment	1 500 000
Bank loan	5 000 000
Government Incentives	*Approx figure*

The table below illustrates the operating costs per year. Regarding investment costs, the operating costs are fully customizable to fit the system's specific needs. These costs come into play after the PV system's installation and operationalization.

Table 14:Operating posts per year

Description	Total costs (ZAR)
Wages or Salaries	187 000
Maintenance	32 000
Monitoring	23 550
Insurance	45 000
Total per year	**295 244/year**

Table 15: Economic evaluation of the system

Detailed economic results (kZAR)

Year	Sold energy	Loan principal	Interest 2.50%	Run. costs	Deprec. allow.	Taxable income	Tax 0.00%	After-tax profit	Cumul. profit	% amorti.
2024	7'817	610	171	288	937	6'421	0	6'748	6'748	78.8%
2025	7'817	625	156	289	937	6'435	0	6'747	13'495	157.8%
2026	7'817	641	140	291	937	6'449	0	6'745	20'240	236.9%
2027	7'817	657	124	292	937	6'464	0	6'744	26'984	316.1%
2028	7'817	674	108	294	937	6'479	0	6'742	33'726	395.6%
2029	7'817	690	91	295	937	6'494	0	6'741	40'467	475.2%
2030	7'817	708	73	297	937	6'510	0	6'739	47'206	554.9%
2031	7'817	725	56	298	937	6'526	0	6'738	53'944	634.9%
2032	7'817	744	38	300	937	6'543	0	6'736	60'680	715.0%
2033	7'817	762	19	301	937	6'560	0	6'735	67'415	795.3%
Total	78'172	6'837	975	2'946	9'372	64'880	0	67'415	67'415	795.3%

kZAR stands for kilo South African Rand (1,000 South African Rand). Based on the economic evaluation, the PV system in Scenario A is a viable investment. The system has a payback period of 11.8 years and is expected to generate positive net income annually. As shown in the table from 2023–2033, there will be an increase in profits from the system. Cash flow was calculated based on the rate from the government, and the green side of the table shows profits from 2024 upwards, starting at 79%, which is the best investment. The investment cost is less than the cumulative profit amount, so positive values result in annual profits from the PV system. The return on investment is already positive as of 2024, which means that the payback period for the system is about 1.3 years, with a percentage of 695% of the capital in 20 years of service. The table also shows that profit from the system is expected to increase over time. This is due to the fact that the operating costs of the system are relatively low, and the price of electricity is expected to rise over time.

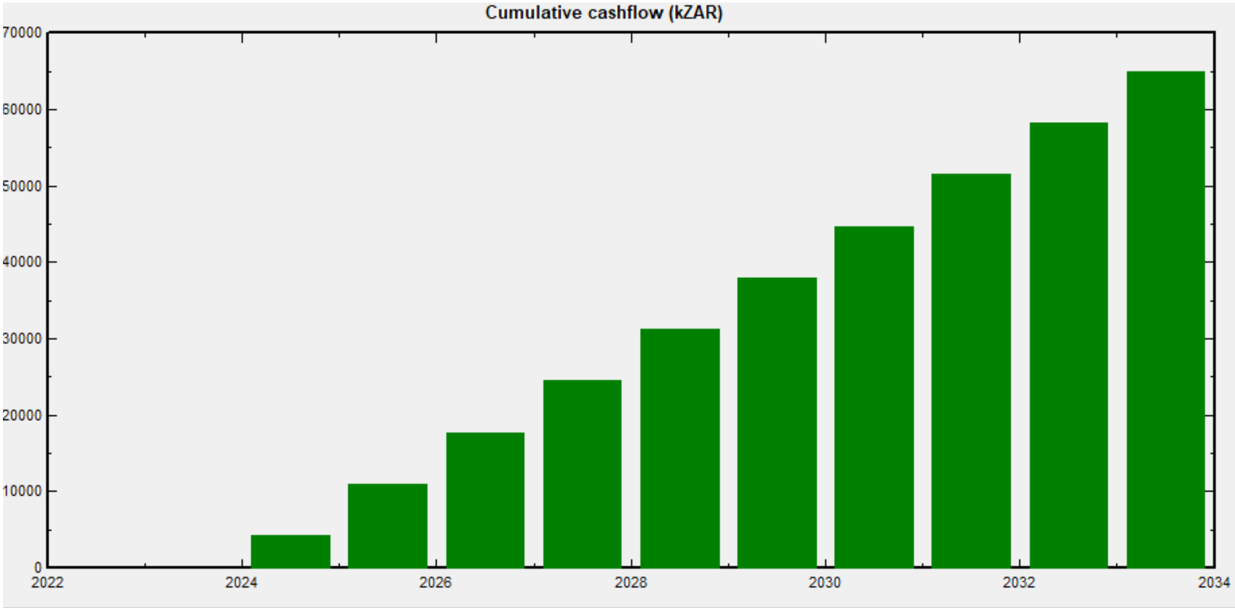


Figure 13: Cumulative cash flow for the PV System

The cumulative profit graph is a valuable metric for evaluating the economic performance of a PV system. Adding up the profit from each year provides a visual representation of the total profit generated over time. The cumulative profit graph shows the total profit generated by the PV system over time. This is calculated by adding the profit from each year. The diagram typically starts at zero and increases over time as the system generates more profit. The cumulative profit graph is a valuable tool for assessing the economic performance of PV systems. A system displaying a high incremental profit is a more substantial investment option than a low cumulative profit. Analyzing scenario A's cumulative profit graph reveals that the PV system is projected to yield a positive incremental profit from its inaugural year of operation from 2024 to 2034. This positive outlook signals the system's likelihood of being profitable. Analyzing the graph trends shows that this is a good indicator of the long-term profitability of a PV system.

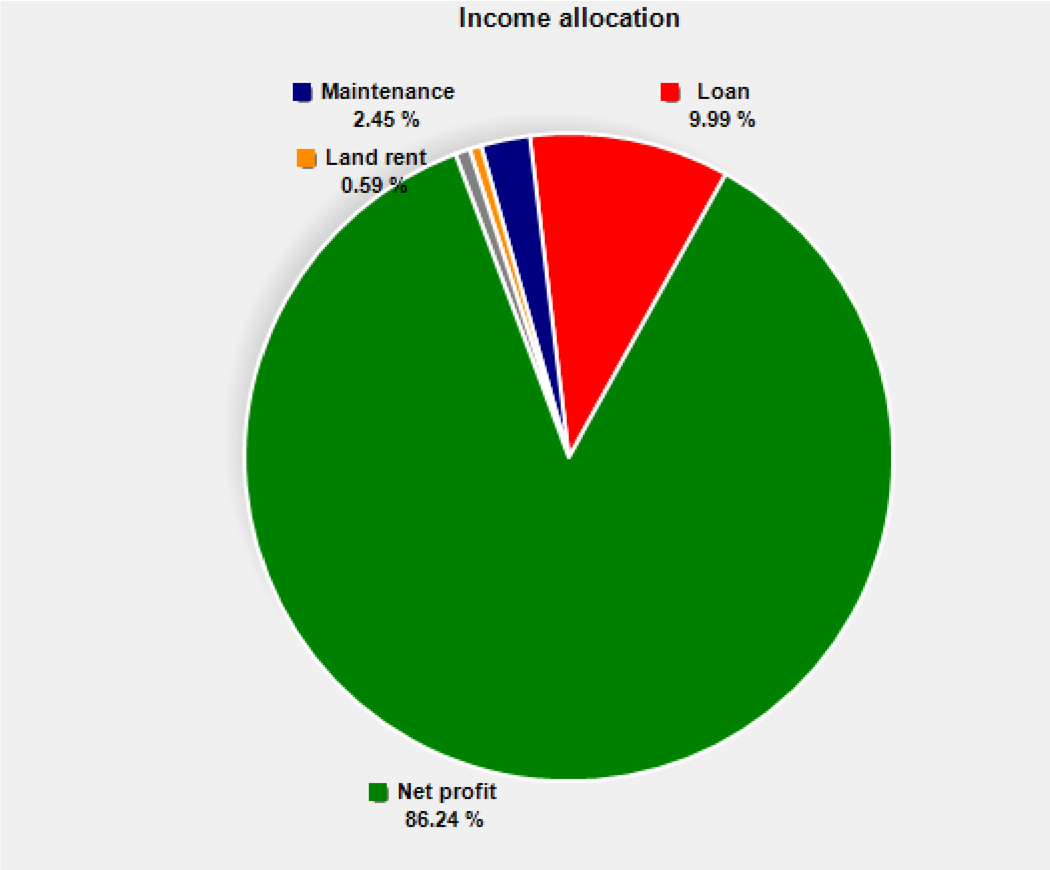


Figure 14:Income allocation from the project

The pie chart above illustrates income allocation for the project and reveals the following income distribution:

Profit: 86.4%

Loan: 9.99%

Maintenance: 2.45%

Land rent: 0.59%

The dominant source of income in scenario A for the PV system is profit. Therefore, a significant portion of the revenue generated by the PV system in scenario A is projected to come from profit. This is a positive sign, indicating that the system is bound to be profitable. Despite the second-highest expense, the loan payment remains modest in relation to the system's profit. This means that covering the loan cost should cause no significant issues, and the maintenance and land rent expenses are relatively small; however, they should still be factored into the overall cost of the system. Overall, the pie chart for scenario A, illustrating the income allocation, shows that the PV system is expected to be profitable.

4.8 Environmental Analysis

The environmental impact of a photovoltaic (PV) system refers to its effects on the environment throughout its life cycle, from its development and installation through operation and disposal. PV systems have a generally favourable environmental impact due to their role in decreasing greenhouse gas emissions and supporting clean energy generation. PV systems do not produce any greenhouse gas emissions or air pollution during operation. The land footprint necessary for a PV system remains relatively compact compared with other energy generation methods, particularly when compared with large-scale coal-fired power plants. The details for this can be further seen in the Appendix.

