



Techno-Economic Analysis of Microgrids with Distributed Energy Resources in Rural Limpopo Province, South Africa

by

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DECLARATION

I, Pfesemani Shammah Netshilonwe, declare that this research dissertation is my original work and has not been submitted for any degree at any other university or institution. The research dissertation does not contain other persons' writing unless expressly acknowledged and referenced accordingly.

Signed:



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ABSTRACT

The United Nations' sustainable energy development portfolio indicates that around 1.3 billion people globally still lack access to grid-based electricity, underscoring the urgent need for sustainable energy solutions. In Sub-Saharan Africa, about 13% of the population faces limited electricity access due to challenging terrains, inadequate energy policies, and insufficient investment. High costs of extending the electrical grid further complicate the issue. Regions with potential for renewable energy resources, such as solar and wind, offer opportunities to improve energy access. In South Africa's Limpopo province, while the electrification rate is 96%, some rural areas remain without electricity due to poor grid infrastructure and unreliable supply caused by load shedding and load reduction. Even where electricity is available, rising energy costs pose a significant burden on economically disadvantaged communities. This deficit of energy supply in rural areas needs attention through microgrid optimisation.

This research aims to techno-economically analyse the feasibility of optimising microgrids in rural Limpopo province, focusing on adopting a system with the least net present cost and levelized cost of energy. Three objectives are the main drive to achieve the aim of this research. The first objective is to provide a review of available and potential renewable energy resources in Limpopo province, focusing on their operational status. Currently, solar PV, biomass, and biogas are available, while geothermal, hydropower, and wind are potential resources. The second objective is to analyse the technical and economic aspects of microgrid optimisation to assess its implementation feasibility without hydrogen production. The third objective evaluates the same elements to determine the feasibility of microgrid implementation with hydrogen production.

The Herman-Beta method was employed for peak load estimation, while Homer Pro analysed maximum daily consumption, developed load profiles, and simulated microgrid configurations. The analysis comprised two parts: one focused on microgrids without hydrogen production and the other with it. The first part evaluated PV/Grid and PV/BES/Grid configurations to identify the optimal microgrid solution for each region. For the hydrogen production configurations, three types of PV modules (250 W, 375 W, and 500 W) with a 48V, 14.4 kWh lithium battery were tested, including PV/H₂/Grid and PV/BES/H₂/Grid setups.

Microgrid optimisation results without hydrogen production show that the PV/Grid configuration is the most cost-effective option across all areas. For Ga-Masekwa, the LCOE is 2.356 R/kWh with an NPC of R 5.4 M. For Ka-Dzingidzingi, the LCOE is 1.292 R/kWh and NPC R 76 M; for Duthuni, 1.216 R/kWh and R 138.7 M; and for Mookgophong NU, 1.197 R/kWh and R 250.3 M. The findings on microgrids with hydrogen production show that the

PV/H₂/Grid configuration is the most cost-effective, offering the lowest NPC and LCOE, and a high return on investment. However, producing green hydrogen requires significant energy, increasing the overall system cost.

Conducting a techno-economic analysis of microgrids with distributed energy resources is essential for assessing their feasibility, sustainability, and cost-effectiveness. This study aids in cost-benefit evaluations, system optimisation, financial risk assessments, and the development of resilient alternative energy systems.

Keywords: Techno-economic analysis, renewable energy resources, microgrids, Homer, Herman-Beta method, hydrogen production, net present cost, levelized cost of energy

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LIST OF ABBREVIATIONS

ADMD	After Diversity Maximum Demand
NPC	Net Present Cost
LCOE	Levelized Cost of Energy
ROI	Return on Investment
SPB	Simple Payback
MG	Microgrid
MW	Megawatt
kW	Kilowatt
kWh	Kilowatt Hour
R/kWh	Rand Per Kilowatt Hour
DC	Direct Current
AC	Alternating Current
PV	Photovoltaic
BES	Battery Energy System
WT	Wind Turbine
HT	Hydro Turbine
H ₂	Hydrogen
FC	Fuel Cell
DG	Diesel Generator
NASA	National Aeronautics and Space Administration
ESKOM	Electricity Supply Commission
HOMER	Hybrid Optimization of Multiple Electric Renewables
GHI	Global Horizontal Irradiance
SBA	Storage Bank Autonomy

PDF	Probabilistic Distribution Function
kVA	Kilo Volt Ampere
N	Number of Consumers
M	Million
SADC	South African Development Community

CHAPTER ONE: INTRODUCTION

1.1. GENERAL INTRODUCTION

Microgrids (MGs) are collections of interconnected loads and distributed energy resources, which can operate either as an islanded or grid-connected system [1]. Reflecting on the history of MGs, the first conventional MG was Thomas Edison's inaugural DC (Direct Current) power plant, which was commissioned in 1882 [2].

By 1886, approximately 58 direct current (DC) motors were constructed and in operation, yet their limitations in providing electricity over short distances became apparent. To address this issue, the alternating current (AC) grid system, primarily developed by the Westinghouse Electric Corporation, emerged as the solution. Since then, the world has embraced the AC grid system [3] [4].

The AC grid system continues to evolve successfully, diminishing MGs' popularity. In South Africa, the Electricity Supply Commission, known as Eskom, was founded in 1923. Following the nation's transition to democracy in 1994, there was an urgent demand to provide electricity to all South Africans. Since then, Eskom has continued to operate as a reliable and effective electricity provider, although it currently grapples with significant challenges, including load shedding and load reduction, driven by high energy demand and intermittent generation capacity deficits [5].

In the ongoing effort to provide reliable and affordable electricity, researchers have developed innovative solutions to address energy scarcity. The MGs featuring distributed energy resources have re-emerged as a viable option and have been implemented in various regions worldwide, particularly in rural areas with limited access to energy. To successfully optimise and implement MGs, a comprehensive technical and economic feasibility study is essential. This analysis plays a critical role in identifying the most suitable configuration, ensuring the delivery of efficient energy while keeping costs manageable. Therefore, conducting this study in the Limpopo province of South Africa is of utmost importance.

1.2. PROBLEM STATEMENT

The sustainable energy development portfolio from the United Nations reveals that approximately 1.3 billion people worldwide still lack access to grid-based electricity services. This considerable gap in energy access highlights the urgent need for sustainable energy solutions and policies that aim to deliver reliable electricity to underserved populations.

Ensuring equitable access to energy is crucial for fostering social and economic development, enhancing quality of life, and achieving broader sustainability objectives [6].

In Sub-Saharan Africa, approximately 13% of the population lives in areas with limited access to electricity, a significant challenge for the region. Several factors contribute to this issue, including the difficult terrains that hinder the expansion of the electrical grid, insufficient energy policies, and a lack of economic investment. Moreover, the high costs associated with extending long transmission and distribution lines from the primary utility grid to remote areas further exacerbate energy expenses [7].

This challenge is especially notable in regions with significant potential for the development and implementation of RER. Addressing this gap not only offers an opportunity to improve energy access but also to harness the abundant renewable resources available in the area, including solar, wind, and hydroelectric power. The transition to sustainable energy solutions can play a pivotal role in promoting economic growth, enhancing living standards, and fostering environmental sustainability in these underserved rural communities [8] [9].

The Limpopo province in South Africa is primarily rural, with an electrification rate of 96% provided by the Eskom utility grid. However, some rural areas still do not have access to electricity due to inadequate grid extension infrastructure. Furthermore, certain regions face challenges with electricity reliability due to load shedding and load reduction measures [10].

Furthermore, individuals with access to electricity are grappling with the increasing burden of rising levelized cost of energy. For economically disadvantaged rural communities, the expense of purchasing electricity has become excessively heavy. These disruptions in electricity supply, combined with soaring energy prices, significantly affect both the private and public sectors [11].

1.3. RATIONALE OF THE STUDY

The current global transition towards green energy is instigating significant transformations in the power generation sector. This shift is in line with the United Nations' sustainable development goals, which seek to safeguard the environment, combat climate change, and provide reliable and affordable energy. Although fossil fuels are expected to remain in use until at least 2050 and will continue to meet critical energy needs, their adverse effects on the environment and other living beings remain a pressing concern [12].

Distributed energy resources and MGs are crucial to the future energy mix, addressing the challenges of diminishing fossil fuel supplies while also helping to reduce greenhouse gas

emissions. It is essential for society to lower its greenhouse gas emissions in the coming decades through the adoption of environmentally sustainable MG solutions [13].

The success of the proposed MGs primarily hinges on their economic performance, which encompasses factors such as capital costs, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Return on Investment (ROI), Internal rate of return (IRR), and payback period (PBY). This information is forecasted through a techno-economic analysis, which examines the design and sizing of the system's structure. Following this, an economic analysis is conducted to determine whether the MG system is financially advantageous for both investors and end users.

This research focuses on three key scenarios. The first scenario assesses the available and potential distributed energy resources to identify those that can be integrated into future MG implementations in the province, considering both environmental sustainability and the welfare of the local population. There is an urgent need to promote clean energy and foster environmental conservation. The second scenario involves a techno-economic analysis utilizing the available distributed energy systems in the province, considering various constraints during the simulations. The third scenario focuses on the feasibility assessment of hydrogen production, this time without constraints applied in the simulations.

The importance of this work lies in its potential to address the energy challenges within the research study area, serving as a reference for tackling rural energy supply challenges. Research work on the analysis of the techno-economic feasibility of implementing MGs in the rural areas of Limpopo remains limited. Thus, bridging this gap and enhancing knowledge through this study is of considerable significance [14].

1.4. RESEARCH QUESTIONS

The following are the research questions that need to be answered. The questions are:

- i. What are the available and potential RER for MG implementation in Limpopo province?
- ii. What socio-demographic factors are taken into consideration for load modelling purposes?
- iii. Which load modelling method is most effective for the South African electricity supply?
- iv. What are the economic feasibility performance metrics for selected locations' MG optimization in the Limpopo province considering a system with and without hydrogen production?

1.5. AIMS AND OBJECTIVES

1.5.1. AIMS

This study aims to review renewable energy resources, hybrid microgrids, simulation tools, and hydrogen production. It will gather population statistics from selected locations and develop technical and economic models to optimise microgrid operations. The Herman-Beta method will estimate maximum daily loads, while Homer software will simulate microgrid configurations. The goal is to techno-economically analyse the feasibility of optimizing microgrids in Limpopo province, focusing on adopting a system with the least NPC and LCOE.

1.5.2. OBJECTIVES

The following objectives will be building blocks to accomplish the aim of the study:

- i. To assess and review the available and potential RER to determine which suits the proposed MG.
- ii. To analyse the technical and economic elements of MG optimization for analysing the techno-economic feasibility of MG implementation without hydrogen production.
- iii. To analyse the technical and economic elements of MG optimization for analysing the techno-economic feasibility of MG implementation with hydrogen production.

1.6. RESEARCH GAPS

To the author's knowledge, based on the literature review, the following research gaps have been identified and need to be addressed in this research work.

- i. There is a notable scarcity of research studies focused on the techno-economic analysis of MG implementation, especially in Limpopo province. This limited body of work highlights the need for further investigation into MGs' economic viability and technical feasibility within this specific region, which could provide valuable insights for policymakers and stakeholders aiming to enhance energy access and sustainability. Exploring these aspects could pave the way for more comprehensive strategies that align with Limpopo's unique challenges and opportunities.
- ii. Various authors have previously employed the medium and low voltage load modelling method known as the Herman beta method, which is primarily used for utility grid load

forecasting in residential load modelling. However, this method has not yet been integrated with Homer software to analyse the cost-effectiveness and feasibility of MG optimization.

- iii. The exploration of green hydrogen in South Africa has gained momentum over recent years, with significant research efforts directed towards its potential applications. However, further exploration is necessary, particularly regarding its adoption in rural areas. Additionally, it is essential to investigate the feasibility of optimizing hydrogen production processes to enhance efficiency and sustainability. Such research will contribute to the broader energy landscape and support rural development initiatives by providing clean energy solutions tailored to the specific needs of these communities.

1.7. HYPOTHESIS

Implementing a microgrid configuration that effectively integrates multiple distributed energy resources can provide a sustainable and cost-effective electricity supply to rural areas, minimizing Net Present Costs and Levelized Cost of Energy while meeting designated electricity demands.

1.8. THE STRUCTURE OF THE DISSERTATION

Chapter **ONE** serves as the introduction. Chapter **TWO** provides a comprehensive literature review. Chapter **THREE** outlines the research methodology employed in this research study. Chapter **FOUR** details the assessment review results for existing and potential RER in the Limpopo province. Chapter **FIVE** presents the results of the techno-economic analysis for MG optimization, excluding hydrogen production considerations. Chapter **SIX** highlights the techno-economic analysis results for MG optimization, incorporating hydrogen production considerations. Finally, Chapter **SEVEN** offers the conclusion and recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1. PREAMBLE

Chapter two delves into the literature review concerning various facets of microgrid (MG) optimization. It will cover several key areas, including the evaluation of existing and potential renewable energy resources (RER) in the Limpopo province, simulation tools for techno-economic analysis aimed at identifying the most effective tools for economic studies, microgrids featuring distributed energy resources, hybrid energy systems for optimized MG performance, hydrogen production, and finally, the techno-economic analysis relevant to MG optimization.

2.2. SOLAR PV OPTIMISATION STATUS IN LIMPOPO PROVINCE

Solar Photovoltaic (PV) is a technology that converts sunlight directly into electricity using semiconductor materials, typically silicon. When sunlight strikes the solar cells, it generates an electric current through the photovoltaic effect. This technology is more operationally efficient in areas with good global horizontal irradiance of about 5 kWh/m²/day, and South Africa has about 4.5 - 6.5 kWh/m²/day [15].

Sub-Saharan Africa's climatological conditions favour various RER, and this advantage extends further downwards south to the SADC regions and South Africa. A study conducted by Liu et al [16] assessed different methods and technologies to address the electrification issues in Sub-Saharan Africa, where Limpopo province falls. Findings showed that solar PV is the most feasible option for implementation as the region's geographical climate and load characteristics favour the technology.

The study conducted by Arend [17] utilized a model programmed on MATLAB R2020a software to simulate the performance of a solar PV system in the province of Limpopo, with the intention of showing and supporting that the climatological characteristics of Limpopo are reliable for the optimization and utilization of solar PV. Masekoameng et al [18] on the other hand, investigated through surveys and questionnaires the types of RER utilized in the Limpopo province. It was supported by this investigation that Limpopo has favourable weather conditions suitable for any solar PV as well as biomass utilizations.

The assessment study conducted by Matasane [19] assessed small-scale RER in the Vhembe district, Limpopo, utilizing empirical models and the NASA database for solar PV suitability estimations. The study acknowledged that the effects of solar radiation and territorial

climatological measurements in the Vhembe district are satisfactory for solar PV energy generation. Further investigations on solar radiation in the Vhembe district were assessed by Maluta et al [20]. The assessment used the solar radiation H-S model to investigate the effects of seasonal change on solar PV power performance in the Vuwani area. Seasonal changes do have an impact on the performance of solar PV as temperature intensity changes.

In Mopani district Jovanovic [21] Evaluated the efficiency of solar photovoltaic systems for a groundwater pumping mechanism through a community involvement strategy and a solar irrigation system. The solar installation generated enough energy to aid the residents of Giyani in achieving domestic and agricultural water security.

An assessment conducted by Solms [22] and Rene et al [23] persisted in advocating that effective solar system technologies are crucial, particularly for large-scale projects, as they can meet the energy demand. A report provided by the Limpopo provincial government recognized that the province hosts some of the largest solar power plants in the country [24].

Soutpan solar plant's successful operation in feeding the national grid was presented by Fraser [25]. A review paper by Husvu [26] confirmed that the Soutpan solar plant and the Witkop solar park, which produces 33 MW of power for the national grid, have achieved success and satisfaction. Additionally, the contentment with large solar PV plants has been further substantiated in [27], where the successful commission and operation of the 66MW Tom Burke solar plant were assessed.

The province of Limpopo boasts favourable climatic conditions for optimising solar PV systems. However, it's important to note that seasonal changes can impact the performance of solar PV, particularly during the winter months when peak sunlight hours are significantly reduced compared to the summer.

2.3. BIOMASS AND BIOGAS UTILISATION STATUS IN LIMPOPO PROVINCE

Biomass is organic material derived from living or recently living organisms, primarily plants and animals; on the other hand, biogas is a renewable fuel produced from the breakdown of organic matter (such as food waste, manure, and sewage) in an oxygen-free environment through a process called anaerobic digestion [28].

Shuma [29] has investigated biomass utilization in South Africa. The investigation findings showed that the Limpopo province ranks second in the country for the use of biomass energy.

Biomass is converted to biogas using anaerobic digestion, and its availability and consumption have been studied by authors like Semanya [30], where the study exhibits the advantages

and benefits of using biogas energy. Following in the same footsteps, Mutezo [31] offered insight into the energy transition in Africa and the dedication of different regions to shift towards a green economy utilizing biogas technology.

In terms of developing models for biogas utilisation in Limpopo province, Uhunamure et al [32] Conducted a field survey and employed a logistic regression model to assess fundamental factors influencing awareness and utilisation of biogas technology and attitudes towards its acceptance and use at the household level in Limpopo. The findings indicated that the uptake of biogas technology has a beneficial effect in the province. Netshiozwi [33] continued to study the human perspective on biogas energy implementation, noting that an awareness gap exists in rural areas.

A study by Roopnarain [34] observed the functionality of biogas technology where the functioning of fixed dome biogas digesters aims to display the developmental achievements of biogas energy in rural communities. It was discovered that biogas energy not only acts as a system that helps protect the environment by decreasing greenhouse gas emissions but also provides a solution for waste management [35].

Advocating for biogas technology, a study by Rasimphi et al [28] discussed the deployment of appropriate biogas technology in the rural regions of the Vhembe district, where fixed dome digesters are employed, and Nethengwe et al [36] supported that biogas technology can enhance communities' economic development, and the authors [37] supported that it is essential to implement small bio-digesters for household usage.

Constraints in biogas implementations are considered. An assessment study conducted by Situmeang [38] showed that barriers to popularizing and implementing biogas digester technologies dwell on technical, economic, and sociocultural constraints. Authors in [39] continued to narrate to provide solutions on barriers behind the low adoption of biogas technology in some areas. An evaluation conducted by Feng [40] demonstrated the advantages of utilizing biogas technology, including health, environmental, and economic benefits. The agricultural benefits of using green manure legumes in maize production have lengthened the advantages of biomass utilisation [41]

Biomass has long been utilized in the province and continues to be. However, there is little awareness of biogas technology, and additional infrastructure for biogas is necessary.

2.4. HYDROPOWER AS THE LIMPOPO PROVINCE'S POTENTIAL ENERGY RESOURCE

Hydropower is the potential RER in the province. The hydropower development report prepared by Vuuren [42] reported that Eskom is constructing a 1500 MW pumped storage hydropower facility in the Tubatse municipality of Limpopo. Karanitsch in [43] demonstrated that small, community-based hydropower facilities can contribute to providing electricity to rural regions.

The evaluation study presented by [44] described the development of South African hydropower opportunities, and the study showed that stakeholders in hydropower need to be made aware of its positive outcomes.

Contrary to the positive benefits that small hydropower can bring, a study conducted by Jonker [45] tackled the issue of insufficient awareness and information on small hydropower by summarising the current status of small hydropower in South Africa. It indicated that small hydropower capacity could be implemented in the provinces of Limpopo, Mpumalanga, KZN, and Free State.

Although hydropower is lifetime investment, building a hydropower plant requires a significant amount of capital and favourable terrains for high-altitude dam construction. This was supported by Kalitsi [46] who investigated the issues and difficulties related to hydropower development in South Africa. Research indicates that insufficient funding is the primary obstacle to hydropower development. This suggests that the province possesses hydropower potential.