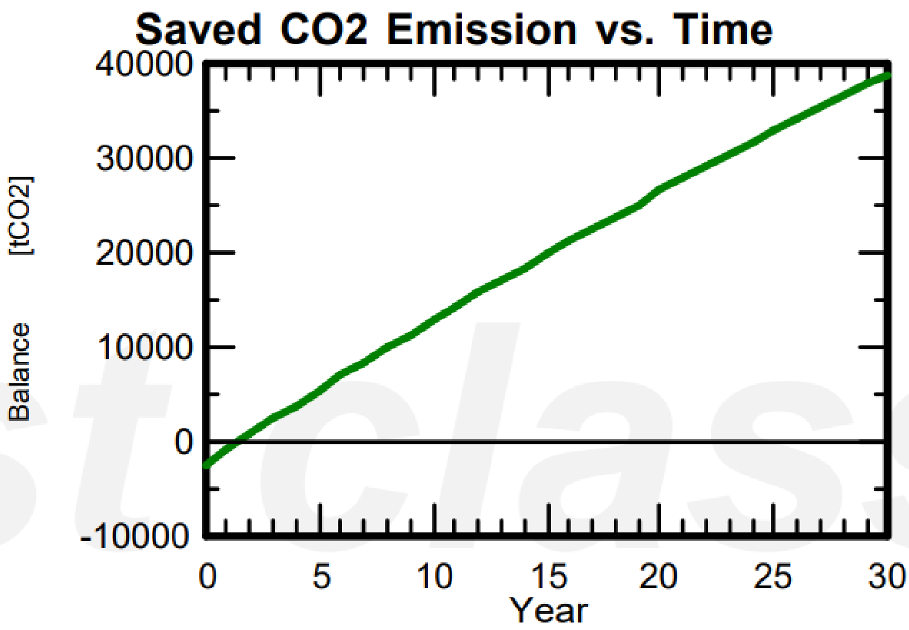


Figure 15: Carbon dioxide emission vs time

The graph showing saved carbon dioxide for the PV system in scenario A shows the cumulative amount of carbon dioxide that will be saved over time using the PV system instead of a traditional fossil fuel-based power source. The graph indicates that the PV system is expected to save significant carbon dioxide over its lifetime. Thus, measuring the environmental benefits of using solar instead of fossil fuel is vital. The graph shows that PV systems can help reduce greenhouse gas emissions and contribute to a more sustainable future. The details are provided in the appendix.

Based on the outcomes obtained from the simulation conducted for Scenario A, it is evident that the employment of the PV system leads to substantial savings in terms of carbon dioxide emissions, thus about 38 996.460 tons in 30 years, as shown in Figure 15 below, which means 3409 tCO2/year, considering an annual degradation of 1%. This value is also 1,001 tCO2/kWp/year, which is acceptable in ecological terms. For more comprehensive information and additional specifics, refer to the Appendix section.

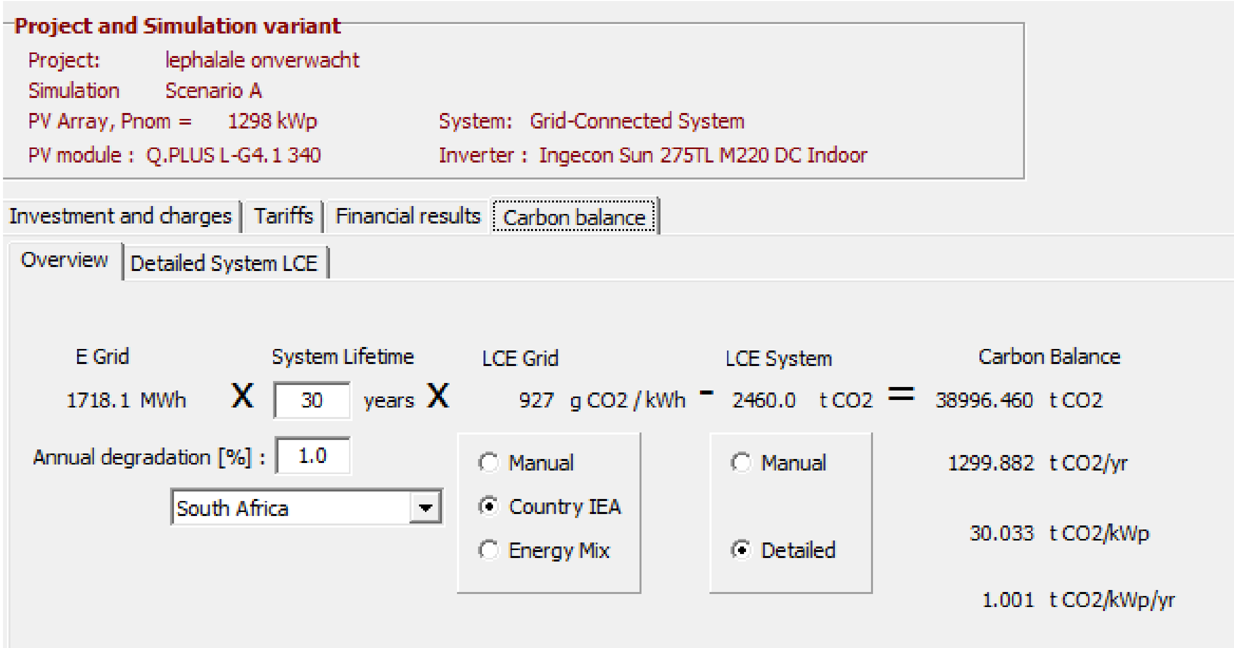


Figure 16: Carbon balance calculation for the system

4.9 The Sustainability Dynamics of the Project

The economic, social, and environmental sustainability benefits of the project in Lephalale demonstrate the potential for positive change within the community while contributing to broader national sustainability goals in South Africa. This aligns with the principles of a well-justified business case, showing the tangible and practical benefits of the investment. The Lephalale Project aligns with the NDP's vision by promoting clean and sustainable energy sources. The project also aligns with the IRP's goals by contributing to the country's renewable energy targets, as outlined in the plan.

4.9.1 Economic Sustainability:

1. Job Creation: A PV system's installation, maintenance, and operation may generate employment opportunities within the local community. Skilled and

unskilled jobs related to the solar industry could emerge and contribute to economic growth.

2. Reduced electricity costs: Lephalale residents and businesses can see lower electricity bills as the solar PV system generates clean power, reducing reliance on the grid.
3. Long-Term Cost Stability: Solar energy systems often have lower operational and maintenance costs than conventional energy sources. This stability in costs can provide economic predictability for the community in the long term.

4.9.2 Social Sustainability

1. Access to Electricity: Lephalale previously faced challenges with reliable electricity access; this project will significantly improve this situation. Residents will have a more reliable and consistent power supply, contributing to an enhanced quality of life, and will become less reliant on the national grid, thereby reducing the impact of power outages.
2. Community Empowerment: The project may encourage community engagement and involvement in sustainable initiatives. Residents can participate in decision-making processes, fostering a sense of ownership and community pride.
3. Improved health: Reduced reliance on coal-fired power plants would lead to cleaner air, improving public health

4.9.3 Environmental Sustainability

1. Reduced Carbon Footprint: Solar energy is a clean and renewable energy source that contributes to a reduction in greenhouse gas emissions. A community can lower its carbon footprint and promote a healthier environment by utilizing solar power.
2. Natural Resource Preservation: Solar power generation involves minimal natural resource consumption compared to traditional energy sources, such as

coal or natural gas. This contributes to the conservation of natural resources and the protection of the local environment.

The project's positive impact can extend beyond Lephalale to contribute to South Africa's broader sustainability goals.

4.10 Conclusion

The chapter thoroughly analyzes the grid-connected PV system from a techno-economic standpoint and evaluates its environmental impact. The results indicate that a grid connection using Scenario A is viable and demonstrates renewable energy sources' superiority over traditional coal-fired power stations regarding sustainability. Furthermore, the analysis demonstrated that renewable energy sources are a more sustainable alternative to traditional coal-fired power stations.

CHAPTER 5 : CONCLUSION AND RECOMMENDATIONS

5.0 Introduction

The previous section analyzed the results of the designed PV system. This study explored the feasibility and optimization of new energy technologies, specifically focusing on grid-connected photovoltaic (PV) systems, using PVsyst as a software tool for design and analysis. The research has revealed several significant findings and insights that contribute to the broader goal of sustainable development.

5.1 Conclusion

New energy technologies play vital roles in sustainable development [16]. They offer the potential to reduce greenhouse gas emissions, improve energy security, and create jobs. However, it is essential to carefully assess the feasibility and optimize the deployment of new energy technologies to ensure they are truly sustainable.

This thesis presents a feasibility analysis and optimization of new energy technologies for sustainable development. After an extensive literature review and research gaps, this research focused on grid-connected photovoltaic systems, one of the most promising renewable energy technologies. This study aimed to evaluate the techno-economic feasibility of a grid-connected photovoltaic system. The research also highlights the importance of adopting renewable energy sources in the fight against climate change and reducing greenhouse gas emissions. The use of renewable energy sources such as solar, wind, and hydropower can significantly reduce the reliance on fossil fuels, which is essential to reduce environmental impact and actively contribute to the mitigation of adverse climate change effects.

The author developed a methodology for designing and optimizing grid-connected PV systems using PV syst software. This methodology was applied to a case study of a PV system in Lephalale, South Africa. The designed and simulated grid-connected PV system using the PVsyst software has proven an effective solution for sustainable energy production. Analysis of grid-connected PV systems has demonstrated the potential of solar energy as a viable and sustainable energy source. A detailed feasibility study, including site selection, energy production estimates, and economic analysis, provides a comprehensive view of the benefits and challenges associated with such systems.