2.5. GEOTHERMAL AS THE PROVINCE'S POTENTIAL ENERGY RESOURCE

Geothermal energy is heat that comes from the Earth's interior. This renewable energy source is generated by the slow decay of radioactive elements and the natural heat of the Earth's core. This energy resource has potential in Limpopo province. A brief study conducted by Omolayo [47] investigated distinct types of RER and their uses. Geothermal energy appeared in the study as a promising renewable resource in Limpopo province, although its exploration remains moderate.

On the foundations of geothermal energy exploration, Johnson [48] presented an exploration study using magnetic and seismic techniques to outline the necessity for geothermal exploration in South Africa. The investigated ancient tectonic boundaries are referred to as mobile belts and greenstone belts, of which in Limpopo province are in considerable

proportion. Regrettably, there has been minimal exploration of geothermal energy despite the potential of the research study area.

An evaluation conducted by Tshibalo [49] indicated that low-enthalpy geothermal energy can be an alternative energy source in the Namaqualand mobile belt and the Limpopo belt. Binary-circle geothermal plants were proposed. Low enthalpy geothermal energy was further investigated in Limpopo province by Dhansay [50] to harness it. The study utilised hydraulic fracturing and magneto-telluric methods to show that a 75 MW geothermal system can be implemented. The survey conducted by Nshimyumuremyi [51] utilized mathematical modelling and numerical simulations in MATLAB to demonstrate that geothermal energy can achieve a power efficiency of 66.6%, indicating the potential for further development.

While geothermal energy is a potential resource in the province, its harvesting and utilisation will be nearly impossible due to political, traditional, and land ownership constraints.

2.6. WIND ENERGY AS THE PROVINCE'S POTENTIAL ENERGY RESOURCE

Implementing wind turbine plants requires careful planning to position wind turbines. Wind speed and wind direction are also important aspects to observe [52]. A study conducted by Mukumba [53] showed that areas with strong wind potential show an average wind speed of 4m/s for small wind turbines and 5.8 m/s for utility-scale turbines.

A study conducted by Meren [54] employed a temporal-spatial data scale method to highlight that Limpopo province has a limited capability for utility wind turbines due to an annual average wind speed of less than 4 m/s. Further on that, Nemiriri [55] support that Limpopo province has limited suitability for wind turbines due to its average annual wind speed of about 3.05 m/s, which is insufficient even for small wind turbines. Additionally, wind turbines operate effectively in areas with strong air currents, which are typically found near oceans, whereas Limpopo is situated at high altitudes [56].

2.7. SIMULATION TOOLS FOR TECHNO-ECONOMIC ANALYSIS STUDIES

Simulation tools are software applications that model, analyse, and predict real-world processes in a virtual environment. They help in decision-making, research, and testing without real-world risks or costs. Several simulation tools are used to conduct MG techno-economic analysis studies; different authors have recognized and utilized them. For instance, Babayomi [57] studied MG simulation tools, which were Hybrid2, RETScreen, TRNSYS, EnergyPRO, COMPOSE, and Homer software.

Examining simulation tools aimed to assess their effectiveness in terms of limitations, benefits, types of evaluation, inputs, and anticipated outputs. It was noted that each tool has its strengths and weaknesses, and selecting the appropriate tool primarily hinges on the user's expected outcomes. Still, Homer was found to be an easy simulation tool.

Lambert [58] analysed different MG simulation tools to assess their effectiveness. The findings indicated that the simulation logic of HOMER is less comprehensive than that of several other time-series simulation models designed for micropower systems, such as Hybrid2, PV-DesignPro, and PV*SOL. HOMER offers more detail than statistical models like RETScreen, which does not perform time-series simulations. Among all these tools, HOMER stands out for its flexibility in simulating various systems.

RETScreen is an Excel-based clean energy analysis tool that has played a role in evaluating the technical and financial feasibility of projects [59]. A feasibility analysis study conducted by Pan [59] analysed the MG system for Chongming County using RETScreen. In their use of the software, they found that RETScreen does not consider time series data and power imports. Consequently, they manually calculated the emission reductions and cost savings related to power imports. One of the benefits of RETScreen is its support for multiple languages.

The TRNSYS simulation tool was reported by [60]. The research outlined the guide for utilizing the software and its constraints. While this software can model techno-economic analysis, it cannot model tidal, wave, nuclear, and hydro energy. Sinha and Chandel [61] evaluated 19 primary features and the present conditions of various software tools. The paper's primary aim was to present the current state of these tools to offer vital insights for researchers in selecting and employing appropriate resources for the research and development of hybrid systems. Findings indicate that HOMER is recognized as the most frequently utilized tool of the nineteen software options due to its ability to integrate a maximum variety of RER.

The review study conducted by [62] explored optimizing the combination of renewable energy hybrid distributed generation through the use of COMPOSE software. This software is effective for economic assessment, uncertainty evaluation, and intermittency analysis, but it does not offer dynamic simulation capabilities. Authors in [63] have assessed solar PV electricity generation utilizing various software programs, including PVWatts, RETScreen, and Homer software. The analysis revealed that Homer is an intuitive software that provides performance outcomes for multiple components. This tool is designed to explore and enhance cost-efficient and dependable hybrid MG systems that incorporate both conventional and RER, as well as manage loads and storage [64]. The authors in [65], utilised Homer to examine all potential configurations to determine the most cost-effective system suitable for rural areas.

The software is designed to generate every conceivable system configuration under consideration. Further, Authors in [66], employed Homer Pro to study the energy balance on each component using hourly time series data.

Nallolla and Peruman [67], used Homer software to create the best MG system for the rural regions of Doddipalli, India. The layouts demonstrated the viable systems organised according to the one with the lowest NPC and minimal levelized cost of energy. Additionally, economic metrics can be assessed for comparison. Authors in [68], presented a model to guarantee that healthcare facilities remain consistently supported. The research employed Homer software. This indicated that the software could model from single to multiple consumer loads. Authors in [69], showed that although Homer is reliable hybrid modelling software, it is time-consuming for large systems with many components.

2.8. MICROGRIDS WITH DISTRIBUTED ENERGY RESOURCES

An MG refers to a localized energy system capable of producing, storing, and distributing power to a particular area or community, functioning autonomously or alongside the larger grid. These MGs are created to improve energy reliability, resilience, and sustainability, frequently integrating RER like solar, wind, or biomass, in addition to energy storage systems and sophisticated control technologies [70].

Wong conducted a study [71], with a focus on enhancing the independent MG in the Sarawak village. The PV/HT MG, which is based on hydrogen, was developed and tested using Homer Pro software, with four different configurations modelled. The findings indicated that the PV/H₂ setup is the most cost-efficient system compared to the other configurations incorporating hydrogen technology.

Ahmed has conducted a feasibility analysis of optimizing optimal MG in rural Sudan [72]. The study aimed to evaluate the solar trackers within an MG framework. It was found that utilizing PV trackers, particularly dual solar trackers, can enhance energy collection by as much as 50%, leading to a reduction in NPCs by approximately 7%.

Quispe conducted the economic feasibility assessment in the 37 rural areas of Peru [73] to achieve the best MG design and identify the most suitable rural locations for its deployment. Homer Pro software was utilised for simulations. The outcomes indicated that the PV/Grid configuration stands out as the most economical system among diverse options, with the capacity for sell-back in every location.

Irshad et al [74] explored the optimisation of PV/BES/Grid to develop the most effective rural PV-based MG by utilising performance analysis metrics for comparing PV technologies. The findings indicated that monocrystalline silicon PV technology outperforms polycrystalline and amorphous silicon.

Khaled et al. conducted the evaluation study [75]. The aim was to the adaptability of incorporating renewable energy technologies into the national grid, using Riphah International University as a case study for energy continuity. Homer was employed for 932 model simulations with varying capacities. The findings indicated that the most cost-effective system includes a PV/BES/Grid combination, while the least effective system consists of a BES/Grid configuration.

An economic evaluation of optimising MGs for university institutions in Nigeria was conducted by [76], to utilise available energy resources effectively. The hybrid system was simulated using Homer Pro software, and the findings indicated that the PV/DG/Grid setup offers the lowest NPC and the most affordable LCOE. The rural area techno-economic analysis of the PV MG study designed for agricultural sustainability was conducted by [77]. The chosen PV/Grid MG demonstrated a significant capacity for power production along with the minimum NPC and the lowest LCOE.

Reference [70] continues expanding hybrid MG power systems by considering integrating various RER such as PV/BES/HT/WT/DG. The simulation results were NPC, levelized energy cost, annual system cost, and fuel consumption. A feasibility comparative study conducted by [78] studied hybrid MGs aimed at rural electrification in Nigeria to affirm that hybrid systems are viable for rural applications. The research employed Homer Pro simulation, and findings indicated that the PV/BES/HT/WT/DG configuration is optimal for rural electrification.

2.9. HYBRID ENERGY SYSTEMS FOR HYDROGEN PRODUCTION

Hydrogen production refers to generating hydrogen gas (H_2), which can be used as a clean fuel or chemical feedstock. Various researchers have explored hydrogen generation across different regions, yet there remains a lack of literature regarding the viability of hydrogen production in rural areas. Within this gap, several authors have undertaken reviews, evaluations, and analyses of the practicality of producing green hydrogen in diverse locations and setups.

For instance, [79], studied the feasibility of a photovoltaic-based off-grid MG for residential use, and the minimum storage capacities necessary for year-round off-grid functionality using hydrogen were identified. The suggested configuration provides technically viable options. The

system's design is greatly affected by high peak electricity demand during low photovoltaic power generation periods, emphasizing the need for intelligent power management. Despite a considerable requirement for battery storage capacity, it is restricted to about 20 kWh. The research concluded that for off-grid functionality, nominal power ratings of at least 4 kW for the fuel cell and between 5 kW and 7 kW for the electrolyser are adequate. Nevertheless, residential properties' annual storage requirement of 170–190 kg of hydrogen is unrealistically high.

Jahangiri et al [80] conducted a feasibility analysis regarding the provision of electricity and hydrogen to Bandar Abbas City in Iran through both renewable grid-connected and off-grid systems. The analysis indicated that the lowest cost for supplying the necessary hydrogen was \$ 0.496 when utilizing the primary grid, and the minimum cost for the produced electricity was \$ 1.55.

The study conducted by [81], assessed the techno-economic viability of two MG configurations, PV/FC/Electrolyser/Biogas and PV/BES/FC/Electrolyser/Biogas. The systems were evaluated using HOMER Pro to analyse energy and hydrogen production in Maroua. The results of the study indicated that the optimal system design for scenario 1 included a 144-kW photovoltaic module, a 15-kW biogas generator, an 11-kW converter, a 15 kW electrolyser, a 15-kW fuel cell, and a hydrogen storage tank with a capacity of 5000 kg. Hassani [12] conducted a study to create an energy management plan for a photovoltaic system integrated with battery storage and fuel cell technology. The suggested standalone photovoltaic system with hydrogen storage functioned efficiently, charging the batteries and the electrolyser while intermittently producing excess energy. The ideal configuration of the system was established using Homer Pro, which employs photovoltaic panels, batteries, and fuel cells for self-sufficient charging, and it was found to be viable.

Elminshawy [82] analysed to study system designs that utilise RER, including photovoltaic, wind, and hybrid PV/WT configurations in designated government areas for large-scale projects. The PV/BES/WT option in Ras Ghareb stands out as the most advantageous choice, providing an annual electricity generation of 16,984.64 kWh and hydrogen production of 3,127.65 m³, along with an overall system average efficiency of 14.41%.

Marocco [83] assessed the cost-effectiveness of the hybrid H₂/BES Power-To-Power (P2P) system in reducing reliance on external energy resources across various loads and environmental conditions. The energy simulations demonstrated that combining renewable energy resources (RER) with a hybrid storage system significantly decreases external energy input requirements. Moreover, the renewable energy strategy was more economically feasible than current and alternative options at all four sites in the short and long term.

The study conducted by [84] investigated the combination of battery energy storage systems (BES) and hydrogen storage systems in conjunction with a small-scale hydropower facility; the system has been examined to fulfil the electricity demands of low-energy consumption (LEC) buildings. The hydrogen storage system consists of a 137-kW electrolyser, a 41-kW fuel cell, and a hydrogen storage capacity of 5247 kg, while the battery system has an overall capacity of 280 MWh. Although the battery system offers a greater round-trip efficiency, it necessitates a considerable financial outlay due to challenges such as self-discharge loss and restrictions on the minimum state of charge.

An assessment study conducted by [84] further evaluated the electricity requirements of a low energy consumption (LEC) facility; options such as integrating battery energy systems (BES), hydrogen storage systems, and a small-scale hydropower plant were being explored. The study conducted by [85], presented an optimal off-grid solar photovoltaic (PV) and hydrogen fuel cell (HFC). The energy system has been proposed to meet the electricity demands of India's northeastern states through renewable energy generation. The annual energy output from the rated PV array ranges from 150,705 to 187,908 kWh, while the hydrogen fuel cell produces between 30,100 and 25,639 kWh annually. This optimal energy system achieves a renewable fraction of 100%.

Nasser [86], examined the effectiveness of hybrid renewable energy systems (photovoltaic and wind turbines) in producing and storing green hydrogen in various climates across Egyptian cities. The annual electricity output for Cairo, Aswan, Asyut, El Arish, and Mersa Matruh is 84,096 kWh, 107,285 kWh, 104,761 kWh, 69,836.5 kWh, and 118,115 kWh, respectively. The study found that photovoltaic panels and wind turbines are appropriate for hydrogen production in all cities except El Arish, where using wind turbines is not advisable.

Adedaja [87] investigated the implementation of hybrid renewable energy systems to supply power to rural medical facilities in Nigeria and South Africa. This study has demonstrated that it is possible to power healthcare facilities in Sub-Saharan Africa using hybrid renewable systems.

In reference [88], following research and evaluation, it was determined that systems based on renewable energy that use hydrogen for energy storage in stand-alone or off-grid hybrid energy systems are viable. The simulation findings indicated that the most economical option is the hybrid energy storage system combining hydrogen and batteries. Nonetheless, all the developed scenarios are technically feasible and financially comparable over an extended period, each presenting its own set of advantages and challenges. The suggested hybrid energy systems have considerable potential to provide affordable electricity to remote communities, lower their carbon emissions, and thus contribute to a sustainable future.

2.10. TECHNO-ECONOMIC ANALYSIS FOR MICROGRID OPTIMISATION

Two important metrics are important to analyse the feasibility of microgrid optimisation: the NPC and the LCOE. The microgrid that results in the least NPC and LCOE is considered economically beneficial. The comprehensive review study conducted by Agajie et al [89], on techno-economic analysis and sizing of the optimal microgrid employing renewable energy resources showed as already stipulated that Homer software is one of the most useful tool for NPC and LCOE and it is vital to design a microgrid with least NPC and LCOE.

Al-Shetwi et al in [90] conducted the techno-economic assessment of a rural hybrid microgrid, focusing on economic feasibility and technical compatibility. Simulations with Homer revealed a viable configuration of solar PV, wind turbine, and grid, resulting in a net present cost of \$213,099 and a cost of energy of \$0.0480/kWh. This implies that a combination of two or three energy resources plays a huge role in minimising NPC and LCOE.

Sultana et al [91] used Homer software to determine the optimal microgrid for an off-grid setting to satisfy the load requirements of a rural community in Bangladesh. The simulation results showed that a combination of solar PV, wind turbine, and diesel generator resulted in a minimum levelized COE of 0.21 \$/kWh and an NPC of \$4.58 million. In this case study, the diesel generator was found to be the optimal option in reducing NPC and LCOE because the area has vast oil reserves for the generator, though the system is not entirely friendly to the environment, and it's noisy.

Authors in [72] evaluated the healthcare facility in rural Bangladesh where a hybrid solar PV microgrid was studied using Homer software. The healthcare centre needs a 24.3 k solar PV system with a net current cost of \$28,705.2. LCOE is \$0.02728 per kWh, and renewable energy will provide 98% of the system's total power requirements.

In the remote areas of Indonesia, three locations have been studied for hybrid renewable microgrids by Surdamadi [92] to study the effect of the variance of potential renewable energy sources on optimisation results. The NPC and LCOE for the Deudap location were found to be \$1.87M and 0.257 \$/kWh, for Senamang was \$5.22M and 0.317\$/kWh and finally, for Madopolo, \$7.35M and 0.245\$/kWh.

In the study conducted by [93] it is further shown that a hybrid microgrid is the optimal system. A techno-economic analysis of a hybrid energy system for a residential property in the Dobrogea region of Romania was presented, incorporating solar PV, wind turbines, and a diesel generator. The optimal system includes 1.97 kW solar PV, 1 kW wind turbine, 4 kW

diesel generator, 3.03 kW power converter, and six batteries. It achieves a renewable fraction of 98.3%, with a minimum COE of \$0.287/kWh and an NPC of \$48,879.

Kr et al [94] presented the techno-economic analysis of a hybrid microgrid for the rural area of Chitrakoot, Madhya Pradesh, showing that Homer Pro and Matlab can be employed for optimisation. A solar PV and wind turbine microgrid was modelled. For such a system, the total net present cost, capital cost, and cost of energy are Rs.428641.60, Rs.379318, and 7.79 Rs/kWh, respectively. Both MATLAB and Homer Pro software were again used by [95] to optimise the hybrid microgrid to fulfil the residential and agricultural electricity demand of the small rural community of Yamunanagar district of Haryana state, India. Solar PV, wind turbine, battery storage, and grid. COE and NPC of 0.288 \$/kWh and \$228,353, respectively.

Towards achieving sustainable development goals by adopting microgrids that consider hydrogen production, Wali [96], conducted a techno-economic assessment of hybrid microgrids in rural Bangladesh using Homer software. The optimal configuration of solar PV, fuel cell, electrolyser, and hydrogen tank had an NPC of \$25,099 and an LCOE of \$0.34/kWh.

Kamran et al in [97], conducted the techno-economic analysis of distributed energy systems for microgrids using Homer Pro software. The intention was to analyse the distributed energy resources for microgrids for economic feasibility. The LCOE was found to be 0.37 \$/kWh for the adopted energy system, comprised of solar PV, wind turbine, battery energy storage, and diesel generator.

Furthermore, on attesting that the hybrid system microgrid is optimal, Adefarati [98], evaluated grid-connected microgrid systems in South African regions with high global solar irradiance using Homer software. Results showed that De Aar has the lowest cost of energy (COE) and net present cost (NPC), at R 0.181/kWh, while Durban has the highest COE and NPC, at R 0.335/kWh. De Aar also generates the highest revenue of R 22,759.6401 with the same load profile.

Authors in [99], evaluated solar photovoltaic hybrid system for providing carbon-free electricity in rural Sierra Leone using HOMER software. The system includes a 45.5 kW PV array, a 31 kW diesel generator, and 68 lead-acid batteries. Economically, it is the most cost-effective option, with a net present cost of \$152,491 and a levelized cost of electricity of \$0.336/kWh. Technically, it is projected to generate 75,121 kWh annually.

Ahmed in [100], evaluated a solar photovoltaic hybrid system for providing carbon-free electricity in rural Sierra Leone using HOMER software. The system includes a 45.5 kW PV array, a 31-kW diesel generator, and 68 lead-acid batteries. Economically, it is the most cost-

effective option, with a net present cost of \$152,491 and a levelized cost of electricity of \$0.336/kWh. Technically, it is projected to generate 75,121 kWh annually.

In Sri Lanka [101], the feasibility study for a hybrid renewable energy system using Homer software showed a total NPC of \$453000 and an initial capital investment of \$203000. It analysed how changes in annual average wind speed and solar radiation affect the system's LCOE. Results indicated that a decrease in annual average wind speed to 4.5 m/s resulted in a \$0.1/kWh increase in LCOE.