Additionally, this thesis emphasizes the significance of considering environmental impacts and local regulatory frameworks to ensure the sustainability of PV projects. By incorporating such considerations into the analysis, we are better equipped to meet the long-term energy needs of communities while minimizing their ecological footprints. Overall, the findings of this thesis suggest that grid-connected PV systems are a feasible and sustainable option for meeting the energy needs in South Africa. This is linked to SDG-7 access to affordable and reliable energy sources. Therefore, grid-connected PV systems can help achieve SDG 7 in several ways. They can provide access to electricity for people without electricity, particularly in rural and remote areas. PV systems can reduce electricity costs, making them affordable to everyone.

5.2 Recommendations

This study demonstrates that a PV system is technically and economically feasible and can substantially impact sustainable development in South Africa. Based on the findings and analysis presented in this thesis, several recommendations can be made for future research in the field of sustainable energy development:

1. Further Research and Development

Continue research on emerging energy technologies, and stay updated with advancements in PV technology. The integration of energy storage solutions, such as batteries, has been explored to enhance the system's reliability. An improvement of this integration should be looked at.

2. Economic incentives and policy support

We are advocating for implementing government incentives and policies that promote renewable energy adoption. Governments and policymakers should support developing and deploying new energy technologies such as grid-connected PV systems. This can be achieved through financial incentives, tax breaks, or other policy measures.

3. Community Education:

Develop educational programs and community outreach initiatives to raise awareness of the benefits of solar energy. A well-informed public member will likely support and invest in sustainable energy solutions.

4. Environmental Impact Mitigation

Invest in the research and development of technologies and practices to minimize the environmental impact of PV systems, such as recycling and sustainable end-of-life management of solar panels. Investors should consider investing in new energy technologies such as grid-connected PV systems. These technologies have the potential to generate attractive returns and contribute toward sustainable development.

5. Continuous Monitoring and Maintenance

The importance of regular monitoring and maintenance of PV systems to ensure that they operate at peak efficiency is emphasized. This includes cleaning, equipment inspection, and software updates.

6. More research and collaboration

Collaboration should be encouraged among academia, industry, and the government to share knowledge, best practices, and data that can improve PV technology and sustainable energy adoption. Therefore, researchers should continue developing and improving new energy technologies. This includes developing more efficient and cost-effective PV systems and new energy-storage technologies.

Overall, the findings of this thesis suggest that grid-connected PV systems are a feasible and sustainable option to meet South Africa's energy needs. By implementing the recommendations above, the government, investors, and community can work together to develop and deploy a successful PV system that will benefit all.

Therefore, by implementing these recommendations, we can work towards a future where sustainable energy technologies, such as grid-connected PV systems, play a central role in achieving our environmental and economic goals. The journey towards sustainable development is ongoing, requiring collective efforts and ongoing research to realize its full potential.

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APPENDIX

Grid-Connected System: Simulation parameters

Project : **lephalale onverwacht**

Geographical Site	**Lephalale**		Country	**South Africa**
Situation	Latitude	0.01° N	Longitude	0.00° E
Time defined as	Legal Time	Time zone UT	Altitude	0 m
	Albedo	0.20		
Meteo data:	**Lephalale**	Meteonorm 7.2 (1991-2010) - Synthetic		

Simulation variant : **Lephalale Project Scenario A**

	Simulation date	06/11/23 22h49
	Simulation for the	**10th year of operation**

Simulation parameters	System type	**No 3D scene defined, no shadings**		
Collector Plane Orientation	Tilt	30°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics

PV module	Si-poly	Model	**Q.PLUS L-G4.1 340**		
Original PVsyst database		Manufacturer	Hanwha Q Cells		
Number of PV modules		In series	19 modules	In parallel	201 strings
Total number of PV modules		Nb. modules	3819	Unit Nom. Power	340 Wp
Array global power		Nominal (STC)	**1298 kWp**	At operating cond.	1168 kWp (50°C)
Array operating characteristics (50°C)		U mpp	646 V	I mpp	1807 A
Total area		Module area	**7615 m²**	Cell area	6693 m²

Inverter	Model	**Ingecon Sun 275TL M220 DC Indoor**		
Original PVsyst database	Manufacturer	Ingeteam		
Characteristics	Operating Voltage	405-820 V	Unit Nom. Power	280 kWac
Inverter pack	Nb. of inverters	8 * MPPT 50 %	Total Power	1120 kWac
			Pnom ratio	1.16

PV Array loss factors

Array Soiling Losses			Loss Fraction	3.0 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	6.0 mOhm	Loss Fraction	1.5 % at STC
Serie Diode Loss	Voltage Drop	0.7 V	Loss Fraction	0.1 % at STC
LID - Light Induced Degradation			Loss Fraction	2.0 %
Module Quality Loss			Loss Fraction	-0.4 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Module average degradation	Year no	10	Loss factor	0.4 %/year
Mismatch due to degradation	Imp RMS dispersion	0.4 %/year	Vmp RMS dispersion	0.4 %/year

Incidence effect (IAM): User defined profile

0°	20°	40°	60°	70°	75°	80°	85°	90°
1.000	1.000	1.000	0.970	0.900	0.830	0.690	0.440	0.000

Spectral correction FirstSolar model. Precipitable water estimated from relative humidity

Coefficient Set	C0	C1	C2	C3	C4	C5
Polycrystalline Si	0.8409	-0.027539	-0.0079224	0.1357	0.038024	-0.0021218

Grid-Connected System: Simulation parameters

Unavailability of the system	7.3 days, 3 periods	Time fraction	2.0 %
Auxiliaries loss	constant (fans) 0 W	... from Power thresh.	0.0 kW

Grid-Connected System: Main results

Project : **lephalale onverwacht**

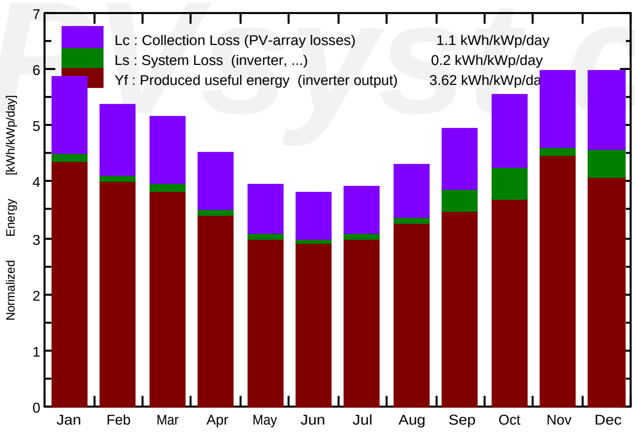
Simulation variant : **Lephalale Project Scenario A**

Simulation for the 10th year of operation

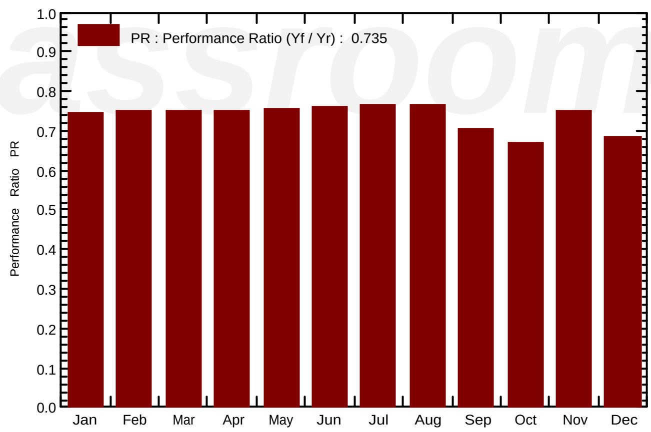
Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340	Pnom	340 Wp
PV Array	Nb. of modules	3819	Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.0	Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1717 MWh/year**	Specific prod.	1323 kWh/kWp/year
	Performance Ratio PR	73.46 %		
Investment	Global incl. taxes	9336595.00 ZAR	Specific	7.19 ZAR/Wp
Yearly cost	Annuities (Loan 3.00%, 10 years)	801457.50 ZAR/yr	Running Costs	288000.00 ZAR/yr
Energy cost		**0.79 ZAR/kWh**	Payback period	**1.3 years**

Normalized productions (per installed kWp): Nominal power 1298 kWp



Performance Ratio PR



Lephalale Project Scenario A

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	167.9	88.60	27.63	181.7	172.9	181.4	176.0	0.746
February	148.6	85.20	27.97	150.1	142.5	150.3	145.8	0.748
March	170.8	92.70	28.17	159.0	150.5	159.5	154.7	0.749
April	163.7	77.90	27.43	135.8	127.5	136.7	132.6	0.752
May	163.4	80.50	27.40	122.5	113.9	123.9	120.1	0.755
June	162.6	73.20	25.58	114.3	105.7	116.5	113.0	0.761
July	169.2	73.40	24.93	121.6	112.8	124.3	120.5	0.763
August	167.3	82.80	25.33	132.8	124.4	135.9	131.7	0.764
September	167.2	76.00	25.76	148.0	139.7	150.1	135.2	0.704
October	174.6	85.70	26.50	171.2	162.3	171.4	149.1	0.671
November	167.0	81.40	26.33	178.9	170.2	179.6	174.3	0.750
December	165.6	82.20	27.19	184.6	175.7	184.7	164.3	0.685
Year	1987.9	979.60	26.68	1800.5	1698.2	1814.4	1717.4	0.735

Legends:

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

Grid-Connected System: Special graphs

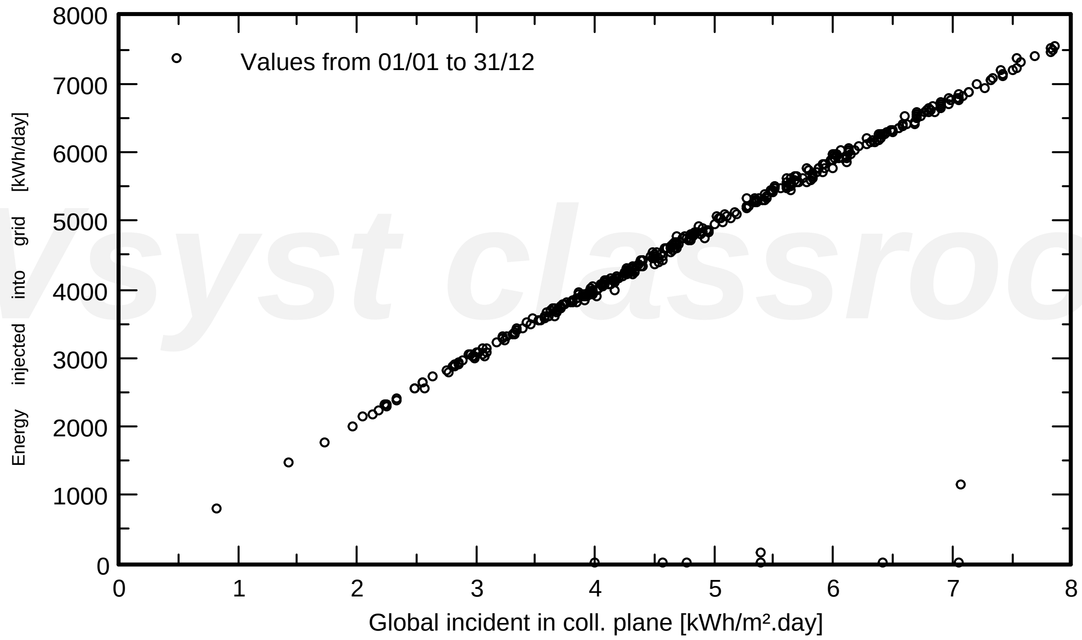
Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario A**

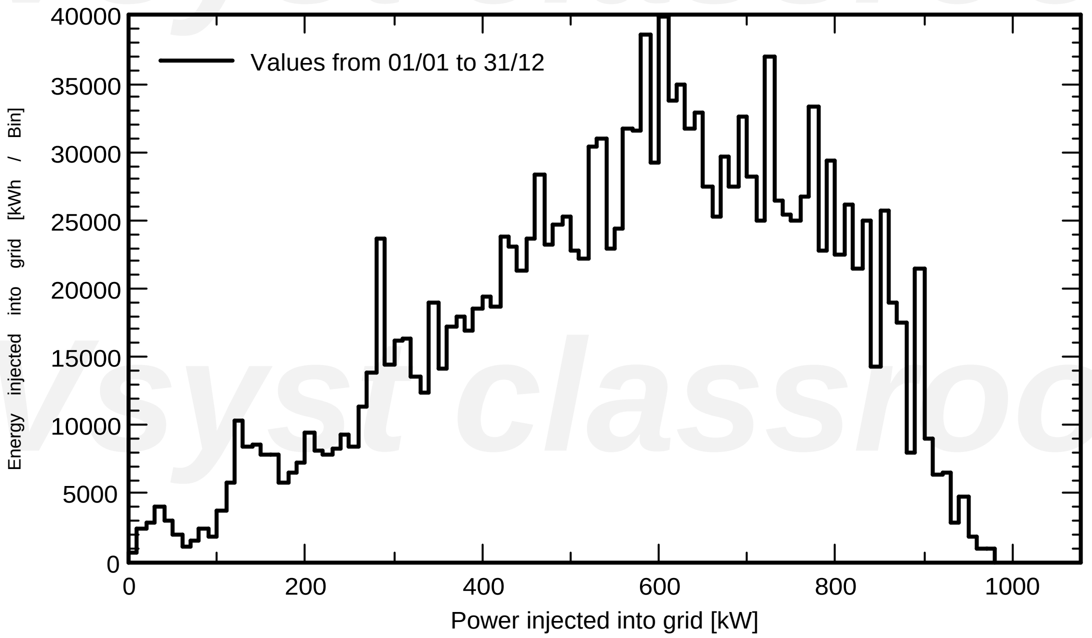
Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340	Pnom	340 Wp
PV Array	Nb. of modules	3819	Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.0	Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)			

Daily Input/Output diagram



System Output Power Distribution



Grid-Connected System: Loss diagram

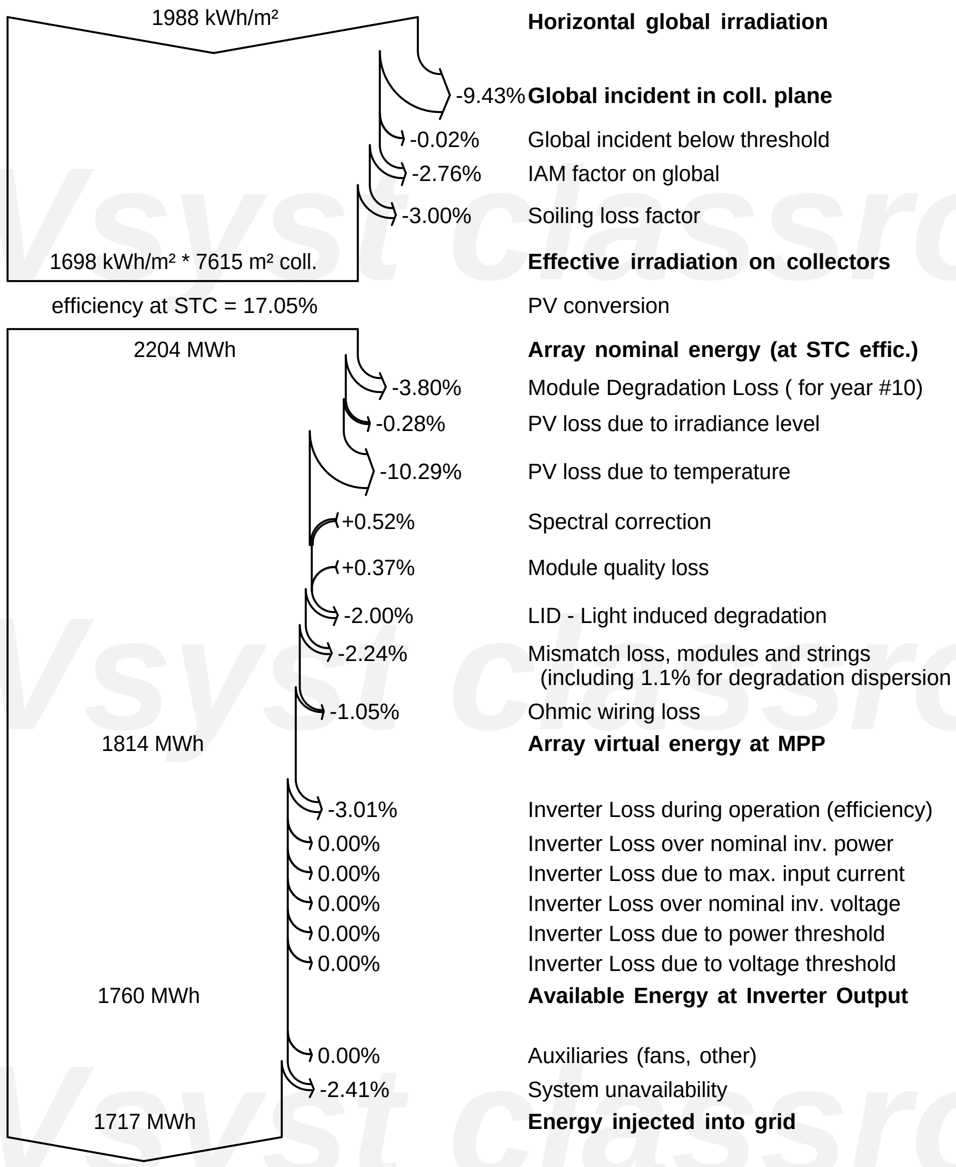
Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario A**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340	Pnom	340 Wp
PV Array	Nb. of modules	3819	Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.0	Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



Grid-Connected System: Economic evaluation

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario A**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340	Pnom	340 Wp
PV Array	Nb. of modules	3819	Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.0	Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)			

Investment

Direct costs			
PV modules			
Q.PLUS L-G4.1 340	3819 units	1'200.00 ZAR / unit	4'582'800.00 ZAR
Supports for modules	3819 units	55.00 ZAR / unit	210'045.00 ZAR
Inverters			
Ingecon Sun 275TL M220 DC Indoor	4 units	4'600.00 ZAR / unit	18'400.00 ZAR
Studies and analysis			
Engineering	5 units	500.00 ZAR / unit	2'500.00 ZAR
Environmental studies	10 units	2'500.00 ZAR / unit	25'000.00 ZAR
Installation			
Transport	50 units	650.00 ZAR / unit	32'500.00 ZAR
Accessories, fasteners	20000 units	0.25 ZAR / unit	5'000.00 ZAR
Wiring	800 units	0.75 ZAR / unit	600.00 ZAR
Settings	5000 units	0.20 ZAR / unit	1'000.00 ZAR
Land costs			
Land preparation	155 units	12'500.00 ZAR / unit	1'937'500.00 ZAR
Land taxes			56'250.00 ZAR
Loan bank charges			2'500'000.00 ZAR
		Gross investment	**9'371'595.00 ZAR**
Taxes and subsidies			
Subsidies			-35'000.00 ZAR
		Net investment (CAPEX)	**9'336'595.00 ZAR**