In northeastern Nigeria [102], presented the techno-economic analysis of off grid renewable energy systems for rural electrification. The study identified that Nganzai district has sufficient solar and wind resources for renewable energy systems. The most economical solution is a PV/diesel system with battery storage, reducing emissions by 36%. Without battery storage, the PV/diesel model still offers lower costs compared to diesel generators. The total energy demand is 1,863,690 kWh/yr, while the PV/diesel system produces 2,398,774 kWh/yr, resulting in an excess of 458,414.2 kWh/yr, or 19% of the demand. To acquire the best system cost and to minimise fuel costs and emission values for microgrids.

The literature indicates that this study has not yet been conducted in the Limpopo province, although similar research has taken place in other regions of South Africa. Additionally, microgrid systems effectively meet the energy needs of rural areas, and hybrid microgrid systems significantly contribute to reducing both the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE).

2.11. CONCLUSION

The chapter reviews literature on MG optimization, focusing on renewable energy resources in the Limpopo province, techno-economic analysis tools, and hybrid energy systems. It identifies existing resources like solar PV, biomass, and limited biogas, while highlighting geothermal, wind, and hydropower as potential options. Common simulation tools include Homer, PVsyst, and RETScreen. Research shows that grid-connected hybrid systems are economically beneficial for hydrogen production and MG optimization, helping to reduce NPC and LCOE. While similar studies have been conducted globally, there has been little focus on rural Limpopo province.

CHAPTER THREE: METHODOLOGY

3.1. PREAMBLE

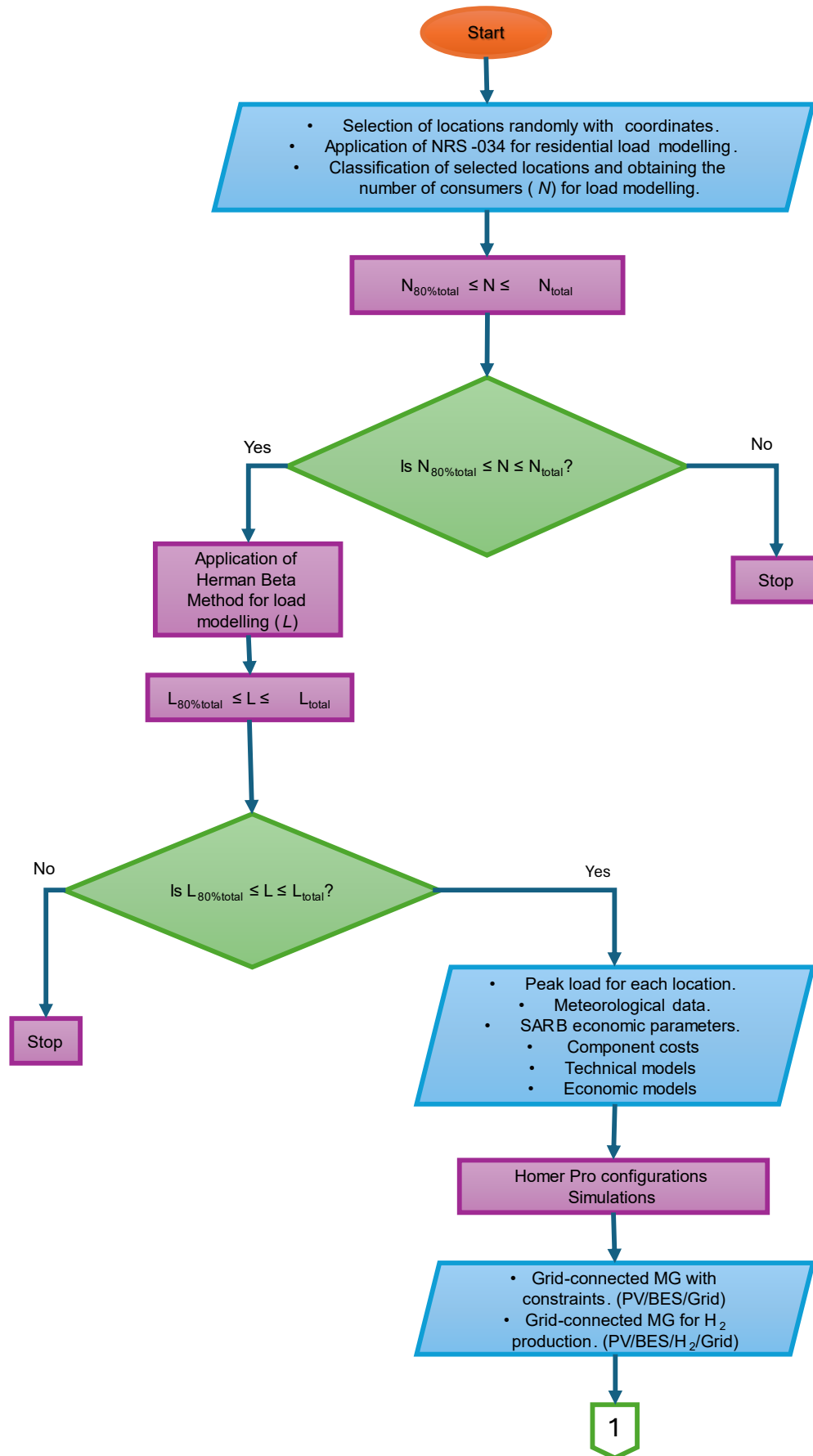
The chapter outlines the research methodology utilized in this study. It includes a review methodology alongside project planning and algorithm development, a description of the selected locations, meteorological data, population statistics, load profiles, key models for techno-economic analysis, the Herman beta method for load estimation, classifications of residential consumer settlements, and specifications for microgrid components. These steps were undertaken to estimate the peak load, which will be modelled in Homer software to analyse various microgrid configurations. The aim is to achieve cost-effective optimisation of microgrids through this modelling process.

3.2. REVIEW METHODOLOGY

The review methodology for this research involved a systematic evaluation of both the technical and economic aspects of microgrid optimisation. The process commenced with the identification and selection of relevant literature, data sources, and case studies sourced from Google Scholar and the Research Gate database. We collected and examined journals and articles published within the last decade. Following this, we assessed key technical parameters such as process efficiency, energy consumption, load profiles, statistical data, and component requirements for the specific location. After considering the technical factors, we analysed economic elements like capital investment, operating costs, Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and market prices for microgrids implemented in various regions. This analysis was conducted in conjunction with the technical data to create detailed cost models. To simplify this information, we created a table in MS Word, detailing the author, title of the article or journal, year of publication, aims, objectives, research, and findings. The objective of this methodology is to provide a comprehensive and comparative assessment to inform decision-making for stakeholders and guide future research and development efforts on microgrids.

3.3. PROJECT PLANNING AND ALGORITHM

The project planning outlines the inputs, outputs, and decision-making for the MG. The algorithm is limited to 80% of the total number of consumers (N) and estimated load (L), meaning it operates at a minimum threshold of 80% of both.



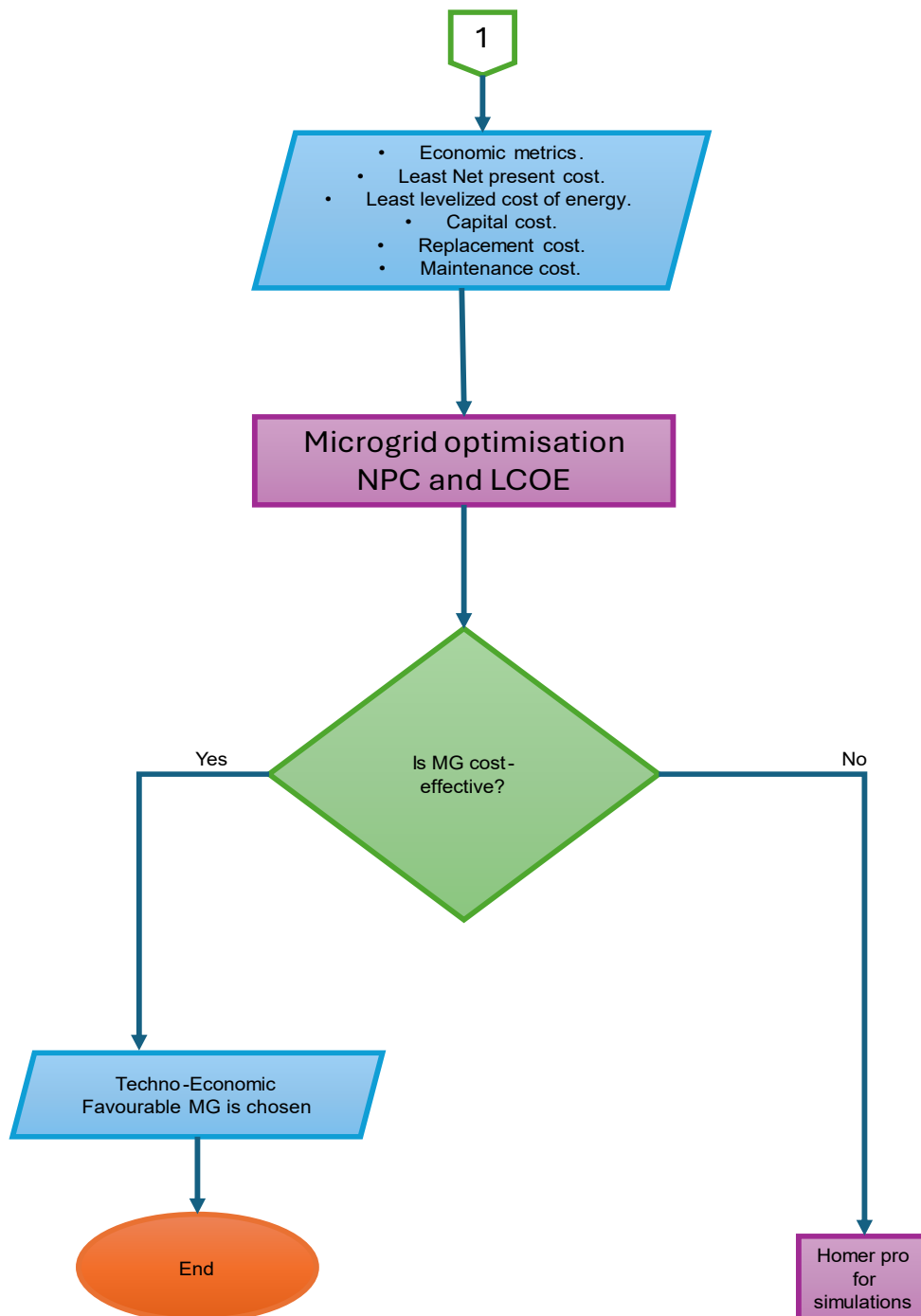


Figure 3.1. Project layout planning and algorithm, showing input data, methodology, limitations and output results.

3.4. SITE DESCRIPTION OF THE SELECTED STUDY LOCATIONS

This work is being undertaken in South Africa, in the Limpopo province. The province is found in the northern part of the country. The province shares borders with Mozambique, Zimbabwe, and Botswana [103].

The province boasts a rich landscape in both agriculture and mining. The energy sector is home to two Eskom coal-fired power stations: Matimba, commissioned in the late 1980s, and Medupi, which began operations in 2015. Beyond conventional electricity generation, the province hosts a significant renewable energy project featuring solar PV as the primary source, followed by biomass and little biogas energy initiatives. Pioneering solar PV projects is due to the advantage of the province having abundant sunshine throughout the entire year [104].

Additionally, there are plans in collaboration with Eskom to construct a pumped hydro power station in the Tubatse area [105] and furthermore, the province has the potential to geothermal [106].

Four rural locations within the province were randomly selected for this study. The chosen sites include Ga-Masekwa in the Blouberg municipality of the Capricorn district, Ka-Dzingidzingi in the Greater Giyani municipality of the Mopane district, Duthuni in the Thulamela municipality of the Vhembe district, and Mookgopong non-urban (NU) in the Mookgopong municipality of the Waterberg district. Table 3.1 below presents the selected locations, districts and municipalities in which the locations are based and their corresponding coordinates and consumer classifications.

Table 3.1. Selected locations for the research study area, including their districts, municipalities, NRS-034-1 consumer settlement classification, and location coordinates.

Selected Locations	Districts	Municipalities	Consumer Class	Location Coordinates
Ga-Masekwa	Capricorn	Blouberg	Rural settlement	23°23.6' S, 28°56.7' E
Ka-Dzingidzingi	Mopani	Greater Giyani	Rural village	23°20.3' S, 30°39.2' E
Duthuni	Vhembe	Thulamela	Rural Village	22°58.3' S, 30°22.9' E
Mookgopong NU	Waterberg	Mookgopong	Rural village	24°31.0' S, 28°43.0' E

As illustrated in Figure 3.2 below, the province of Limpopo is divided into five districts and comprises 21 local municipalities. For this study, four distinct locations were randomly chosen from four different districts within the province, highlighting the variations in population sizes among these locations. Figure 3.2 shows the map of Limpopo province, where the study was conducted.

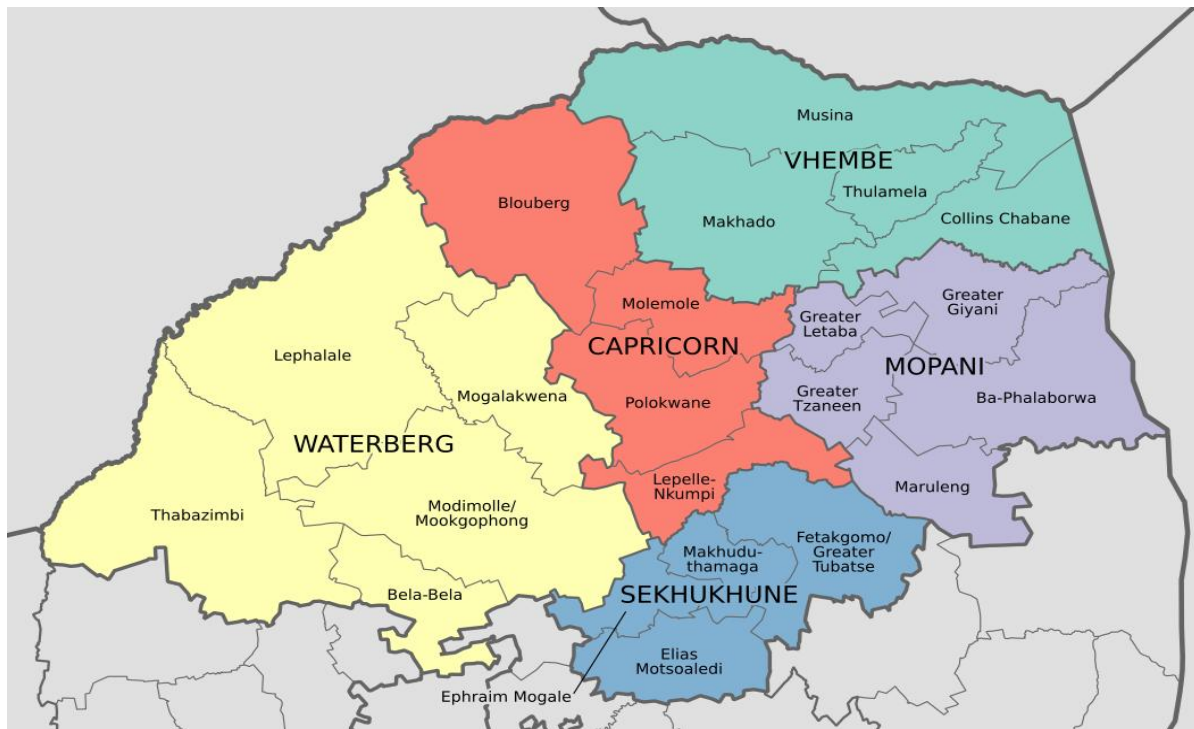


Figure 3.2. The map of Limpopo province shows districts and local municipalities' demarcations, where selected research study locations are picked.

3.5. METEOROLOGICAL DATA OF SELECTED LOCATIONS

It is essential to incorporate relevant meteorological information into the utilised software to effectively model the MG appropriately for adoption in the selected locations. This meteorological data encompasses monthly average solar global horizontal irradiance, monthly average temperature, and monthly average clearness index. These parameters are critical for accurately assessing the climatic conditions and understanding their impact on solar energy potential and other environmental factors within the specified regions. Comprehensive data analysis will enable the formulation of reliable models that can be used for energy planning and resource management in various applications.

The average solar global horizontal irradiance, monthly average temperature, and monthly average clearness index data are presented in Figure 3.3 - Figure 3.6. This informational dataset has been sourced from the National Renewable Energy Laboratory database and NASA's worldwide energy resources, utilizing Homer Pro software for analysis.

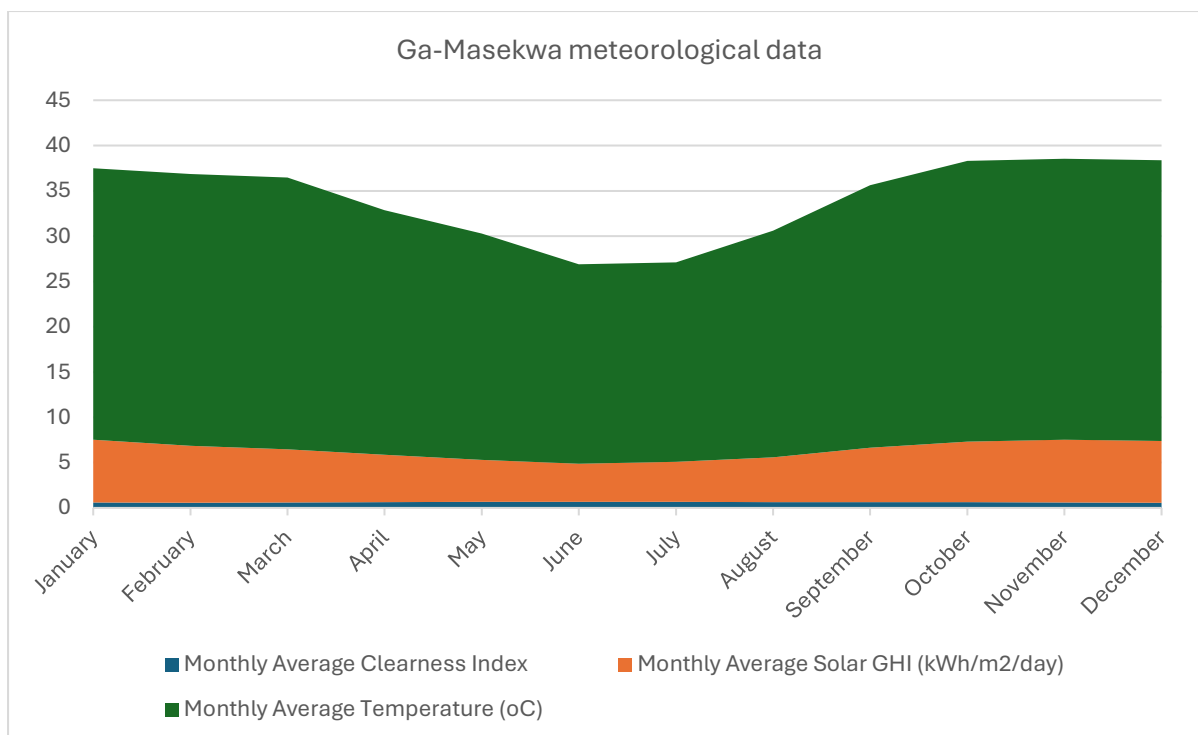


Figure 3.3. Meteorological data for Ga-Masekwa, obtained from Homer, shows the monthly average clearness index, monthly average solar irradiance and monthly average temperature.

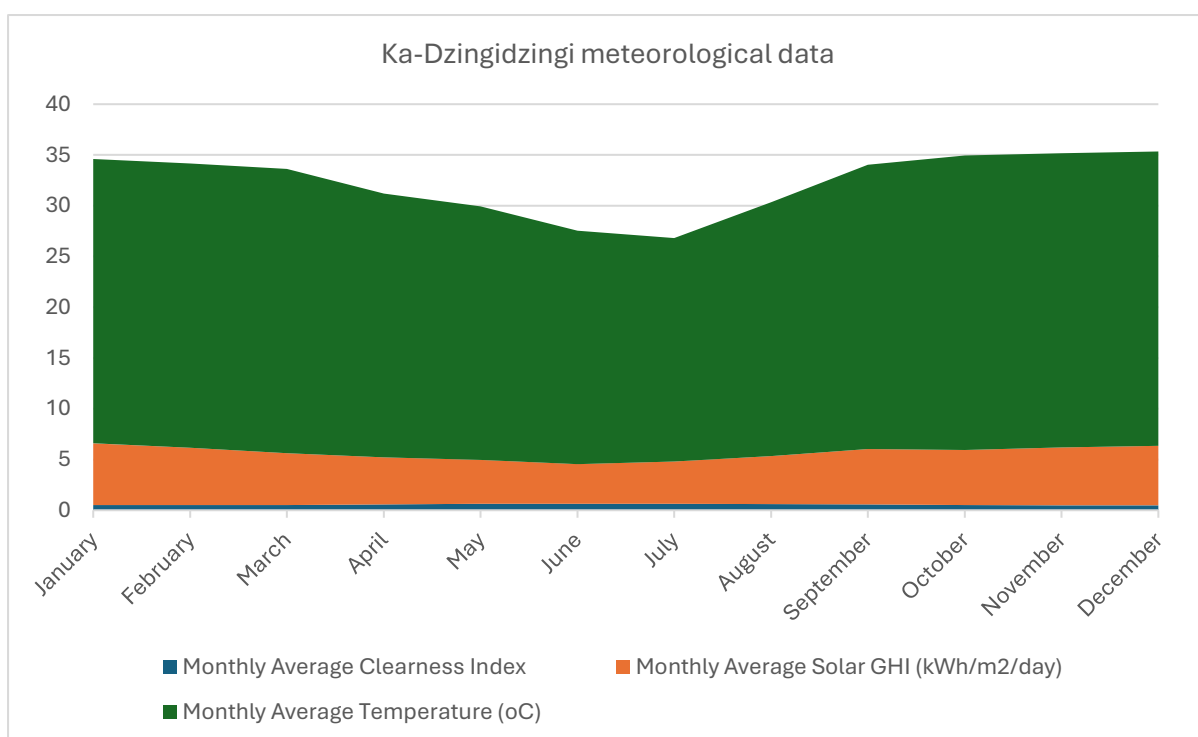


Figure 3.4. Meteorological data for Ka-Dzingidzingi obtained from Homer shows the monthly average clearness index, monthly average solar irradiance and monthly average temperature.

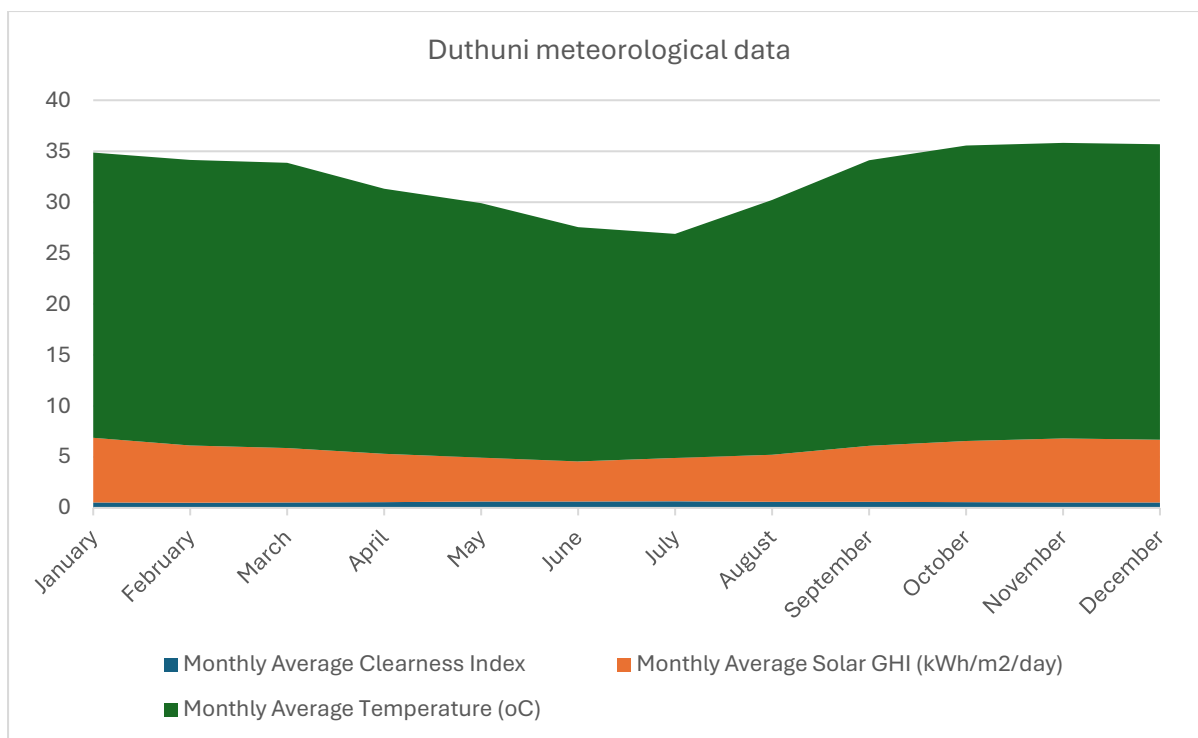


Figure 3.5. Meteorological data for Duthuni obtained from Homer, shows the monthly average clearness index, monthly average solar irradiance and monthly average temperature.

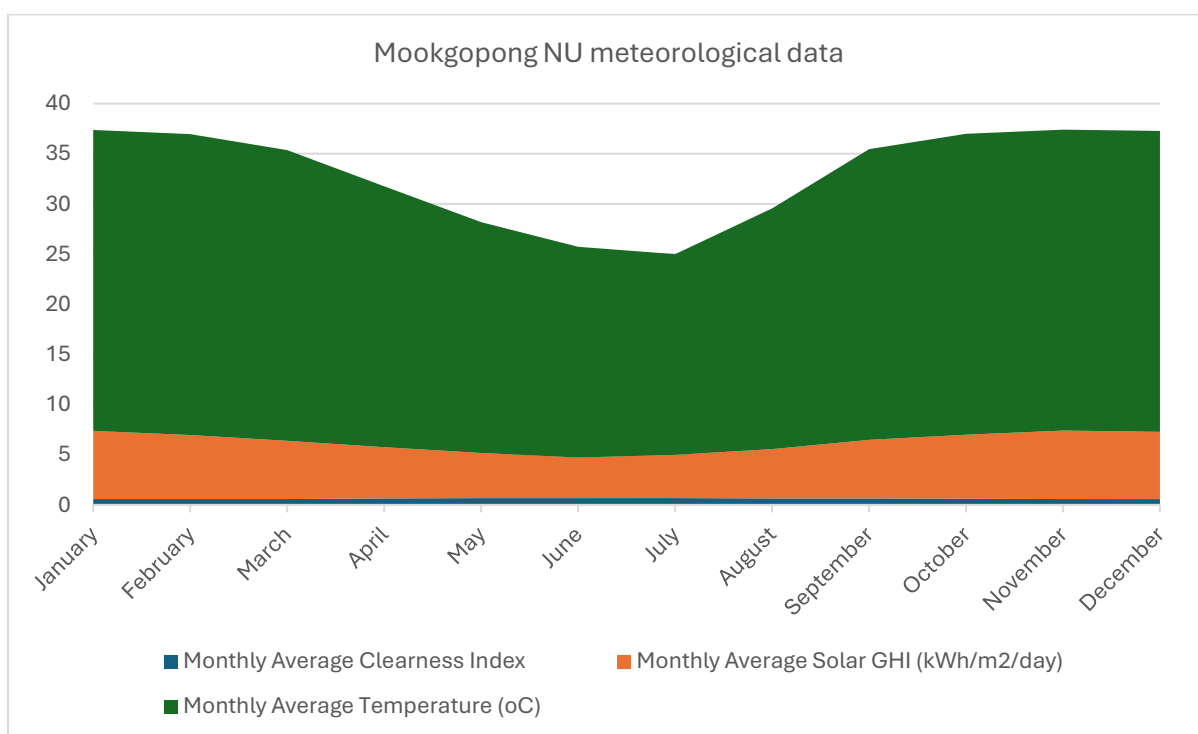


Figure 3.6. Meteorological data for Mookgopong NU obtained from Homer, shows the monthly average clearness index, monthly average solar irradiance and monthly average temperature.

3.6. SELECTED LOCATIONS 2011 AND 2022 CENSUS STATISTICS DATA

The statistical data for the selected locations was obtained from the Statistics South Africa census of 2011 and 2022. This data encompasses population size, number of households, types of dwellings, and the consumer price index for various consumer classifications. Figure 3.7 shows the population statistics for the selected locations, providing essential information for the methodology used in this study.

Figure 3.7 outlines the population data for each location in 2011 and 2022 and the number of consumers or households during the same years. This information can be crucial for analysing demographic changes, economic trends, and consumer behaviour across different locations over time.

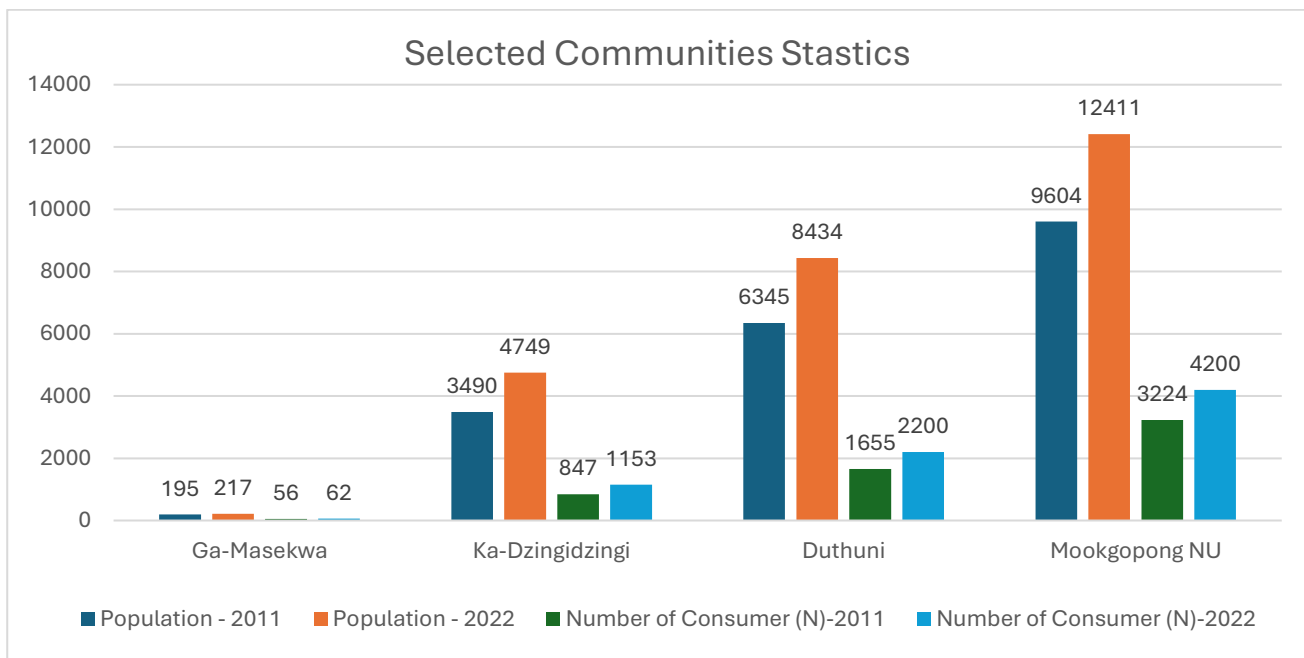


Figure 3.7. Population statistics data show the 2011 and 2022 population size and number of consumers in selected locations [11].

3.7. LOAD PROFILES

Figure 3.8 - Figure 3.11 illustrate the daily load profiles for the study areas. The demand during winter surpasses that of summer, with peak demand occurring between 18:00 and 20:00, while off-peak demand is observed from midnight into the early morning hours. Load profiles have been modelled using MS Excel and Homer Pro for simulations. In the graphs, the blue line denotes the winter load profile, while the orange line represents the summer load profile.

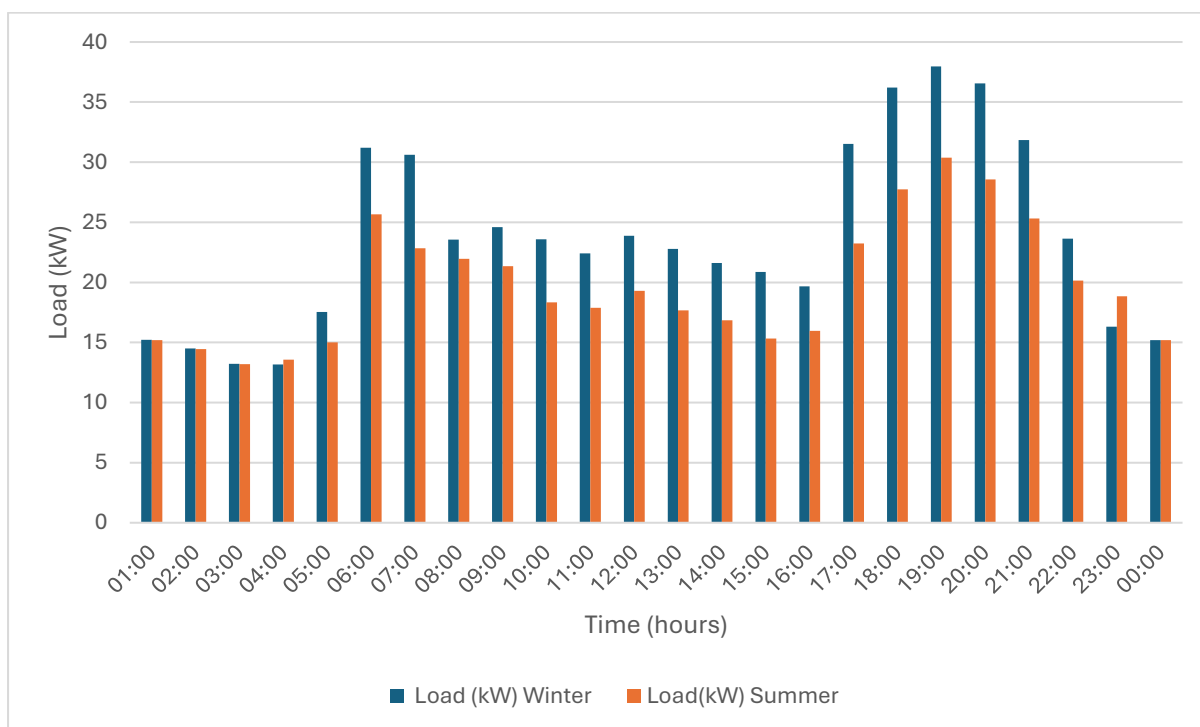


Figure 3.8. The load profile for Ga-Masekwa shows daily demand for the summer and winter seasons.

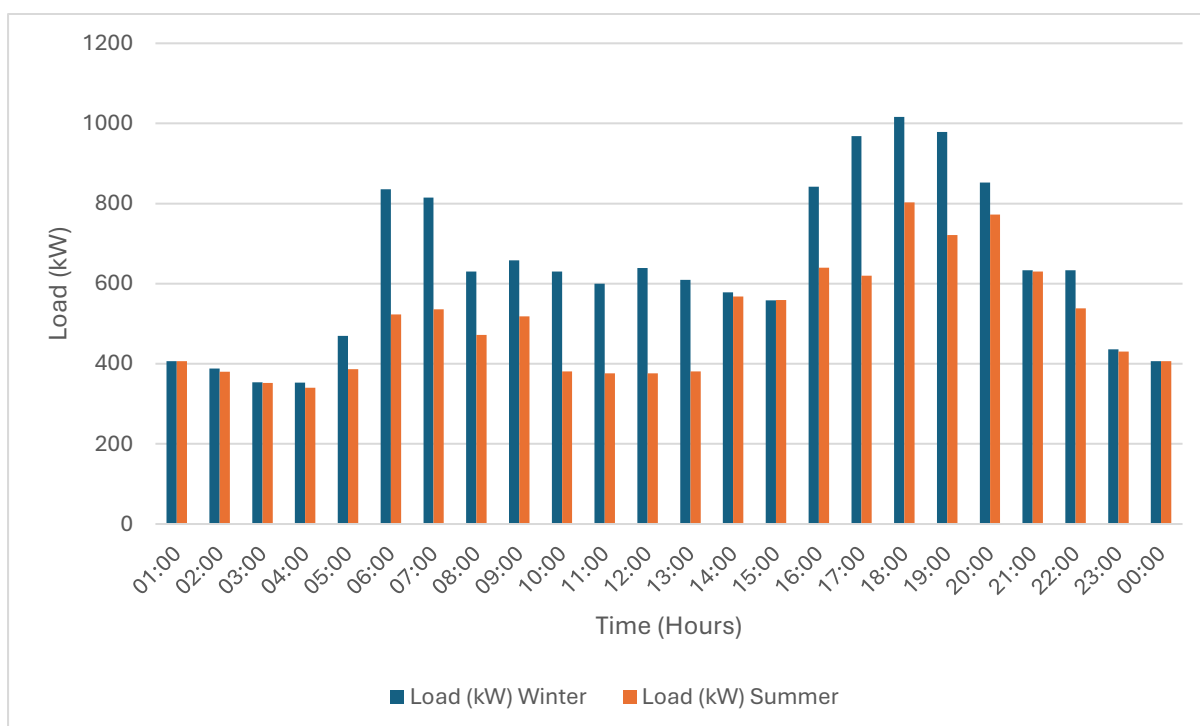


Figure 3.9. The load profile for Ka-Dzingidzingi shows daily demand for summer and winter seasons.

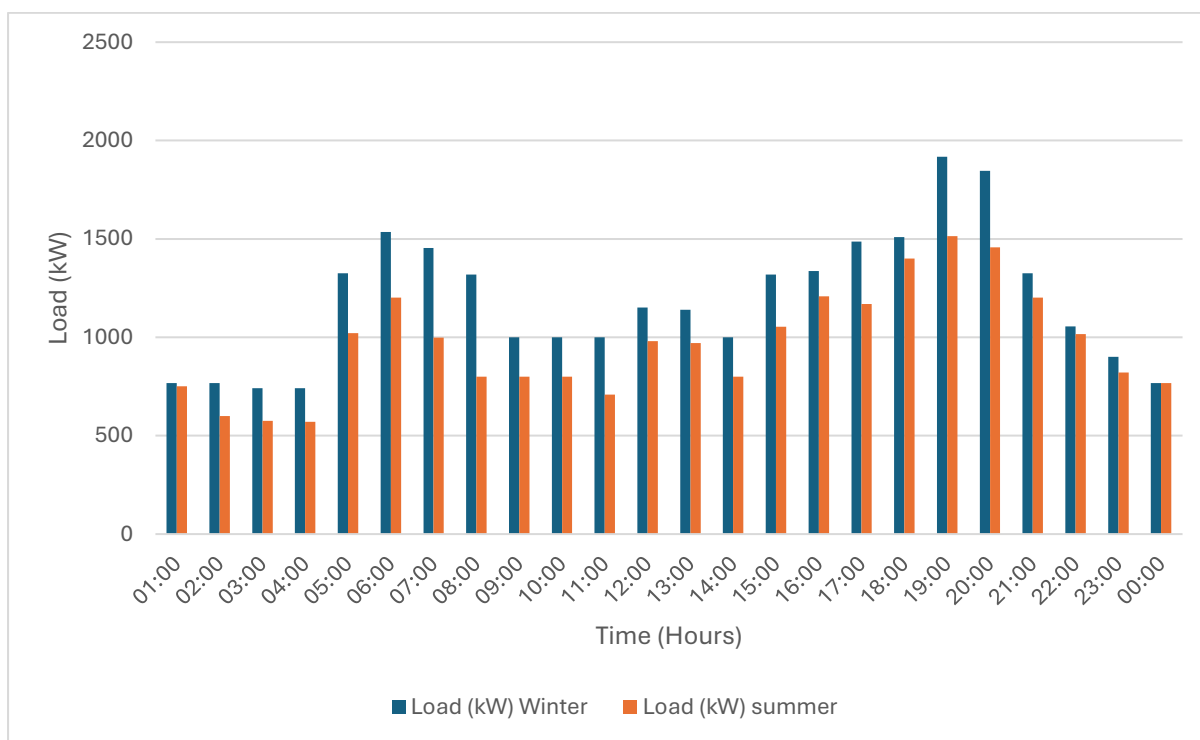


Figure 3.10. The load profile for Duthuni shows daily demand for the summer and winter seasons.