Operating costs

Maintenance	
Salaries	85'000.00 ZAR / year
Reparation	50'000.00 ZAR / year
Cleaning	34'000.00 ZAR / year
Security fund	18'000.00 ZAR / year
Land rent	45'000.00 ZAR / year
Bank charges	56'000.00 ZAR / year
Total (OPEX)	**288'000.00 ZAR / year**
Operating costs (OPEX) incl. Inflation (1.00%)	**298'613.59 ZAR / year**

System summary

Net investment	**9'336'595.00 ZAR**
Own funds	2'500'000.00 ZAR
Loan (10 years) Rate 3.00 % / year Annuities 801'457.50 ZAR / year	6'836'595.00 ZAR
Total yearly cost (inc. inflation 1.00 % / year)	**1'100'071.08 ZAR / year**
Produced Energy	**1717 MWh / year**
Cost of produced energy	**0.786 ZAR / kWh**

(sum of costs over lifetime / total production over lifetime)

Grid-Connected System: Long Term Financial Balance

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario A**

Simulation for the 10th year of operation

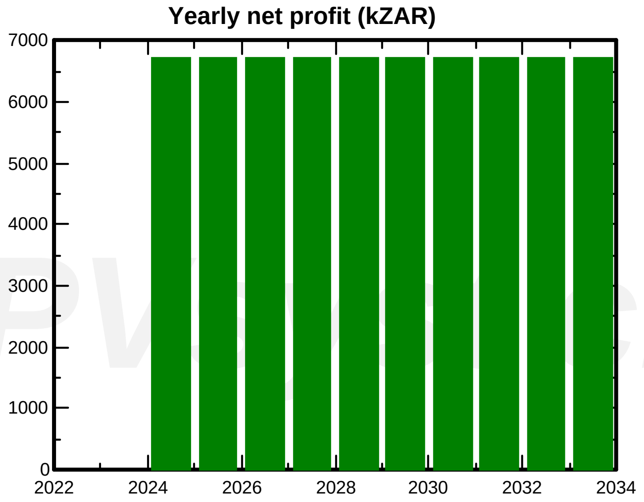
Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340	Pnom	340 Wp
PV Array	Nb. of modules	3819	Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.0	Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)			

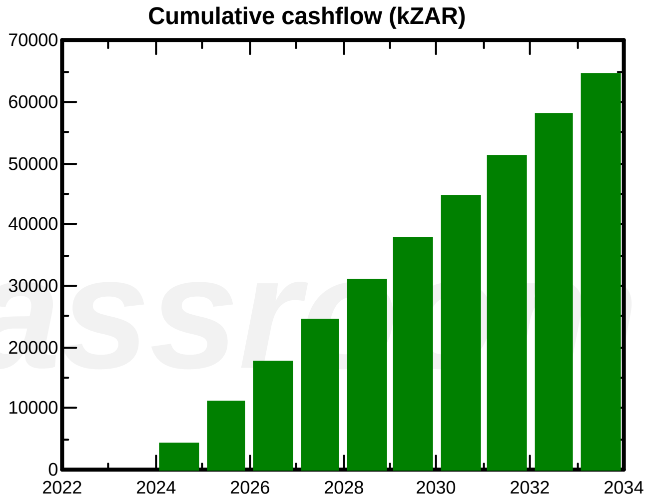
Electricity sale

Feed-in tariff	**4.55 ZAR/kWh**
Duration of tariff warranty	20 years
Annual connection tax	0.00 ZAR
Annual tariff variation	0.0 % / year
Feed-in tariff variation after warranty	-50.00 %

Return on investment

Project lifetime	**10 years**
Payback period	**1.3 years**
Net profit at end of lifetime	**64'613'588.47 ZAR**
Return on investment (ROI)	**692.0 %**





Grid-Connected System: Long Term Financial Balance

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario A**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**			
PV Field Orientation	tilt	30°		azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340		Pnom	340 Wp
PV Array	Nb. of modules	3819		Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor		Pnom	280 kW ac
Inverter pack	Nb. of units	4.0		Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)				

Detailed economic results (kZAR)

Year	Sold energy	Loan principal	Interest 3.00%	Run. costs	Deprec. allow.	Taxable income	Tax 0.00%	After-tax profit	Cumul. profit	% amorti.
2024	7'814	596	205	288	937	6'384	0	6'725	6'725	78.4%
2025	7'814	614	187	291	937	6'399	0	6'722	13'446	157.0%
2026	7'814	633	169	294	937	6'414	0	6'719	20'165	235.7%
2027	7'814	652	150	297	937	6'430	0	6'716	26'881	314.6%
2028	7'814	671	130	300	937	6'447	0	6'713	33'594	393.7%
2029	7'814	691	110	303	937	6'464	0	6'710	40'304	473.0%
2030	7'814	712	89	306	937	6'482	0	6'707	47'011	552.5%
2031	7'814	733	68	309	937	6'500	0	6'704	53'715	632.1%
2032	7'814	755	46	312	937	6'519	0	6'701	60'416	712.0%
2033	7'814	778	23	315	937	6'539	0	6'698	67'114	792.0%
Total	78'141	6'837	1'178	3'013	9'372	64'579	0	67'114	67'114	792.0%

Grid-Connected System: CO2 Balance

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario A**

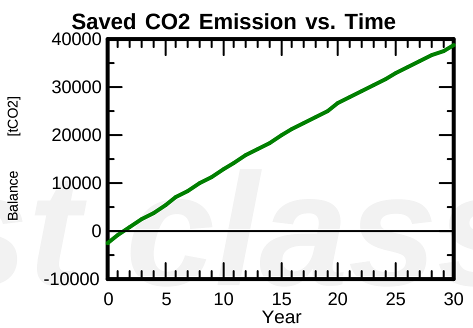
Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	Q.PLUS L-G4.1 340	Pnom	340 Wp
PV Array	Nb. of modules	3819	Pnom total	**1298 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.0	Pnom total	**1120 kW ac**
User's needs	Unlimited load (grid)			

Produced Emissions	**Total:**	**2460.03 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**47760.6 tCO2**		
	System production:	1717.39 MWh/yr	Lifetime:	30 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	927 gCO2/kWh		
	Source:	IEA List	Country:	South Africa
CO2 Emission Balance	**Total:**	**38980.2 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	1713 kgCO2/kWp	6.18 kgCO2/kg
Quantity	1298 kWp	38190 kg
Subtotal [kgCO2]	2223898	236132



Grid-Connected System: Simulation parameters

Project : **lephalale onverwacht**

Geographical Site	**Lephalale**		Country	**South Africa**
Situation	Latitude	0.01° N	Longitude	0.00° E
Time defined as	Legal Time	Time zone UT	Altitude	0 m
	Albedo	0.20		
Meteo data:	**Lephalale**	Meteonorm 7.2 (1991-2010) - Synthetic		

Simulation variant : **Lephalale Project Scenario B**

	Simulation date	06/10/23 10h15
	Simulation for the	**10th year of operation**

Simulation parameters	System type	**No 3D scene defined, no shadings**		
Collector Plane Orientation	Tilt	45°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics

PV module Si-poly	Model	**ET-P660_255WWCO Maxim**		
Original PVsyst database	Manufacturer	ET Solar		
Maxim integrated optimizers	Model	**VT8020**	Unit Nom. Power	3 x 93 W
Number of PV modules	In series	21 modules	In parallel	280 strings
Total number of PV modules	Nb. modules	5880	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**1499 kWp**	At operating cond.	1346 kWp (50°C)
Array operating characteristics (50°C)	U mpp	572 V	I mpp	2354 A
Total area	Module area	**9566 m²**	Cell area	8586 m²

Inverter	Model	**Ingecon Sun 275TL M220 DC Indoor**		
Original PVsyst database	Manufacturer	Ingeteam		
Characteristics	Operating Voltage	405-820 V	Unit Nom. Power	280 kWac
Inverter pack	Nb. of inverters	9 * MPPT 50 %	Total Power	1260 kWac
			Pnom ratio	1.19

PV Array loss factors

Array Soiling Losses			Loss Fraction	3.0 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	4.1 mOhm	Loss Fraction	1.5 % at STC
Serie Diode Loss	Voltage Drop	0.7 V	Loss Fraction	0.1 % at STC
LID - Light Induced Degradation			Loss Fraction	2.0 %
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Module average degradation	Year no	10	Loss factor	0.4 %/year
Mismatch due to degradation	Imp RMS dispersion	0.4 %/year	Vmp RMS dispersion	0.4 %/year
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
Spectral correction	FirstSolar model. Precipitable water estimated from relative humidity			

Coefficient Set	C0	C1	C2	C3	C4	C5
Polycrystalline Si	0.8409	-0.027539	-0.0079224	0.1357	0.038024	-0.0021218

Unavailability of the system	7.3 days, 3 periods	Time fraction	2.0 %
Auxiliaries loss	constant (fans) 0 W	... from Power thresh.	0.0 kW

Grid-Connected System: Main results

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario B**

Simulation for the 10th year of operation

Main system parameters System type **No 3D scene defined, no shadings**

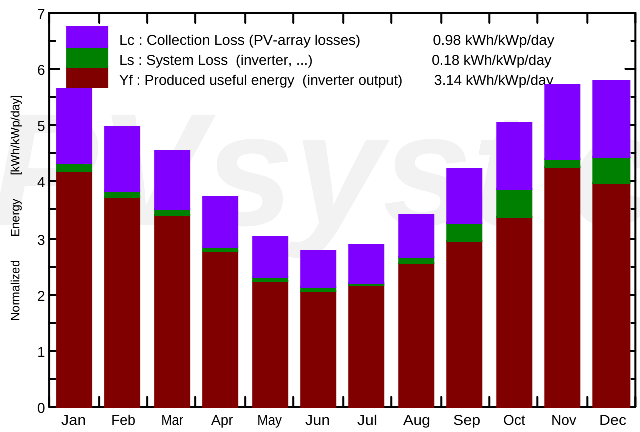
PV Field Orientation	tilt	45°	azimuth	0°
PV modules	Model	ET-P660_255WWCO Maxim	Pnom	255 Wp
PV Array	Nb. of modules	5880	Pnom total	**1499 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.5	Pnom total	**1260 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results

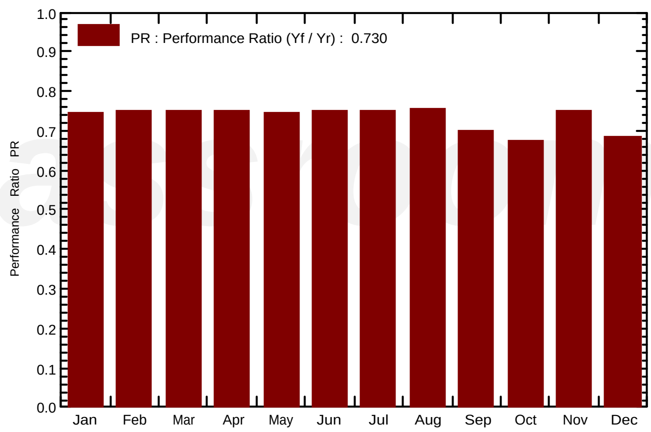
System Production **Produced Energy** **1720 MWh/year** Specific prod. 1147 kWh/kWp/year

Performance Ratio PR 73.04 %

Normalized productions (per installed kWp): Nominal power 1499 kWp



Performance Ratio PR



Lephalale Project Scenario B

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	167.9	88.60	27.63	174.4	164.6	200.7	195.2	0.746
February	148.6	85.20	27.97	139.6	131.2	161.2	156.7	0.749
March	170.8	92.70	28.17	140.9	131.5	162.8	158.3	0.749
April	163.7	77.90	27.43	111.5	102.5	128.6	125.0	0.748
May	163.4	80.50	27.40	93.3	84.8	107.5	104.4	0.746
June	162.6	73.20	25.58	82.8	74.5	95.8	92.9	0.748
July	169.2	73.40	24.93	89.1	80.4	103.5	100.4	0.751
August	167.3	82.80	25.33	105.7	96.7	123.4	119.9	0.757
September	167.2	76.00	25.76	126.7	117.4	147.8	133.1	0.701
October	174.6	85.70	26.50	156.3	146.3	180.6	157.6	0.673
November	167.0	81.40	26.33	170.8	161.0	197.7	192.2	0.750
December	165.6	82.20	27.19	179.5	169.6	206.9	184.5	0.686
Year	1987.9	979.60	26.68	1570.6	1460.6	1816.4	1720.1	0.730

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

Grid-Connected System: Special graphs

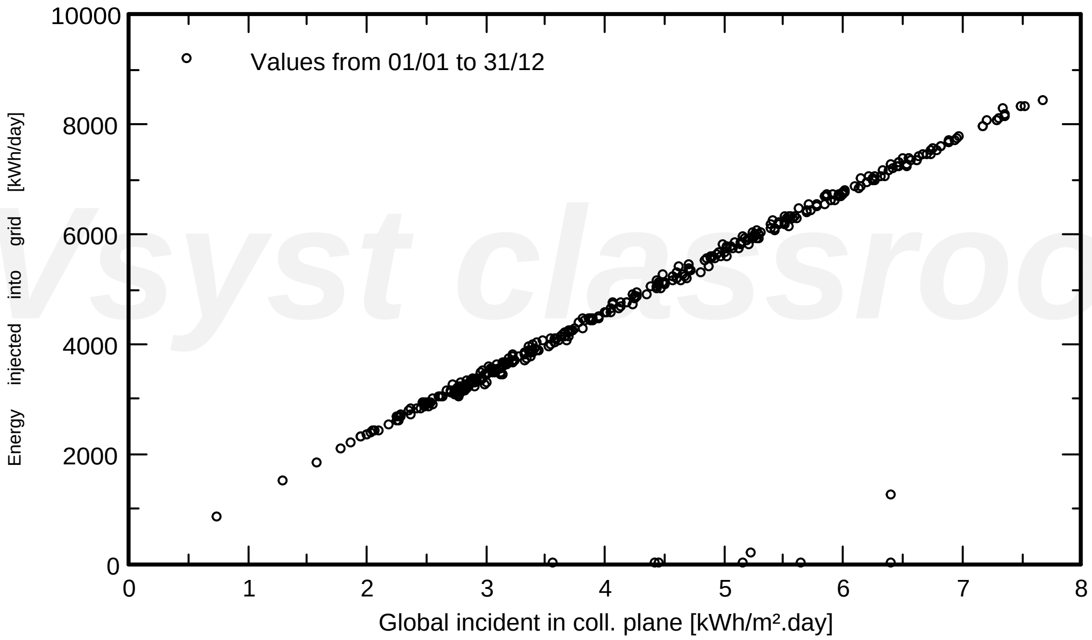
Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario B**

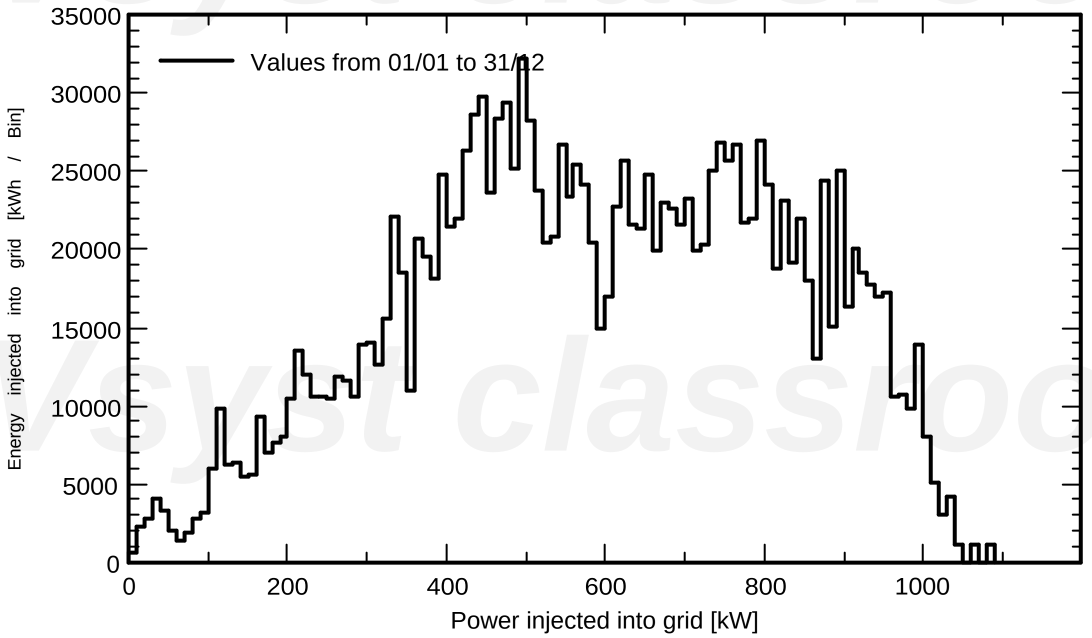
Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	45°	azimuth	0°
PV modules	Model	ET-P660_255WWCO Maxim	Pnom	255 Wp
PV Array	Nb. of modules	5880	Pnom total	**1499 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.5	Pnom total	**1260 kW ac**
User's needs	Unlimited load (grid)			

Daily Input/Output diagram



System Output Power Distribution



Grid-Connected System: Loss diagram

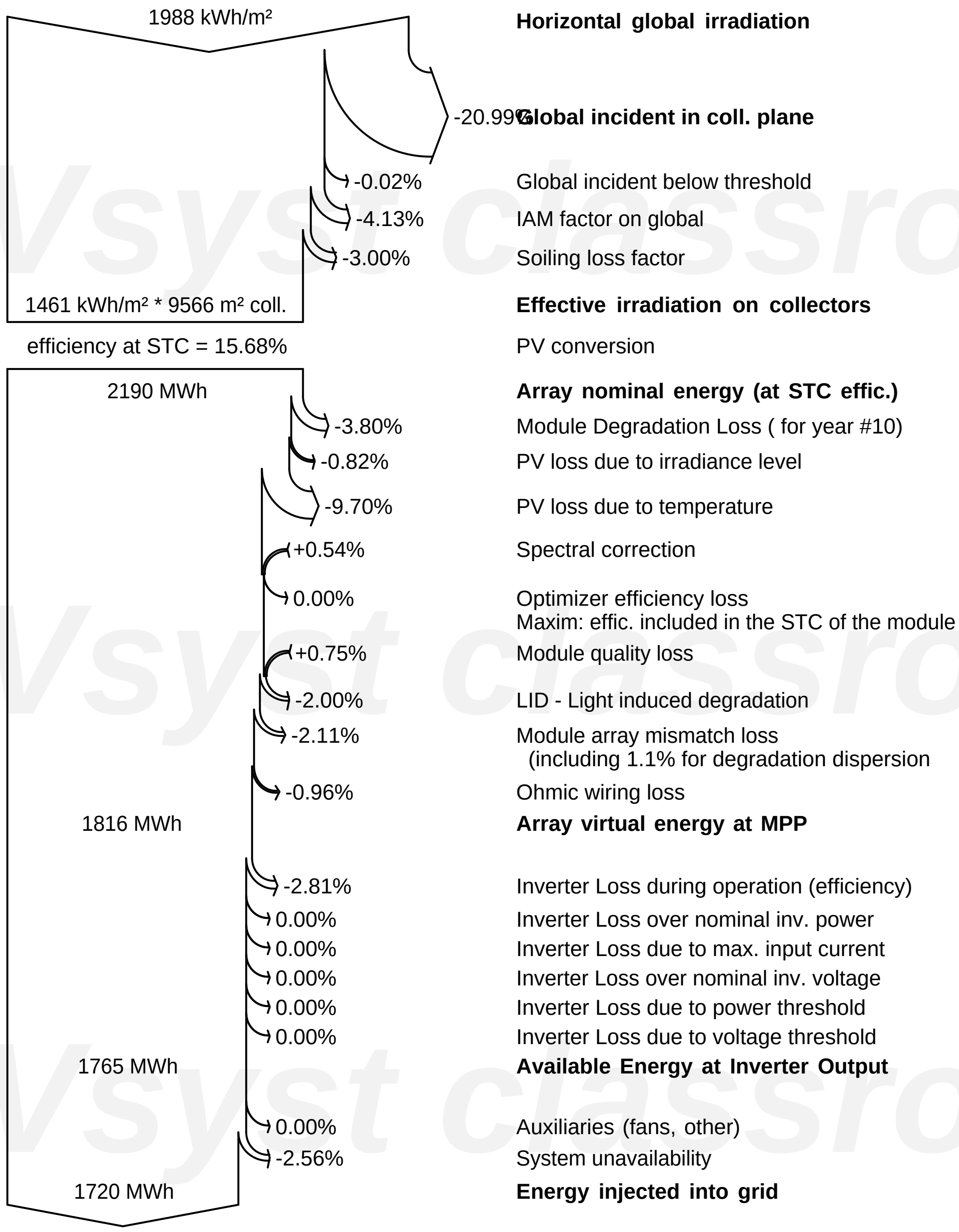
Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario B**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	45°	azimuth	0°
PV modules	Model	ET-P660_255WWCO Maxim	Pnom	255 Wp
PV Array	Nb. of modules	5880	Pnom total	**1499 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.5	Pnom total	**1260 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