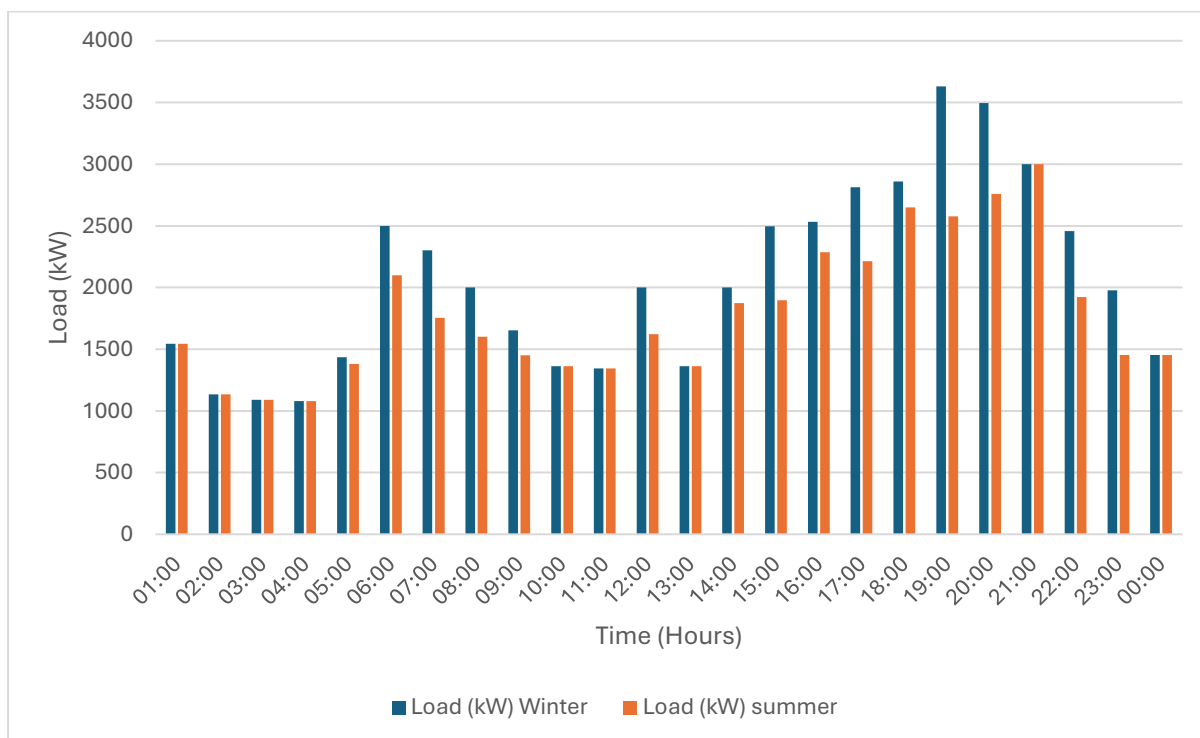


Figure 3.11. The load profile for Mookgopong NU shows daily demand for the summer and winter seasons.

3.8. SOUTH AFRICAN RESERVE BANK ECONOMIC INFORMATION

The economic information pertains to the discount rate, inflation rate, annual capacity shortage, and project lifetime. This information was used for modelling and simulation of MGs. The economic information was found on the South African Reserve Bank website [107]. The information is as follows:

Discount rate: 8.25%

Inflation rate: 5.40%

Project lifetime: 25 years

3.9. TECHNO-ECONOMIC MODELS

3.9.1. TECHNICAL MODELS OF MICROGRID OPTIMISATION

The following power generation output and operational models outline the principles of distributed energy resources employed in the design of microgrids for this study. These models illustrate the operational principles of solar PV systems, BES, electrolyzers, H₂ systems, hydrogen tanks, and the grid.

3.9.1.1. MICROGRID SYSTEM POWER BALANCE

For the stable MG, the total power generated must be equal to the total power that has been consumed plus the losses. The power balance is depicted for all selected locations by schematics in Figure 12-15. The power balance of the MG can be expressed as follows:

$$P_{Load} = P_{PV} + P_{Grid} \pm P_{BES} \quad (3.1)$$

Where P_{Load} is the load demand, the P_{BES} is the charge and discharge power from the battery system, P_{PV} , $P_{Electroliser}$, and P_{Grid} are the power generated from solar PV, Electrolyser, and Grid [70].

3.9.1.2. SOLAR PV PRINCIPLE OF OPERATION

PV technology is an array of PV cells connected in parallel or series to convert solar energy to electrical energy. The power output of the PV system can be expressed as:

$$P_{PV} = \eta_{PV} * A_{PV} * I_{PV} \quad (3.2)$$

On solar PV, P_{PV} , η_{PV} , A_{PV} , and I_{PV} are the power output of PV, PV module efficiency, surface area of the PV system, and global horizontal solar irradiance [70].

3.9.1.3. BATTERY ENERGY SYSTEM

A battery energy system is a process by which electricity imported from RER can be stored during the off-peak period when the power consumption is low and feedback into the power system at the peak load period when the power demand is high. The storage bank autonomy (SBA_{batt}) is the ratio of the BES size to the electric load. The SBA_{batt} of the battery can be estimated by using the following equation [70]:

$$SBA_{batt} = \frac{N_{ess} V_n Q_n \left(1 - \left(\frac{q_{min}}{100}\right)\right) \left(\frac{24}{d}\right)}{P_{prim,ave} (100Wh/kWh)} \quad (3.3)$$

where V_n is the nominal voltage of a single BES (V), N_{ess} is the number of BESs in a bank, Q_n is the nominal capacity of a single BES (Ah), $P_{prim,ave}$ is the average primary load (kWh/d), and q_{min} is the minimum state of charge of the BES bank (%). The BES charge efficiency can be expressed as:

$$\eta_{BES,c} = \sqrt{\eta_{BES,rt}} \quad (3.4)$$

where $\eta_{BES,c}$ is the BES charge efficiency and $\eta_{BES,rt}$ is the BES round trip efficiency. The maximum BES charge power in relation to the maximum charge current is given in (5) as [70]:

$$P_{BES} = \frac{N_{BES} * I_{max} * V_n}{1000} \quad (3.5)$$

where N_{BES} is the number of BESs in the storage bank, and I_{max} is the BES maximum charge current (A). The efficiency of selected BES is shown in equation 4.

3.9.1.4. GRID POWER OPERATION

Power generated from the power grid depends on the voltage and current flowing in the transmission lines. For one phase, power generated from the grid can be expressed as follows:

$$P_{GRID} = V * I * \cos(\theta) \quad (3.6)$$

V is the voltage, I is the current on the line, and $\cos(\theta)$ is the power factor, accounting for the phase difference between voltage and current in an AC system. The power factor typically ranges from 0 to 1.

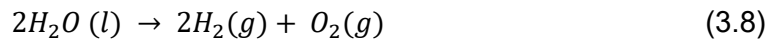
For the three-phase transmission, power can be expressed as:

$$P_{GRID} = \sqrt{3} * V_L * I_L * \cos(\theta) \quad (3.7)$$

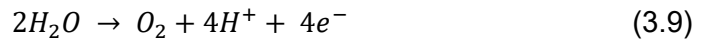
Where $\sqrt{3}$, reflects the intrinsic relationship between voltages and currents in a three-phase power system, which is crucial for accurate power calculations and system design. V_L , I_L , and $\cos(\theta)$ represent line voltage, line current, and power factor [108].

3.9.1.5. HYDROGEN PRODUCTION MODELS

An electrolyser is needed for hydrogen production from the electrolysis process. An electrolyser is a device that uses electricity to split water into hydrogen and oxygen. Inside the electrolyser is the electrolyte that facilitates the movement of ions. Solid oxide, solid polymer membrane, and alkaline electrolytes can be chosen. Utilising the proton exchange membrane electrolyte as in this study, the following equation facilitates hydrogen production [88].



The half-reaction at the anode, where water molecules lose electrons and produce oxygen gas and protons, is given by:



The half-reaction of the cathode, where protons travel through the electrolyte to the cathode, gaining electrons and forming hydrogen gas.



3.9.1.6. HYDROGEN TANK MODEL

The hydrogen storage follows principles of thermodynamics, fluid dynamics, and material science in real gas behaviour, given by the following equation:

$$\left(P + \frac{a}{V_m^2}\right) (V_m - b) = RT \quad (3.11)$$

Where P , V_m , a , b , R and T are the pressure, molar volume of gas (m^3/mol), intermolecular attraction coefficient, volume excluded by molecules, universal gas constant ($8.314 J/(mol \cdot K)$) and temperature in (K) [88].

3.9.2. ECONOMIC MODELS OF MICROGRID OPTIMISATION

3.9.2.1. ANNUAL COST OF THE SYSTEM (ACC)

The system's annual cost is defined as the total expenses incurred in the operation, maintenance, and management of the MG over one year. This is the annualised sum of capital, replacement, and maintenance costs, excluding the salvage value [70].

$$ACS = \sum_{i=1}^n [ACC + ARC + AMC - S], \quad R/year \quad (3.12)$$

Where ACC , ARC , AMC , and S represent annual capital costs, annual replacement costs, annual maintenance costs, and the salvage value.

3.9.2.2. THE ENTIRE MICROGRID'S TOTAL ACS IS GIVEN AS:

The model for the entire MG's total annualised cost of the system is expressed as follows:

$$ACS_{total} = CRF(i, n) * NPC_{total}, \quad R/year \quad (3.13)$$

Where CRF , NPC , i , and n represent the capital recovery factor, NPC, annual discount rate, and project lifetime.

3.9.2.3. SALVAGE VALUE (S)

This is the residual worth of each component on the MG at the end of its lifetime [15].

$$S = C_{rep} * \frac{R_{rlc}}{R_{cl}}, \quad R/year \quad (3.14)$$

Where C_{rep} , R_{rlc} , and R_{cl} represent replacement costs, the remaining life of components, and component lifetime.

3.9.2.4. CAPITAL RECOVERY FACTOR (CFR)

This is the model that is used to calculate the annualised cost of an investment over its lifetime, and it is expressed in equation 15.

$$CRF(i, n) = \frac{i*(1+i)^n}{(1+i)^n - 1} \quad (3.15)$$

3.9.2.5. **NET PRESENT COST (NPC)**

The NPC is defined as the present sum of the MG costs incurred throughout its lifetime [70].

$$NPC_{total} = \frac{ACS_{total}}{CRF}, \quad R/year \quad (3.16)$$

3.9.2.6. **LEVELIZED COST OF ENERGY (LCOE)**

The levelized cost of the energy is the cost of producing a unit of electrical energy.

$$LCOE = \frac{ACS_{total}}{AES} \quad (3.17)$$

The LCOE is obtained from ACS and AES, and AES represents the annual generated energy by the system.

3.9.2.7. **INTERNAL RATE OF RETURN (IRR)**

The ROI is the discount rate at which power systems under financial and technical assessment have the same NPC. It is the rate at which an investment breaks even in terms of present value [70].

$$IRR = \frac{\sum B_n - C_n}{(1+i)^n} = 0 \quad (3.18)$$

Where B_n is the yearly benefits, C_n is the yearly costs, and n is the project lifetime.

3.9.2.8. **SIMPLE PAYBACK YEARS (SPB)**

The SPB is the metric that is used to calculate the number of years to recoup all costs injected into the project [15].

$$SPB = \sum \frac{I_c}{Y_b - Y_c} \quad (3.19)$$

Where I_c is investment costs, Y_b is yearly benefits, and Y_c is annual costs.

3.10. **MICROGRID DESIGN SCHEMATICS**

An MG is a small-scale energy system comprising distributed energy resources and loads. It can be designed to operate as a grid-connected or off-grid system. This system is the alternative way to generate and provide reliable and affordable energy for consumers. This

section contains the models of all components that constitute the MG system designed for this study. The MG designed for this study comprised solar photovoltaic (PV), battery energy storage (BES), electrolyser, hydrogen tank, converter, and utility grid (GRID). Figure 3.12 - Figure 3.15 depict the MG design in Homer Pro software. The schematic diagrams also show the peak load in kW and average daily energy in kWh/day for each selected location.

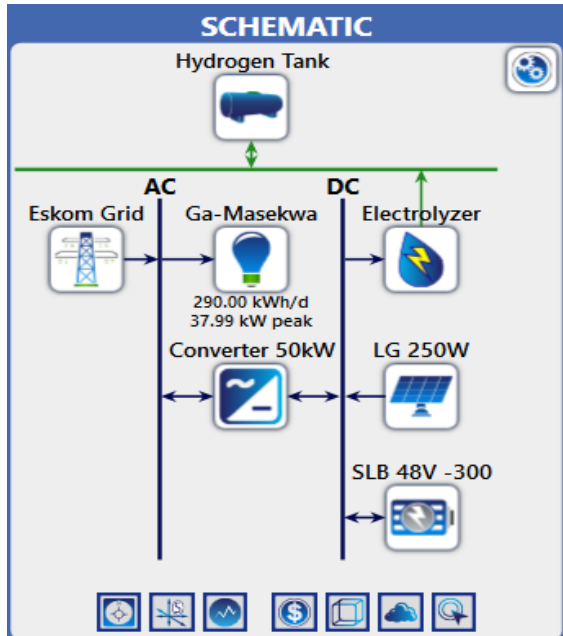


Figure 3.12. Homer Pro schematic MG design diagram for Ga-Masekwa location.

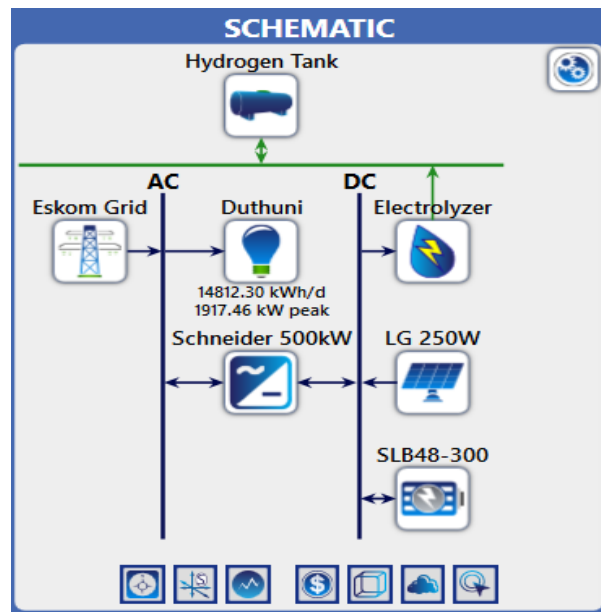


Figure 3.14. Homer Pro schematic MG design diagram for Duthuni location.

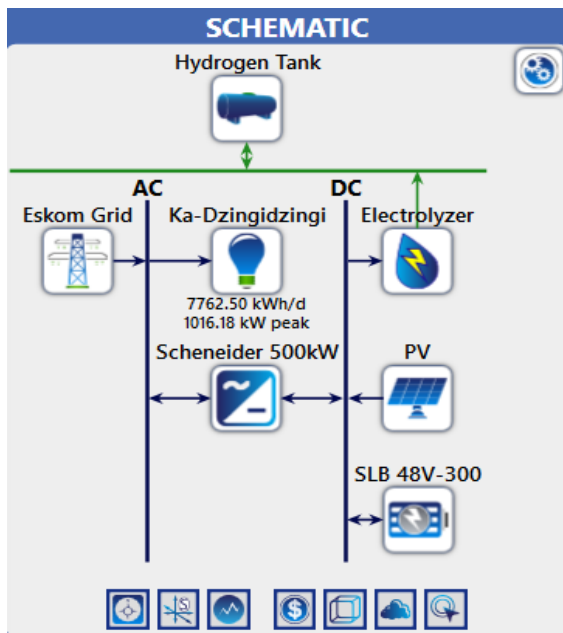


Figure 3.13. Homer Pro schematic MG design diagram for Ka-Dzingidzingi location.

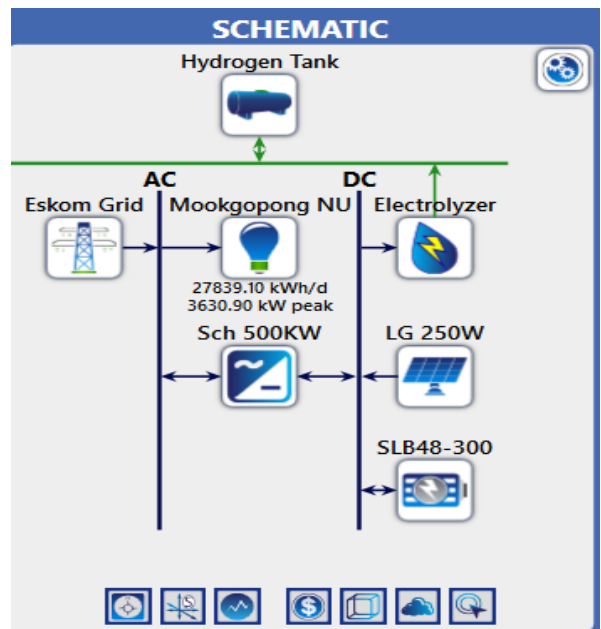


Figure 3.15. Homer Pro schematic MG design diagram for Mookgopong NU location.

3.11. THE HERMAN-BETA METHOD FOR LOAD MODELLING ESTIMATIONS

Planning and designing residential distribution require optimal sizing and placement of electrical equipment. This is done to predict consumer load using a statistical model of loads rather than a deterministic model to deal with load uncertainty [109]. Each consumer's current load can be depicted using an average and a standard deviation. While a set of potential load parameters may be available for a community, the load parameter for an individual consumer remains uncertain [58]. Residential loads can roughly represent a constant current in static load flow analyses. The suggested load model presumes that all consumer categories exhibit constant current characteristics.

This assumption may result in overestimations of voltage regulation and losses for very low-income consumers. The load currents observed at peak demand, or any given moment follow a statistical distribution. This distribution can be illustrated as a histogram that shows the frequency of occurrence (or probability) in relation to current (measured in amperes). From this histogram, a statistical expression known as a probabilistic distribution function (PDF) can be formulated. One frequently encountered PDF is the Gaussian or normal PDF, depicted in Figure 16.