Grid-Connected System: CO2 Balance

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario B**

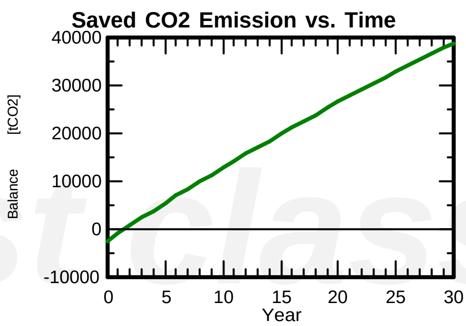
Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	45°	azimuth	0°
PV modules	Model	ET-P660_255WWCO Maxim	Pnom	255 Wp
PV Array	Nb. of modules	5880	Pnom total	**1499 kWp**
Inverter		Ingecon Sun 275TL M220 DC Indoor	Pnom	280 kW ac
Inverter pack	Nb. of units	4.5	Pnom total	**1260 kW ac**
User's needs	Unlimited load (grid)			

Produced Emissions	**Total:**	**2460.03 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**47835.5 tCO2**		
	System production:	1720.08 MWh/yr	Lifetime:	30 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	927 gCO2/kWh		
	Source:	IEA List	Country:	South Africa
CO2 Emission Balance	**Total:**	**39045.1 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	2284 kgCO2/kWp	6.18 kgCO2/kg
Quantity	974 kWp	38190 kg
Subtotal [kgCO2]	2223898	236132



Grid-Connected System: Simulation parameters

Project : **lephalale onverwacht**

Geographical Site	**Lephalale**		Country	**South Africa**
Situation	Latitude	0.01° N	Longitude	0.00° E
Time defined as	Legal Time	Time zone UT	Altitude	0 m
	Albedo	0.20		
Meteo data:	**Lephalale**	Meteonorm 7.2 (1991-2010) - Synthetic		

Simulation variant : **Lephalale Project Scenario C**

	Simulation date	06/10/23 10h45
	Simulation for the	**10th year of operation**

Simulation parameters	System type	**No 3D scene defined, no shadings**		
Collector Plane Orientation	Tilt	15°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics

PV module	Si-poly	Model	**ET-P672_325WWCO Maxim**		
Original PVsyst database		Manufacturer	ET Solar		
Maxim integrated optimizers		Model	**VT8024**	Unit Nom. Power	3 x 110 W
Number of PV modules		In series	16 modules	In parallel	302 strings
Total number of PV modules		Nb. modules	4832	Unit Nom. Power	325 Wp
Array global power		Nominal (STC)	**1570 kWp**	At operating cond.	1410 kWp (50°C)
Array operating characteristics (50°C)		U mpp	537 V	I mpp	2627 A
Total area		Module area	**9376 m²**	Cell area	8467 m²

Inverter	Model	**BG60KTR (60kw,3 phase with 2 MPPT)**		
Original PVsyst database	Manufacturer	INVT Solar technology		
Characteristics	Operating Voltage	280-800 V	Unit Nom. Power	60.0 kWac
Inverter pack	Nb. of inverters	45 * MPPT 50 %	Total Power	1350 kWac
			Pnom ratio	1.16

PV Array loss factors

Array Soiling Losses			Loss Fraction	3.0 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	3.4 mOhm	Loss Fraction	1.5 % at STC
Serie Diode Loss	Voltage Drop	0.7 V	Loss Fraction	0.1 % at STC
LID - Light Induced Degradation			Loss Fraction	2.0 %
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Module average degradation	Year no	10	Loss factor	0.4 %/year
Mismatch due to degradation	Imp RMS dispersion	0.4 %/year	Vmp RMS dispersion	0.4 %/year
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

Spectral correction FirstSolar model. Precipitable water estimated from relative humidity

Coefficient Set	C0	C1	C2	C3	C4	C5
Polycrystalline Si	0.8409	-0.027539	-0.0079224	0.1357	0.038024	-0.0021218

Unavailability of the system	7.3 days, 3 periods	Time fraction	2.0 %
Auxiliaries loss	constant (fans) 0 W	... from Power thresh.	0.0 kW

Grid-Connected System: Main results

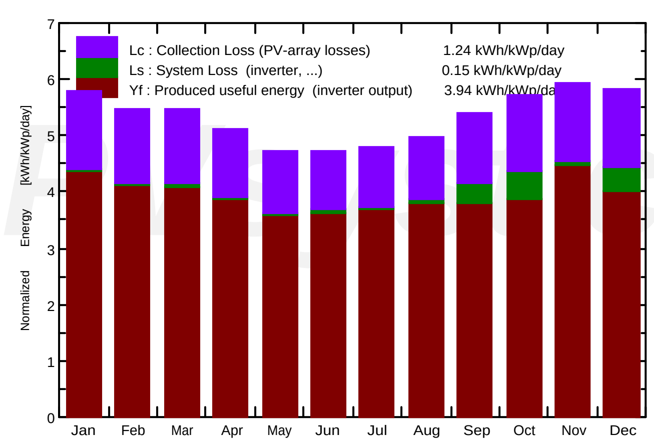
Project : **lephalale onverwacht**

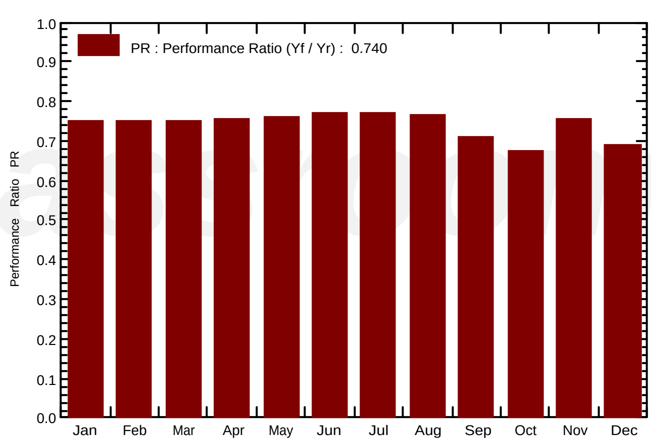
Simulation variant : **Lephalale Project Scenario C**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	ET-P672_325WWCO Maxim	Pnom	325 Wp
PV Array	Nb. of modules	4832	Pnom total	**1570 kWp**
Inverter		BG60KTR (60kw,3 phase with 2 MPPT)	Pnom	60.0 kW ac
Inverter pack	Nb. of units	22.5	Pnom total	**1350 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**2259 MWh/year**	Specific prod.	1438 kWh/kWp/year
	Performance Ratio PR	74.02 %		





Lephalale Project Scenario C

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	167.9	88.60	27.63	179.5	169.1	214.7	211.9	0.752
February	148.6	85.20	27.97	153.2	144.1	183.3	180.9	0.752
March	170.8	92.70	28.17	169.2	158.9	202.2	199.5	0.751
April	163.7	77.90	27.43	153.6	143.8	184.3	181.9	0.754
May	163.4	80.50	27.40	146.3	136.3	177.0	174.6	0.760
June	162.6	73.20	25.58	141.7	131.9	173.5	171.3	0.770
July	169.2	73.40	24.93	148.9	138.7	182.4	179.9	0.770
August	167.3	82.80	25.33	153.9	143.8	187.8	185.3	0.767
September	167.2	76.00	25.76	161.8	151.8	195.5	179.7	0.707
October	174.6	85.70	26.50	177.4	166.8	211.9	187.7	0.674
November	167.0	81.40	26.33	177.6	167.3	213.5	210.8	0.756
December	165.6	82.20	27.19	179.8	169.4	215.8	195.1	0.691
Year	1987.9	979.60	26.68	1943.0	1821.9	2341.9	2258.6	0.740