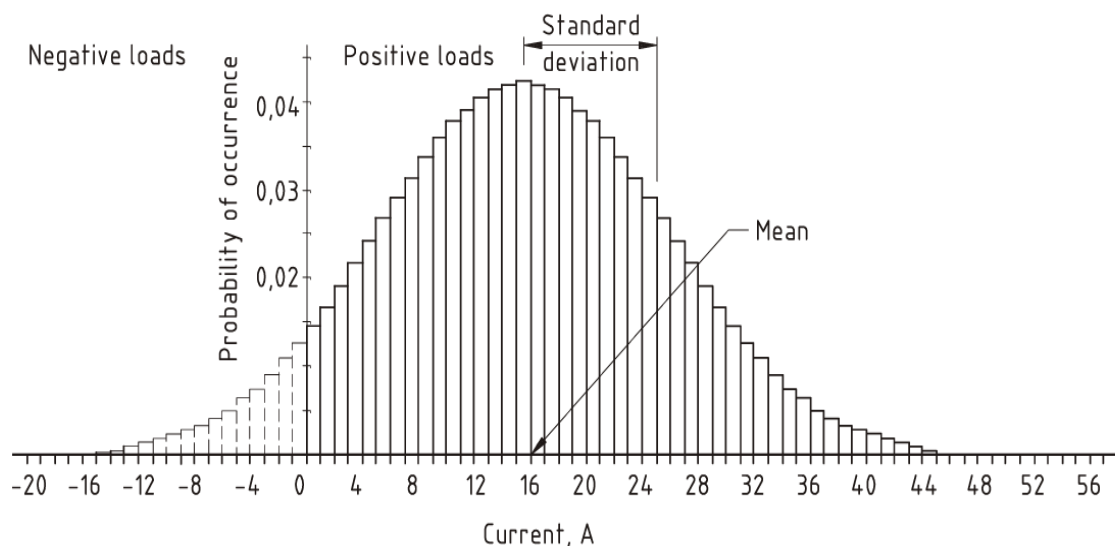


Figure 3.16. The Gaussian probabilistic distribution function graph

While this symmetrical characterization is effective for a sizable number of combined loads (greater than 30), it is often unsuitable for smaller groups, such as those found in reticulation design. In these cases, the load currents' probability density function (PDF) may exhibit a bias towards either the right or left, as demonstrated in Figure 17. A symmetrical distribution, such

as the Gaussian PDF, requires two statistical parameters for its description; however, when accounting for skewness, three parameters become necessary.

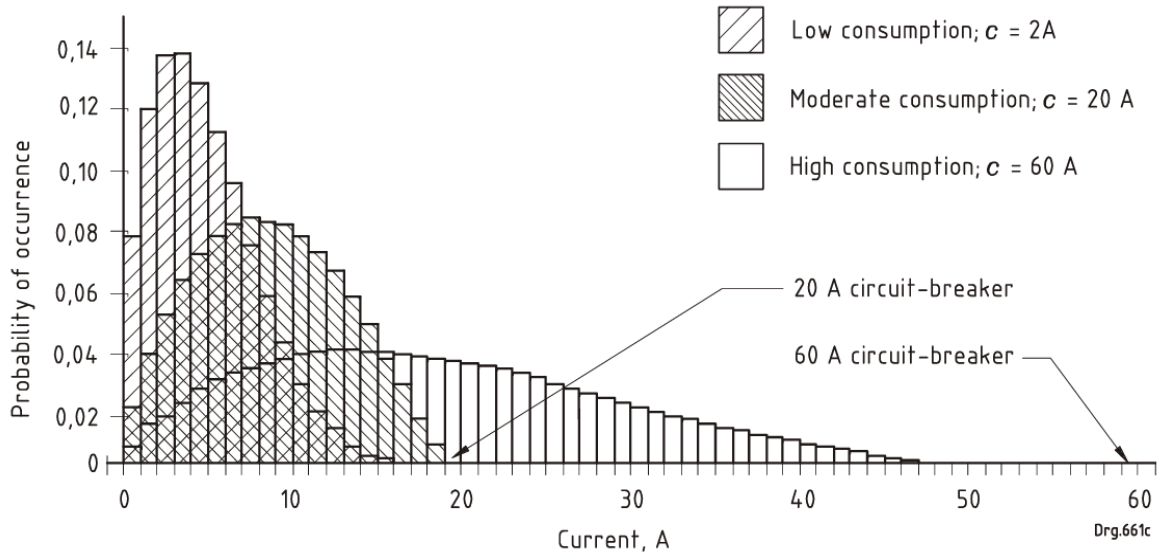


Figure 3.17. The skewness in Gaussian probabilistic distribution function graph.

The Herman-beta method, utilizing parameters a , b , and c , serves as a convenient probability density function (PDF) for skewness and is regarded as the most precise technique for calculating voltage drop in low-voltage residential feeders. This method outperforms the British method, the Loss of Diversity method, and the Monte Carlo simulation. It can generate a set of curves that effectively accommodate nearly all realistic load distributions. The average value of the beta probability density function (PDF) is articulated as follows:

$$\mu = C * \frac{a}{a+b} \quad (3.20)$$

Where a and b are current load parameters, c is the scaling value or circuit breaker size.

Where load data are available, parameters a and b can be derived for any value of c , utilizing mean (μ) and standard deviation (σ) of the data.

$$a = \frac{\mu(c\mu - \mu^2 - \sigma^2)}{c\sigma^2} \quad (3.21)$$

$$b = \frac{(c - \mu)(c\mu - \mu^2 - \sigma^2)}{c\sigma^2} \quad (3.22)$$

The following formula estimates the maximum load demand in kilovolt amperes (kVA) for any location with a known number of consumers.

$$L = 0.23 * N * \frac{c}{a+b} * \left[a + 1.28 \sqrt{\frac{a*b}{N(a+b+1)}} \right] \quad (3.23)$$

Where:

L The estimated maximum load in kVA

N Total number of consumers

a , b , and c Load current model parameters

Estimating the load for urban or rural residential users is crucial for the financial aspects of the electrification system. An overestimation can lead to excessive capital investment, while an underestimation can result in subpar supply quality, necessitating costly upgrades in the future. The probabilistic load model is the most appropriate approach for the South African context due to the cost-efficient strategies that network designers and planners must consider during the electrification process.

3.12. DOMESTIC CONSUMER SETTLEMENT CLASSIFICATION ACCORDING TO THE SOUTH AFRICAN STANDARD DOCUMENT (NRS 034-1)

The South African standard document on electricity distribution (NRS 034-1) identifies eight consumer classes, including rural settlements and villages. This study focuses specifically on these areas, which include residential homes, small shops, primary healthcare facilities, and schools. The consumer classification for rural settlements and villages, based on design load parameters a , b , and c , is projected over a 15-year period, as detailed in Table 3.2 below.

Table 3.2. Consumer settlement classification of selected locations with their design load parameters based on NRS 034-1 [109].

Consumer Class	a	b	c	ADMD (kVA)	μ (A)	σ (A)
Rural settlement	0.35	2.88	20	0.50	2.17	3.03
Rural village	0.48	2.13	20	0.84	3.65	4.07

3.13. PEAK LOAD ESTIMATIONS FOR SELECTED LOCATIONS

The number of consumers, which can also be referred to as the number of households in this methodology, along with the design load parameters, have been employed in the Herman-Beta model to estimate the maximum daily load consumption for each selected location. Table 3.3 below presents the chosen locations, alongside the number of consumers (N), the estimated maximum load measured in kilo-volt amperes (kVA), and the estimated daily peak load, calculated at 80% operational capacity. This 80% peak load estimation, derived from the Herman-Beta method, is intentionally framed to represent a typical operational scenario, as distribution transformers in rural areas typically function at around 80% capacity during peak hours. This estimation illustrates the anticipated demand during the peak hours of the day for each selected location.

Table 3.3. Estimated maximum/peak load for each selected location based on the Herman Beta method application.

Selected locations	Number of consumers (N)	Estimated Peak Load (kVA)	Estimated Peak Load 80% (kVA)
Ga-Masekwa	62	37.98	30.38
Ka-Dzingidzingi	1153	1016.18	812.94
Duthuni	2200	1917.46	1533.97
Mookgophong NU	4200	3630.91	2904.73

3.14. MICROGRID COMPONENTS SPECIFICATIONS WITH THEIR COST PER KW

This study simulates two distinct systems. The first system consists of solar PV panels, BES, and the Grid, while the second system includes solar PV, BES, an electrolyser, a hydrogen tank, and the Grid. Various configurations have been developed for both systems, yielding the most favourable economic outcomes selected as the proposed system for each specified location. The analysis encompasses two primary elements: the technical aspect of the microgrid, which evaluates its capacity to generate energy and meet demand without any unmet energy, excess energy, or consumption percentage, and the renewable fraction of the microgrid. The second aspect focuses on the economic analysis of microgrid operations, assessing metrics such as return on ROI, IRR, SPB, NPC, and LCOE.

To conduct these analyses, we must identify the types of components we will utilise, their specifications, and the costs per kW. These costs encompass capital expenses per kW, replacement per kW, and operational expenses per kW. The costs were sourced from energy retailer domains, while the operational costs were estimated based on a reference of 10% of the capital cost, a benchmark used by other authors [73] [110] [71] and [111]. Table 3.4 below presents the specifications and costs associated with the MG components. This study evaluated two types of inverters: a 50-kW inverter designated for the rural settlement of Ga-Masekwa, and a 500-kW inverter intended for the other research areas. Additionally, three solar PV modules were analysed to assess their economic performance. The electrolyser and hydrogen storage tank capacities were determined based on the load requirements. For battery energy storage, lithium-ion batteries were selected, featuring a voltage of 48 V and a capacity of 14.4 kWh, with the quantity needed depending on the load size.

Table 3.4. MG design components specifications and estimated costs per kW

Components	Specifications	Capital Cost (R/kW)	Replacement Cost (R/kW)	Operational Cost (R/kW)
Solar PV	Name: LG Electronics Capacity: 250W Type: Monocrystalline Temperature coefficient: -0.458900 Operating temperature: 44.9°C Efficiency: 13% Open circuit voltage: 38.26V Short circuit voltage: 8.62A Lifetime: 25years	8000	6400	800
	Name: LG Electronics Capacity: 375W Type: Monocrystalline Temperature coefficient: -0.390000 Operating temperature: 47.5°C Efficiency: 13% Open circuit voltage: 48.60V Short circuit voltage: 9.99A Lifetime: 25years	10135	8108	1014
	Name: TenkSolar Capacity: 500W Type: Monocrystalline Temperature coefficient: -0.35 Operating temperature: 45°C Efficiency: 22.78% Open circuit voltage: 51.10V Short circuit voltage: 11.88A Lifetime: 25years	10000	8000	1000
Battery	Nominal voltage: 48V Nominal capacity: 14.4kWh Nominal capacity: 300Ah Round trip Efficiency: 96%	30000	24000	3000

	Maximum charge rate: 0.32A/Ah Maximum charge current: 95A Maximum discharge current: 95A			
Inverter	Capacity: 50kW Lifetime=15 years Efficiency=98.50%	1500	1200	150
	Capacity: 500kW Lifetime: 15 years Efficiency: 95.5%	3000	2600	90
Electrolyser	Capacity: 1 kW Lifetime: 15 years Efficiency: 85%	65000	65000	650
	Capacity: 25 kW Lifetime: 15 years Efficiency: 85%	65000	65000	650
	Capacity: 48 kW Lifetime: 15 years Efficiency: 85%	65000	65000	650
	Capacity: 90 kW Lifetime: 15 years Efficiency: 85%	65000	65000	650
Hydrogen tank	Size: 1 kg Lifetime: 25 years	25000	16000	250
	Size: 5 kg Lifetime: 25 years	25000	16000	250
	Size: 10 kg Lifetime: 25 years	25000	16000	250
	Size: 15 kg Lifetime: 25 years	25000	16000	250

Table 3.5 provides a comprehensive overview of the sizing of components employed in the design of MGs, clearly distinguishing between scenarios that incorporate hydrogen production considerations and those that do not. This sizing analysis examines three specific types of solar modules, detailing their individual characteristics such as efficiency ratings, power output, and suitability for various environmental conditions.

Additionally, the analysis includes information on the necessary inverters, tailored to optimise the performance of the chosen solar modules for the specific geographical location in which the microgrid is implemented. It also assesses the number of backup batteries required to ensure a reliable energy supply, evaluating both configurations with hydrogen production capabilities and those that operate independently of hydrogen production. By comparing these scenarios, the Table 3.5 aims to provide insights into the overall system efficiency, cost implications, and the sustainability benefits that hydrogen production might offer in the context of microgrid design.

Table 3.5. The component sizing and designing of an MG using Homer Pro considers three different solar PV modules, inverters, and batteries.

Selected Locations	Solar PV Array Size (kW)	Number of Solar Panels		Number of Inverters	Number of Batteries without Hydrogen Production	Number of Batteries with Hydrogen Production
		size	#			
Ga-Masekwa	60	250W	240	1 x 50kW	18	3
		375W	160			
		500W	120			
Ka-Dzingidzingi	1509	250W	6036	3 x 500kW	437	71
		375W	4024			
		500W	3018			
Duthuni	2879	250W	11516	4 x 500kW	814	134
		375	7678			
		500	5758			
Mookgophong NU	5410	250	21640	8 x 500kW	1560	253
		375	14427			
		500	10820			

3.15. CONCLUSION

Load estimations for selected locations were calculated using the Herman-Beta method, while Homer software was utilised to simulate different MG configurations. For the setup of these simulations and load modelling, statistical and meteorological data were gathered and employed in the calculations with Homer Pro. Additionally, two systems were examined: one without hydrogen production and one with hydrogen production, focusing on their technical and economic robustness. For the system without hydrogen production, the investigation compared PV/Grid and PV/BES/Grid configurations using two different inverter sizes, ultimately selecting the most cost-effective option. In the system with hydrogen production, three solar PV modules, two inverter sizes, battery storage, various electrolyser sizes, and a hydrogen tank for storing produced hydrogen were optimised using Homer software to assess the economic feasibility of the microgrids.

CHAPTER FOUR: AN OVERVIEW ASSESSMENT OF AVAILABLE AND POTENTIAL RENEWABLE ENERGY RESOURCES FOR LIMPOPO PROVINCE

4.1. PREAMBLE

This chapter offers a thorough overview of the RER available and potential in Limpopo province, assessing their resource availability and operational status. The findings highlight solar PV, biomass, and biogas as the existing resources, while hydropower, wind turbines, and geothermal energy are identified as potential resources in the province.

4.2. THE ASSESSMENT REVIEW OF AVAILABLE RENEWABLE ENERGY RESOURCES IN LIMPOPO PROVINCE FOR MICROGRID OPTIMISATION

The review assessment conducted for the province of Limpopo indicates that among the recognized RER, only solar PV, biomass, and a small proportion of biogas are currently in use. Biomass serves as the primary option for cooking and heating, followed by solar PV and then biogas. Despite the province's abundance of biomass resources, there is a notable gap in biogas production, as the technology is not widely known or acknowledged. However, certain areas, such as the University of Venda, do have existing infrastructures for biogas production [112].

Solar PV technology is increasingly reaching remote rural areas, thanks to its tangible optimisation capabilities. The province has made significant strides in attracting investors and developing a range of solar PV systems, from small-scale installations for residential use to large-scale solar plants with capacities measured in megawatts. While many people still rely on biomass for cooking and heating, and utility grid electricity for nighttime lighting, there is a positive trend towards the adoption of solar PV for energy integration, helping to address the high cost of electricity.

The village of Mpheni has resorted to solar PV technology to solve energy scarcity challenges. The village has about 50 consumers or houses, and each house has an estimated daily energy consumption of 7.846 kWh. The size of the solar PV system to be installed is directly impacted by the number of consumers and the daily usage of energy per household for that area of interest. That is why the system to be built for the village of Mpheni needs to have a daily energy of about 392.3kWh/day. This figure is greater than that of the village of Gwakwani because Gwakwani has about 40 consumers, and each house is estimated to be 1.26 kWh per day, amounting the total energy to about 50 kWh/day.

Solar PV is also an alternative way to generate affordable and reliable energy; the technology can operate in parallel with the utility. This has been found in The Vuwani Science Resource Centre located in the Vuwani area. The centre has a solar PV system to run basic electric loads such as in-house lighting and fans. The system is designed to generate a power output of about 225kW and is currently in operation. This initiative highlights the potential for solar PV energy utilisation in rural areas.

Limpopo province is focusing on small-scale solar PV systems and several large solar plants with varying capacities. The Soutpan Solar Plant generates about 28 MW and annually produces around 61,000 MWh, supplying the Eskom distribution system at 22 kV. It was financed with approximately 1.2 billion rands and can meet the energy needs of at least 13000 average South African households.

Witkop solar plant, near Polokwane, generates 33 MW and produces about 62,000 MWh annually for the Eskom grid, with an investment of 1.5 billion rands. In contrast, Tom Burke solar plant generates 66 MW and approximately 122,000 MWh per year, supplying clean energy to 38000 households, with a capital investment of about 2.5 billion rands.

Limpopo province has a favourable climate for both small-scale and large-scale solar PV systems. Despite some mountainous areas, a vast expanse of land is suitable for PV implementation [15].

As mentioned in the literature review, The province of Limpopo is ranked in second position as a region where biomass (wood, dung, etc.) is mainly used, and energy means has been in the picture for centuries as the essential energy source for cooking and heating in the province's households. A study by [35] and [113] has indicated that biomass is the basic ingredient for biogas production through biodigesters, and few are in the province.

In the Vhembe district, fixed dome bio-digesters have been developed with support from SANEDI in Chavani village to convert agricultural waste into energy. The Mafuneko project in Gawula village uses cow dung to produce biogas, which is sold to residents at affordable prices. This initiative has created jobs, developed community skills, and enabled cooking with biogas. The Tzaneen municipality uses a bio-digester for wastewater treatment, generating dried sludge for farmers. Additionally, two bio-digesters at the Makhado military bases help manage kitchen waste and provide valuable manure for local farmers. These initiatives are the entry point for biogas realization and awareness, and more digesters are expected to be built in the coming to further enhance and support SDG 7 and 13.

4.3. THE ASSESSMENT REVIEW OF POTENTIAL RENEWABLE ENERGY RESOURCES IN LIMPOPO PROVINCE

While reviewing available RER, it is also vital to consider reviewing potential RER to discover the promising resources that will come into play if all considerations are accepted. Potential RER found are hydropower, geothermal, and wind turbines.

The primary potential energy resources in the region are hydropower through pumped storage systems, followed by geothermal energy. Wind turbine energy is also a possibility, but its feasibility is diminished due to the province's high altitudes, which result in lower air density and reduced suitability for wind turbine operations. The Tubatse pumped storage hydroelectric plant, currently under construction by Eskom, is a promising project anticipated to generate 1500 MW of power, although it has not yet been commissioned [114]. This shows that the province has hydropower potential with the flowing rivers.

The geothermal sector in the province has about 23 thermal springs across Waterberg, Drakensberg, and Soutpansberg, with potential for energy use. The Council for Geosciences highlights the Tshipise thermal spring as a promising site for geothermal drilling, featuring a temperature of 58°C and a flow rate of 10 litres per second. There is also potential for a 75 MW geothermal plant in Makuleni, but ongoing land ownership politics and advocacy for nature conservation hinder development. Currently, pumped hydropower remains the most viable resource.

Observations on wind turbine energy operations indicate that this technology is not well-suited for the province because the province's high altitude results in thinner, less dense air, which means that wind turbines cannot rotate effectively in such conditions. Furthermore, it has been noted that Limpopo province has limited potential for utility-scale wind turbines, primarily due to an annual average wind speed below 4 m/s.

4.4. CONCLUSION

The assessment highlighted solar PV, biomass, and biogas as currently utilised RER. In contrast, hydropower, geothermal, and wind energy show significant potential as emerging RER. The region's climate is ideal for solar PV, with average solar irradiance over 5 kWh/m²/day and temperatures above 30°C, which enhances microgrid optimisation. If regulations are adjusted to ease restrictions on these resources, they could make a substantial contribution to South Africa's energy supply.

CHAPTER FIVE: AN ECONOMIC PERFORMANCE OVERVIEW OF MICROGRIDS FOR LIMPOPO PROVINCE RURAL AREAS

5.1. PREAMBLE

This chapter reviews the economic performance and analyses MGs in four rural areas of Limpopo province. It aims to provide a technical and financial assessment of MG implementation, focusing on load modelling with the probabilistic distribution function (PDF). The goal is to identify systems with the lowest NPC and LCOE, high ROI, and shorter SPB. A combination of techno-economic analysis and the Herman beta method was used for these estimates. This research is important due to the lack of studies on techno-economic analysis in Limpopo and the novel application of the Herman beta method with Homer software. The expected outcome is that a system using solar PV, BES, and grid connections will provide the best economic benefits.

5.2. THE TECHNICAL PERFORMANCE ANALYSIS FOR MICROGRID OPTIMIZATION IN SELECTED LOCATIONS

The 2022 census by Statistics South Africa reveals that Limpopo province has a 96% rate of utility electrification, ensuring almost all areas, including remote rural regions, have electricity access. However, frequent supply interruptions continue to pose challenges in electricity reliability. To address this, the technical and economic performances of proposed MGs have been modelled to evaluate their potential benefits.

Four rural locations were randomly selected to implement MGs for analysis. Table 3.3 and Table 3.5 present the technical details, including estimated peak load and microgrid sizing, derived using the Herman Beta method. This method highlights that consumer count and load parameters are independent variables in determining daily maximum demand in kVA.

The study assessed two configurations for identifying a suitable Microgrid (MG) for each location: PV/Grid and PV/BES/Grid. Table 5.1 and Table 5.2 illustrate the technical performance of these configurations, emphasising key metrics such as energy production, energy consumption, excess energy, and the percentage of renewable energy for each location.

Energy production varies by source and location. The PV/Grid configurations consistently produce more energy than the PV/BES/Grid setups. Ga-Masekwa, with the fewest consumers, shows the lowest energy production, while Mookgopong NU, having the most consumers,

records the highest output. This suggests a direct correlation between energy production and consumer numbers, which is used to estimate maximum peak load. The PV/Grid configuration minimises storage inefficiencies and conversion losses, while the PV/BES/Grid setup prioritises self-consumption and energy independence, sacrificing some efficiency.

Energy consumption refers to the amount of energy used by consumers. Analysis of energy consumption in PV/Grid versus PV/BES/Grid configurations, as shown in Table 5.1 and Table 5.2, reveals that PV/Grid setups consume more energy in all locations. This is due to the optimised self-consumption in PV/BES/Grid configurations, which reduces grid dependence and transmission losses. The inclusion of a battery enhances energy efficiency and decreases reliance on external sources.

Excess energy refers to surplus electricity generated but not immediately used. The analysis of excess energy data shows that the PV/BES/Grid configuration consistently produces more excess energy than the PV/Grid configuration across all locations. While PV/Grid systems export surplus solar energy instantly, the PV/BES/Grid configuration stores energy before exporting it, leading to higher excess energy measurements due to different usage patterns.

The renewable fraction in MG represents the proportion of total energy consumption or production that comes from renewable sources. This metric is vital for assessing sustainability and tracking progress in energy transition initiatives. The findings reveal that both configurations and all locations achieve a renewable fraction exceeding 50%, demonstrating a strong commitment to the energy transition. The PV/Grid configuration harnesses energy directly and exports any surplus to the grid, resulting in a higher renewable fraction compared to the PV/BES/Grid setup, as shown in Table 5.1 and Table 5.2.

The configuration with the lowest NPC and LCOE is selected as the most economically beneficial system from the Homer Pro software outputs. The capital costs for PV/Grid configurations are lower than those for PV/BES/Grid in all selected locations, as shown in Table 5.3 and Table 5.4. This is because the one-time, long-term investment expenses for MG are less for PV/Grid setups.

The author of the dissertation [108] concentrated on the development of load models for Eskom's residential customers. It explored various methods employed in several G7 countries for electricity distribution. The findings revealed that, akin to the conclusions of this research, the Herman-Beta method is the most appropriate approach for designing residential distribution systems for electricity supply in South Africa. The application of this method in the current study directly reflects the outcomes related to energy production, energy consumption, excess energy, and the renewable fraction.

Table 5.1. Technical performance of PV/Grid configuration for selected locations with no hydrogen production

Selected Locations	Energy Production (kWh/yr)	Energy Consumption (kWh/yr)	Excess Energy (kWh/yr)	Renewable Fraction (%)
Ga-Masekwa	171 433	169 517	305	62.4
Ka-Dzingidzingi	4 188 033	4 080 050	41 880	56.2
Duthuni	8 105 141	7 793 659	104462	56.4
Mookgophong NU	15 816 383	15 260 560	130 136	59.2

Table 5.2. Technical performance of PV/BES/Grid configuration for selected locations with no hydrogen produced

Selected Locations	Energy Production (kWh/yr)	Energy Consumption (kWh/yr)	Excess Energy kWh/yr	Renewable Fraction (%)
Ga-Masekwa	170 797	166 002	2 705	62
Ka-Dzingidzingi	4 170 887	4 051 899	1 113	56.3
Duthuni	8 074 141	7 654 416	200 393	56
Mookgophong NU	15 753 529	14 933 696	367 738	58.7

5.3. THE ECONOMIC PERFORMANCE ANALYSIS FOR MICROGRID OPTIMIZATION IN SELECTED LOCATIONS

Table 3.4 shows both the specifications and the cost per kW of selected components. Tables 8 and 9 present economic performance results for PV/Grid and PV/BES/Grid configurations. The performance analysis is done under capital costs, replacement costs, operation and maintenance costs, NPCs, and LCOE criteria.

The results presented in Table 5.3 and Table 5.4 were derived from simulations conducted using the Homer Pro software. These simulations explored various configurations, including PV/Grid and PV/BES/Grid setups. Homer Pro optimizes these configurations, leading to a range of outcomes with distinct economic metrics. The configuration with the lowest NPC and LCOE is selected as the most economically advantageous system from those generated by the Homer.

The capital costs associated with microgrids (MG) represent a one-time, long-term investment incurred at the outset of optimising the microgrid system. As evidenced in Table 5.3 and Table 5.4, the capital costs for PV/Grid configurations are consistently lower than those for PV/BES/Grid configurations across all selected locations. This reduced capital cost for PV/Grid systems can be attributed to the absence of significant upfront expenses related to batteries and their associated components.

The replacement cost refers to the amount of money needed to replace an asset with a new one of the same type and functionality at current market prices. Simulation results show that the replacement costs for PV/Grid systems are lower than those for PV/BES/Grid systems. This is primarily because PV/Grid systems do not depend on batteries, which have a limited lifespan and necessitate expensive periodic replacements. Conversely, PV/BES/Grid systems require multiple replacements throughout their lifespan, leading to higher overall costs. A similar trend is observed in operation and maintenance costs.

The NPC represents the total expenses of owning, operating, and maintaining an asset over its lifecycle, adjusted to present value. Analysis shows that NPC for PV/Grid systems is lower than for PV/BES/Grid systems. For instance, Ga-Masekwa has NPCs of 3.1 million (PV/Grid) and 3.5 million (PV/BES/Grid), while Ka-Dzingidzingi shows 93.8 million (PV/Grid) and 101 million (PV/BES/Grid). Duthuni reports 170 million (PV/Grid) and 185 million (PV/BES/Grid), and Mookgopong NU reflects 310 million (PV/Grid) and 341 million (PV/BES/Grid). Although PV/BES/Grid systems can lead to long-term savings through better energy management, their higher initial investment and maintenance costs usually result in a greater NPC compared to simpler PV/Grid systems.

The Levelized Cost of Electricity (LCOE) measures the average cost per unit of electricity over an energy project's lifespan. Simulations indicate that the LCOE for photovoltaic (PV) systems combined with BES is higher than for PV alone. Ga-Masekwa has the lowest LCOE due to its small consumer base and compact microgrid design, while Mookgopong NU has the largest microgrid reflecting its higher population. A PV/Grid system typically has lower LCOE thanks to reduced capital and maintenance costs, longer solar panel lifespans, and fewer inefficiencies. Notably, the LCOE for the utility grid in rural areas is about 2.20 R/kWh, which is 52.7% higher than that of the PV/Grid system, making the latter more cost-effective.

The economic analysis of microgrids (MG) for both configurations—PV/Grid and PV/BES/Grid—has provided valuable insights into the potential costs associated with optimizing MGs. The selected locations serve as benchmarks for estimating costs that vary based on the size of the area. This methodology can also be applied to rural villages with differing consumer numbers compared to the locations studied here. Additionally, a study

evaluating the cost-effectiveness of a solar PV plant at Nelson Mandela University found that constructing a 1MW solar plant necessitates an estimated capital investment of R16.5 million. This figure has been used as the foundational capital cost for designing the MGs in this research [115].

In contrast to the successful configuration involving PV/Grid and economic considerations, there is a minor difference from what other authors have suggested. The study by [116] investigated the integration of PV, DG, WT, BES, and Grid technologies. The analysis reveals that this configuration is more cost-effective compared to systems with fewer energy resources, as demonstrated in this dissertation research. This conclusion is supported by the use of HOMER software in the simulations, which enabled a thorough exploration of a defined search space for the microgrid implementation, whereas on [116] Homer optimiser for the generalised sizing of the MG was done.

Table 5.3. Economic performances of PV/Grid configurations in selected locations with no hydrogen production.

Selected Locations	Capital Cost (R)	Replacement Cost (R)	Operation And Maintenance (R)	NPC (R)	LCOE (R/kWh)
Ga-Masekwa	675 000	40 211	134 833	3.1 M	1.02
Ka-Dzingidzingi	19.6 M	2.6 M	4 M	93.8 M	1.28
Duthuni	34.8 M	3.5 M	7.5 M	170 M	1.21
Mookgophong NU	66.1 M	6.9 M	13.6 M	310 M	1.13

Table 5.4. Economic performance of PV/BES/Grid configurations for selected locations with no hydrogen production

Selected Locations	Capital Cost (R)	Replacement Cost (R)	Operation And Maintenance (R)	NPC (R)	LCOE (R/kWh)
Ga-Masekwa	765 000 M	133 166	150 116	3.5 M	1.16
Ka-Dzingidzingi	21.7 M	3.8 M	4.4 M	101 M	1.39
Duthuni	38.8 M	5.6 M	8.1 M	185 M	1.34
Mookgophong NU	73.7 M	11.3 M	14.8 M	341 M	1.27

5.4. THE ECONOMIC METRIC ASSESSMENT IN SELECTED LOCATIONS FOR MICROGRID OPTIMIZATION

Table 5.5 and Table 5.6 present the economic metrics for both configurations: PV/Grid and PV/BES/Grid. The economic metrics under analysis include the present worth of the MG, ROI, IRR, and SPB. This information is crucial for selecting a microgrid system that is economically viable and appealing to investors.

The present worth of a microgrid (MG) represents the current value of all future cash flows from its operation and maintenance, discounted to the present using an interest rate. This metric is crucial for assessing the economic feasibility of MG projects. The consumer sizes in the selected location are ranked as follows: Ga-Masekwa, Ka-Dzingidzingi, Duthuni, and Mookgopong NU. The present worth is proportional to the MG size, similar to capital costs. Additionally, PV/Grid configurations have a higher present worth than PV/BES/Grid systems due to higher initial costs and ongoing maintenance of the latter.

The ROI is a financial metric used to evaluate the efficiency or profitability of an investment. It measures the gain or loss generated relative to the investment's cost. The MG with the highest ROI in Ga-Masekwa is located in the small MG system, followed by Mookgopong NU, and Duthuni and Ka-Dzingidzingi are in between. The same trend occurs in the ROIs and SPB.

In the case of PV/BES/Grid systems, the present worth of Ka-Dzingidzingi and Duthuni is negative, indicating that these locations have the highest number of payback years. This shows that the PV/BES/Grid system in these locations is not economically beneficial.

Economic metrics data results in Table 5.5 and Table 5.6 indicate that adopting PV/Grid MG is more beneficial than adopting PV/BES/Grid in all locations, looking at present worth, ROI, IRR and SPB. Results similar to these were obtained by [117] where the most effective cost and economic metric results are obtained for PV/Grid/Generator with the smallest electricity price of \$0.280 per kWh and a 1.5-year payback period.

Table 5.5. The economic metrics of PV/Grid configuration in selected locations with no hydrogen production.

Selected Locations	Present Worth (R)	ROI (%)	IRR (%)	SPB (Years)
Ga-Masekwa	555 738	6.1	9	9.64
Ka-Dzingidzingi	4 M	2.7	4.5	13.78
Duthuni	13.3 M	3.7	5.8	12.37
Mookgophong NU	39 M	4.9	7.5	10.70

Table 5.6. The economic metrics of PV/BES/Grid configuration for selected locations with no hydrogen production.

Selected Locations	Present Worth (R)	ROI (%)	IRR (%)	SPB (Years)
Ga-Masekwa	190 617	3	4.8	15.38
Ka-Dzingidzingi	-3 M	0.8	-1.4	22.79
Duthuni	-1.7 M	1.3	2.3	20.53
Mookgophong NU	9.8 M	2.3	3.9	17.46

5.5. CONCLUSION

This chapter presents an analysis of the technical and economic performance metrics for the proposed MGs set for implementation in specific locations, excluding hydrogen production considerations. The simulation results comparing PV/Grid and PV/BES/Grid configurations reveal that the PV/Grid setup is the most economically advantageous among all the configurations simulated.

CHAPTER SIX: FEASIBILITY ASSESSMENT OF HYBRID ENERGY SYSTEM WITH HYDROGEN PRODUCTION FOR RURAL LIMPOPO PROVINCE COMMUNITIES

6.1. PREAMBLE

This chapter presents a techno-economic feasibility analysis for optimising microgrids MG for hydrogen production in rural Limpopo. It employs the Herman Beta method for load modelling to estimate the maximum daily loads for each community, addressing the lack of such studies in the province. This research uniquely applies the Herman Beta method with Homer software for economic and sizing simulations. The hypothetical system, consisting of solar PV, BES, hydrogen, and the grid, aims to minimise NPC and level the cost of energy LCOE.

6.2. ECONOMIC PERFORMANCES AND METRICS FOR MICROGRIDS OPTIMIZATION IN SELECTED LOCATIONS FOR HYDROGEN PRODUCTION

Figure 6.1 - Figure 6.4 represent economic standpoint simulation results for hydrogen production feasibility assessment in the Limpopo province's rural selected areas. Simulations were done using Homer Pro software to compare the economic feasibility of two configurations. PV/H₂/Grid and PV/BES/H₂/Grid are two configurations.

Three different solar modules were simulated for each configuration, 250W, 375W, and 500W, to determine the most cost-effective option based on economic performance. For the configuration with battery storage, a 48V, 14.4kWh capacity lithium-ion battery was chosen due to its favourable energy storage capabilities for grid-scale capacities.

The PV/H₂/Grid configuration with a 250W module exhibited the lowest capital cost, net present cost NPC, and LCOE, while offering a higher ROI and a shorter payback period.

The 500W module follows the 250W module in terms of economic effectiveness when considering PV/H₂/Grid integration. It is regarded as the second most favourable option after the 250W module due to its capital costs. Specifically, the 500W module ranks second in terms of capital cost, NPC, levelized cost of the system, ROI, and simple payback.

Thirdly, the PV/H₂/Grid configuration with 375 modules possesses higher capital, most NPC, LCOE, less interest return, and more years to recoup the investment than the other two modules. This effect comes from the capital cost, where the capital cost of the 375W quality module was found to be a little bit steeper than that of the 250W and 500W modules.

The ROI is a key performance indicator used to assess the efficiency or profitability of an investment, as well as to compare the effectiveness of various investment options. In all scenarios examined, the PV/H₂/Grid configuration that utilises a 250W module shows a superior ROI compared to the PV/BES/H₂/Grid configuration. This improved performance can be attributed to the 250W system's lower capital investment requirements, as well as its reduced NPC and LCOE.

Additionally, the 375W module consistently yields the lowest ROI due to the higher investment capital required for this configuration. This also indicates that the rate of return from the 375W module is lower than that of the 250W and 500W modules. The ROI period for the combined PV/BES/H₂/Grid system exceeds that of a standalone hydrogen production system without an integrated battery energy storage at each respective location. As delineated in Figure 6.1 - Figure 6.4, the payback period for the PV/BES/H₂/Grid configuration is approximately 20 years, suggesting that this system may not offer substantial financial returns to investors during the residual lifespan of the project.

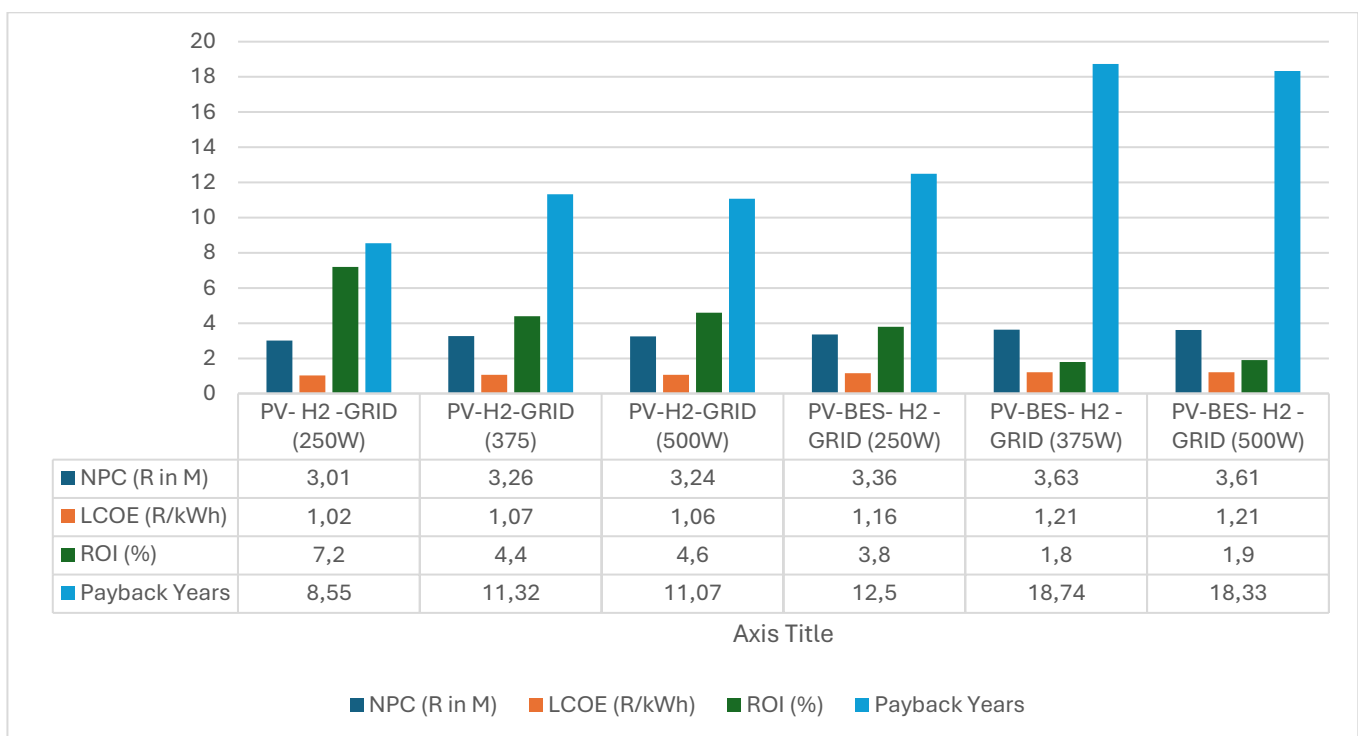


Figure 6.1. Economic performances and metrics for hydrogen production MG results for Ga-Masekwa