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

Grid-Connected System: Special graphs

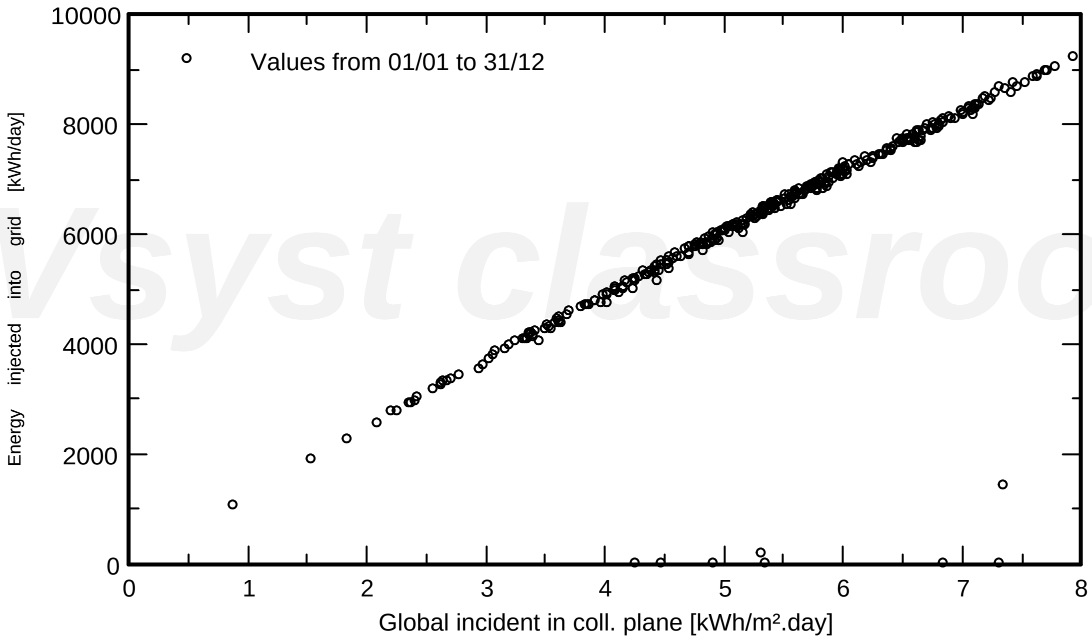
Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario C**

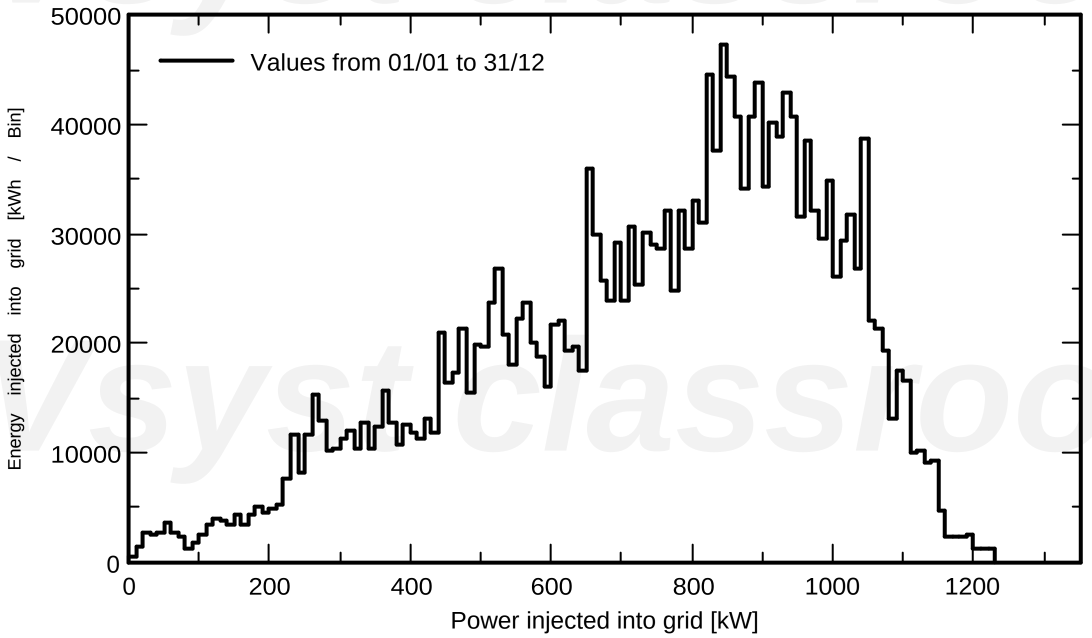
Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	ET-P672_325WWCO Maxim	Pnom	325 Wp
PV Array	Nb. of modules	4832	Pnom total	**1570 kWp**
Inverter		BG60KTR (60kw,3 phase with 2 MPPT)	Pnom	60.0 kW ac
Inverter pack	Nb. of units	22.5	Pnom total	**1350 kW ac**
User's needs	Unlimited load (grid)			

Daily Input/Output diagram



System Output Power Distribution



Grid-Connected System: Loss diagram

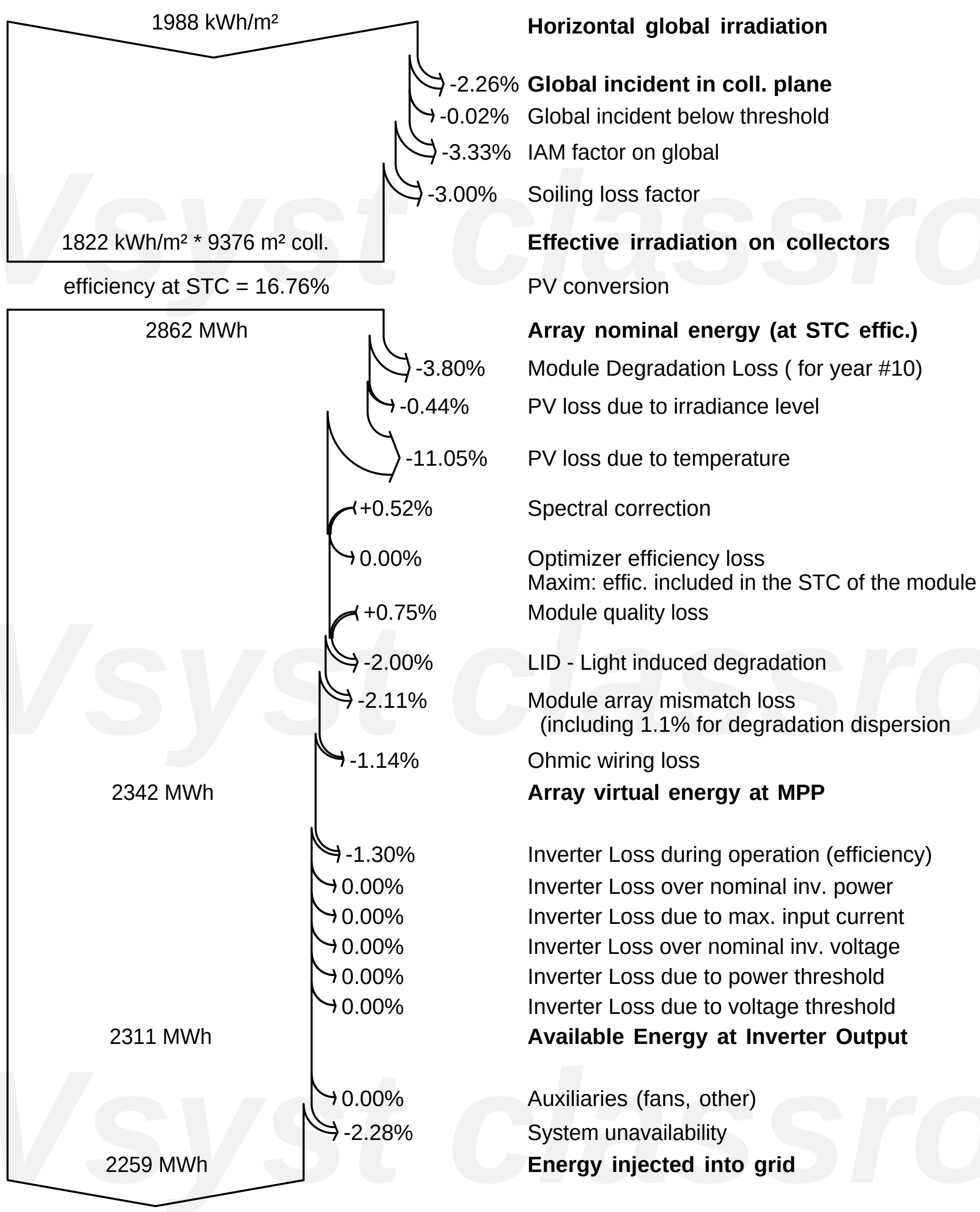
Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario C**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	ET-P672_325WWCO Maxim	Pnom	325 Wp
PV Array	Nb. of modules	4832	Pnom total	**1570 kWp**
Inverter		BG60KTR (60kw,3 phase with 2 MPPT)	Pnom	60.0 kW ac
Inverter pack	Nb. of units	22.5	Pnom total	**1350 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



Grid-Connected System: CO2 Balance

Project : **lephalale onverwacht**

Simulation variant : **Lephalale Project Scenario C**

Simulation for the 10th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	ET-P672_325WWCO Maxim	Pnom	325 Wp
PV Array	Nb. of modules	4832	Pnom total	**1570 kWp**
Inverter		BG60KTR (60kw,3 phase with 2 MPPT)	Pnom	60.0 kW ac
Inverter pack	Nb. of units	22.5	Pnom total	**1350 kW ac**
User's needs	Unlimited load (grid)			

Produced Emissions	**Total:**	**2460.03 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**62812.6 tCO2**		
	System production:	2258.63 MWh/yr	Lifetime:	30 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	927 gCO2/kWh		
	Source:	IEA List	Country:	South Africa
CO2 Emission Balance	**Total:**	**52040.3 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	1792 kgCO2/kWp	6.18 kgCO2/kg
Quantity	1241 kWp	38190 kg
Subtotal [kgCO2]	2223898	236132