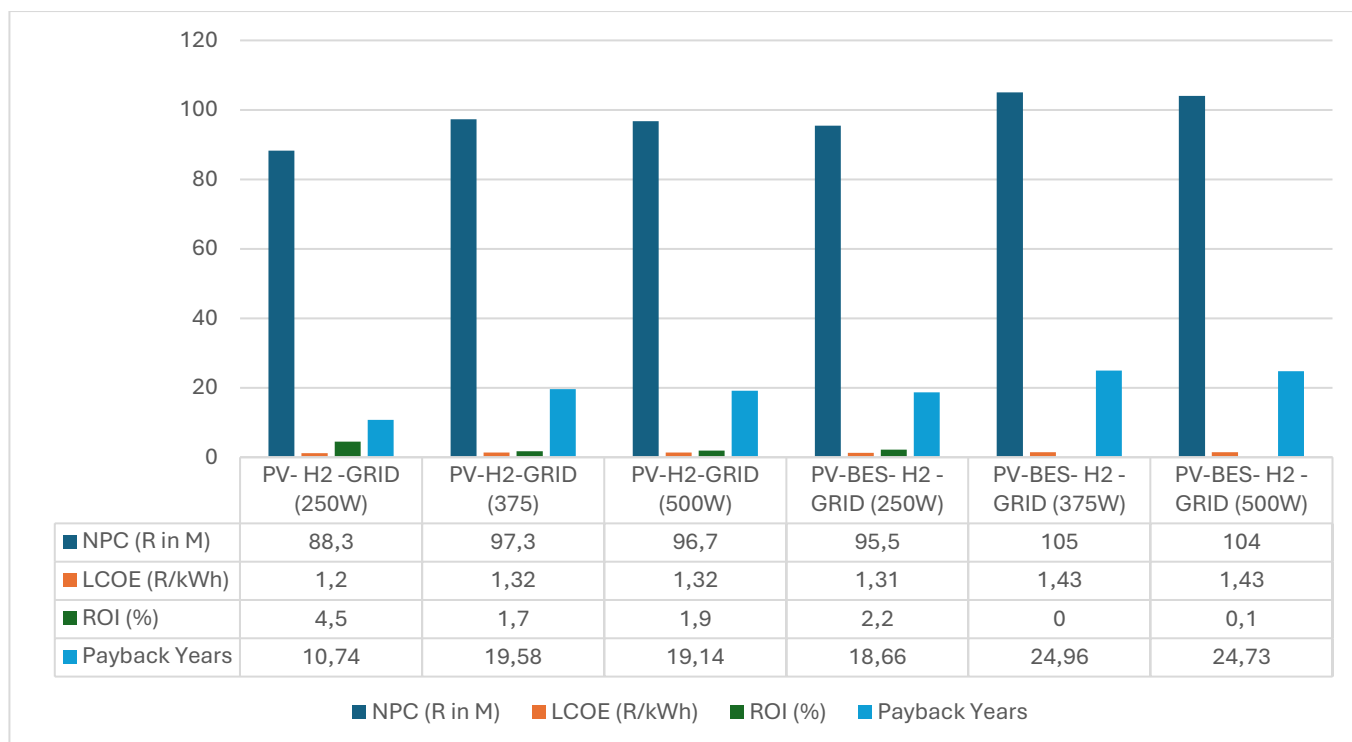


Figure 6.2. Economic performances and metrics for hydrogen production MG results for Ka-Dzingidzingi

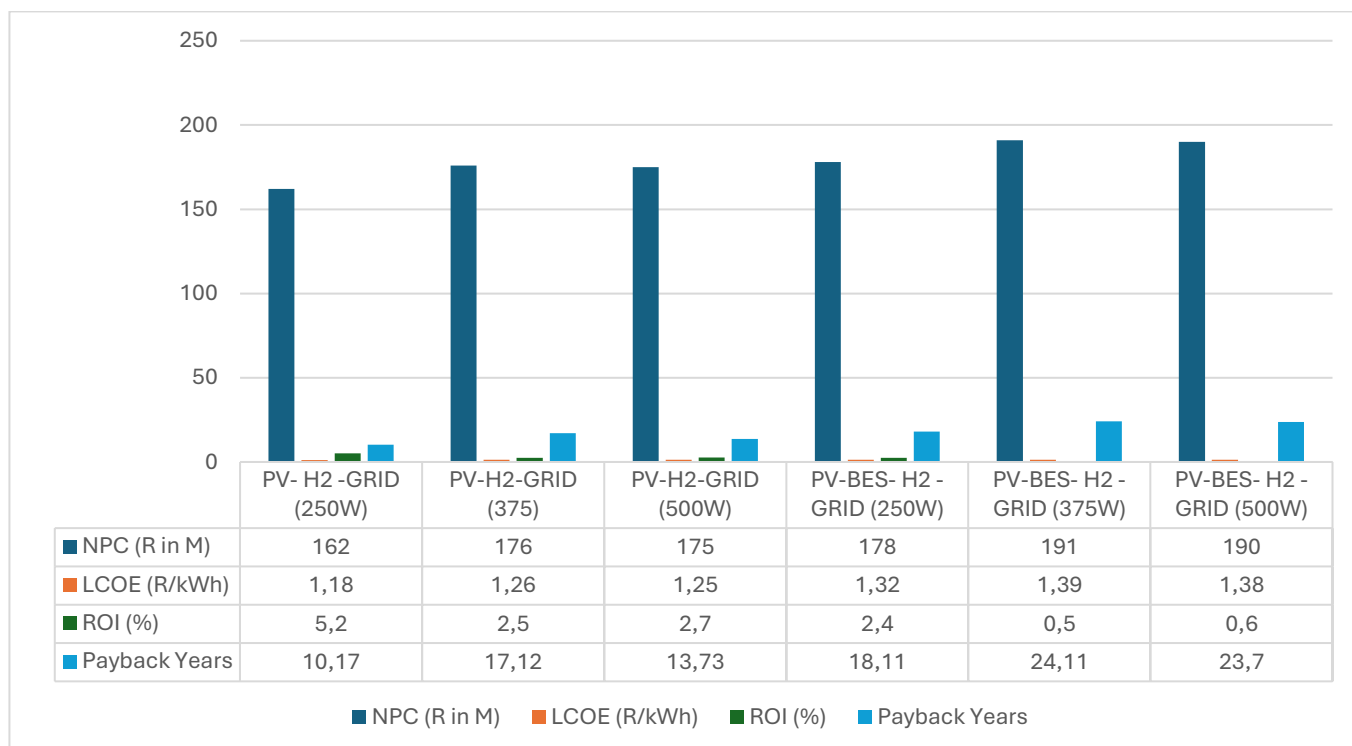


Figure 6.3. Economic performances and metrics for hydrogen production MG results for Duthuni.

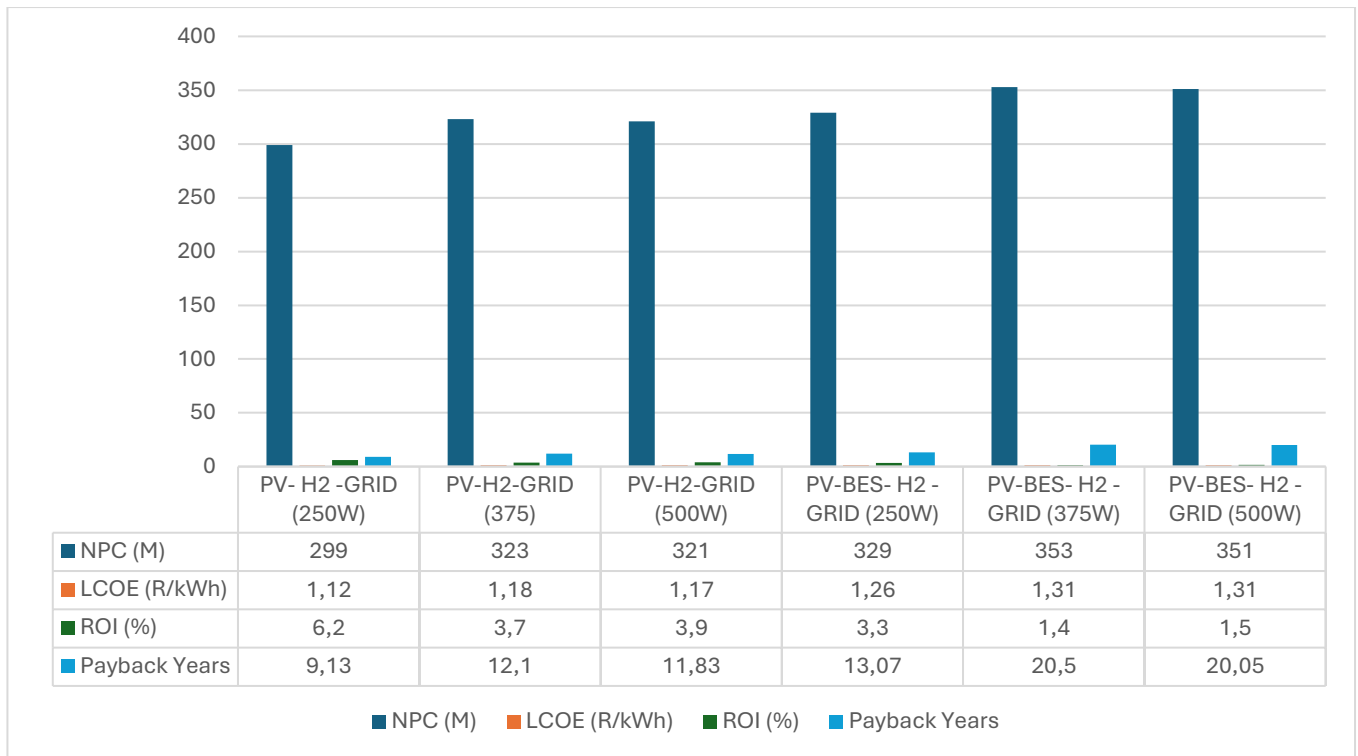


Figure 6.4. Economic performances and metrics for hydrogen production MG result for Mookgopong NU.

6.3. HYDROGEN PRODUCTION CONFIGURATIONS AND SIZING FOR SELECTED LOCATIONS

Table 6.1 outlines locations, winning configurations, energy metrics, and renewable fraction. Table 6.2 details winning configurations, electrolyser and hydrogen tank sizes, and hydrogen production for each microgrid MG. Simulations show that the PV/H₂/Grid with a 250W module is the most cost-effective, with the lowest NPC and LCOE compared to PV/BES/H₂/Grid. Larger MG sizes require bigger Electrolysers and hydrogen tanks, with energy production exceeding consumption and no unmet load.

Hydrogen production varies with consumer size, with Ga-Masekwa showing the least production, followed by Ka-Dzingidzingi, Duthuni, and Mookgopong. As the MG system increases, so does hydrogen production. However, producing hydrogen is energy-intensive, requiring substantial energy to split it from water or hydrocarbons. Thus, significant energy is essential for substantial hydrogen production.

The hydrogen production is minimal since the MG prioritises load satisfaction first. Only surplus energy is used to generate hydrogen after meeting the load. Although supplying maximum energy to the electrolyser can increase hydrogen production, the limited energy dedicated to hydrogen remains a constraint for this technology.

Upon analysing the microgrid for hydrogen production, just like in [118], generating a significant amount of hydrogen requires a substantial amount of excess electricity. The techno-economic feasibility assessment of hydrogen production and storage systems has yet to be fully realized, making it a promising area for development [119].

Table 6.1. Energy production, consumption and excess energy for the winning configuration in all selected locations

Selected Location	Configuration	Energy Production (kWh/yr)	Energy Consumption (kWh/yr)	Excess Energy (kWh/yr)	Renewable Fraction (%)
Ga-Masekwa	PV / H ₂ / GRID	165 652	164 122	1 530	61.2
Ka-Dzingidzingi	PV / H ₂ / GRID	4 188 033	4 080 055	107 978	56.2
Duthuni	PV / H ₂ / GRID	7 848 640	7 631 099	17 846	55.5
Mookgopong NU	PV / H ₂ / GRID	15 238 211	14 825 351	7 233	58.1

Table 6.2. Hydrogen production and production output results

Selected Location	Configuration	Electrolyser Size (kW)	Hydrogen Tank Size (kg)	Hydrogen Production (kg/year)
Ga-Masekwa	PV / H ₂ / GRID	1	1	0.500
Ka-Dzingidzingi	PV / H ₂ / GRID	25	5	2.50
Duthuni	PV / H ₂ / GRID	48	10	5
Mookgophong NU	PV / H ₂ / GRID	90	15	7.5

6.4. CONCLUSION

This chapter presents the technical and economic performance metrics for the proposed implementation of MGs in selected locations, with a focus on hydrogen production. Simulation results comparing PV/H₂/Grid configurations and PV/BES/H₂/Grid reveal that a 250W module utilising the PV/H₂/Grid configuration offers the greatest economic advantage among all simulated configurations, outperforming the 375W and 500W module results. Additionally, it is important to note that hydrogen production necessitates a substantial amount of energy.

CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS

The aim of this research was to review and assess available and potential renewable energy resources in Limpopo province, assess hybrid microgrids in various locations, and review simulation tools for techno-economic analysis to observe which tool is optimal for the analysis. Techno-economic analyses have been reviewed to observe the performance of other microgrids economically and to determine if they are technically feasible. This progressed to include the hydrogen production configurations to widen the scope. The main goal was to techno-economically analyse the feasibility of optimising microgrids in Limpopo province, focusing on adopting a system with the least NPC and LCOE. And that has a reasonable return on investment.

The first objective stipulated the assessment and review of the existing and potential renewable energy resources in Limpopo province to ascertain their operational status and identify the most suitable options for the proposed microgrid. To achieve this objective, a comprehensive review of the relevant literature was conducted. This review focused on publications on available and potential renewable energy resources for the Limpopo province. The assessment results showed that solar PV, biomass, and biogas are the most commonly utilised renewable energy resources. The demand for solar PV is attributed to its affordability, which encompasses only the costs associated with manufacturing and installation, as well as the province's advantageous geographical location. The region's climate is particularly conducive to solar PV deployment, boasting an average solar irradiance exceeding 5 kWh/m²/day and temperatures above 30°C, both of which contribute to optimal microgrid performance.

The utilisation of biomass is driven by the abundance of biomass materials across various locations and the potential for minimising the levelized cost of energy for households. The assessment further noted that while implemented solar PV projects generally operate at expected efficiency levels, some small-scale solar systems have underperformed due to negligence and inadequate customer maintenance. Additionally, there is a recognition that potential renewable energy resources such as wind turbines, hydropower, and geothermal energy are available, yet they remain underexplored and underutilised because of political, cultural, and financial challenges. It is clear that solar PV emerges as the most viable technology for adoption. This technology not only addresses the high utility levelized cost of energy but also advances efforts toward sustainable development and environmental conservation. The province must attract more investors to establish additional power plants to enhance energy security and create jobs.

The second objective is to analyse the techno-economics of microgrids, but without considering hydrogen production configurations. This analysis progressed after identifying the available and potential renewable energy resources. Four rural locations were chosen to evaluate the economic viability of implementing microgrids. For the technical design, essential factors such as load profiles, component sizing, meteorological data, geographic coordinates, statistical data and consumer classification based on the NRS 034-1 guidelines were utilised in the Herman-Beta method for peak load estimation. The key technical outcomes measured included energy production, energy consumption, excess energy, and the renewable fraction. The estimated peak load selected location, Ga-Masekwa, Ka-Dzingidzingi, Duthuni and Mookgopong NU are respectively 37.98 kW, 1016.18 kW, 1917.46 kW and 3630.91 kW.

On the economic front, various metrics were analysed using HOMER software, including capital costs, replacement costs, operational costs, return on investment, net present cost, and levelized cost of energy. Two configurations, namely PV/Grid and PV/BES/Grid, were simulated. The results highlighted the superiority of the solar PV/Grid configuration in providing optimal economic benefits, marked by the lowest NPC and LCOE across all selected locations.

The LCOE and NPC for Ga-Masekwa were determined to be R 2.356/kWh and R 5.4 million, respectively. For the other locations, Ka-Dzingidzingi, Duthuni, and Mookgopong NU, the LCOE and NPC were R 1.292/kWh and R 76 million; R 1.216/kWh and R 138.7 million; and R 1.197/kWh and R 250.3 million, respectively. The reduction in economic metrics is due to the combination of the microgrid with the utility grid. These findings underscore the economic advantages of producers and consumers in adopting microgrids.

Consequently, power utilities and policymakers are encouraged to leverage these results to implement cost-effective energy systems in rural communities. The analysis also indicated that the number of consumers per location significantly influences peak load consumption estimates and the overall economic performance of the systems. The comprehensive technical and economic evaluations recommend a strong case for the PV/Grid system's adoption across all investigated sites for energy security and mitigating the utility's high cost of energy.

After addressing microgrids that do not involve hydrogen production, it is vital to explore configurations of MGs that incorporate hydrogen production. A feasibility assessment has been conducted to evaluate the economic viability of hydrogen production for rural applications utilizing a hybrid energy system. This research included the random selection of four locations in the Limpopo province of South Africa for analysis. Technical and economic evaluations were performed using Homer Pro software, while load modelling was carried out

using the Herman-beta method. This analysis aims to optimise hydrogen production through hybrid energy systems. Results indicate that a configuration integrating solar PV/H₂/Grid components is the most effective solution across all locations, achieving the lowest net present cost and levelized cost of electricity. This system demonstrates a high return on investment, presenting an attractive opportunity for potential investors, and it is the one that is being recommended in this study for adoption and implementation. Additionally, the findings highlight that hydrogen production requires a substantial energy input, leading to the hybrid system being more expensive than conventional systems optimised with hydrogen production methods.

FUTURE WORK

The future work will focus on the techno-economic analysis of microgrids that incorporate distributed energy resources for hydrogen production, storage, and feasibility assessment. This study will utilise approaches such as artificial intelligence-based optimisation algorithms, including particle swarm optimisation and genetic algorithms, along with multi-criteria decision-making methods. The goal is to identify an optimal configuration that balances various sustainability criteria.

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APPENDIX

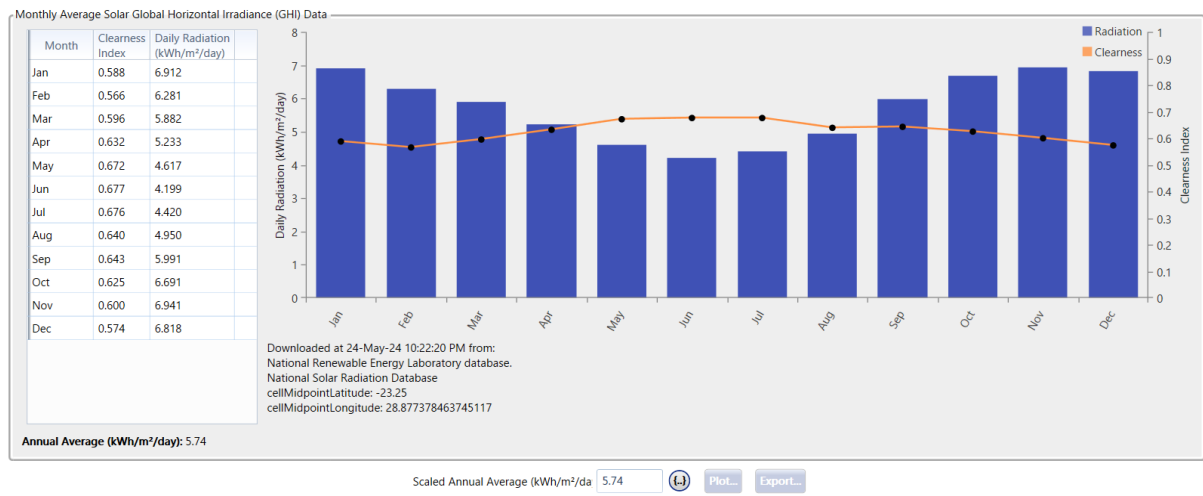


Figure A1. Monthly average solar global horizontal irradiance of Ga-Masekwa.

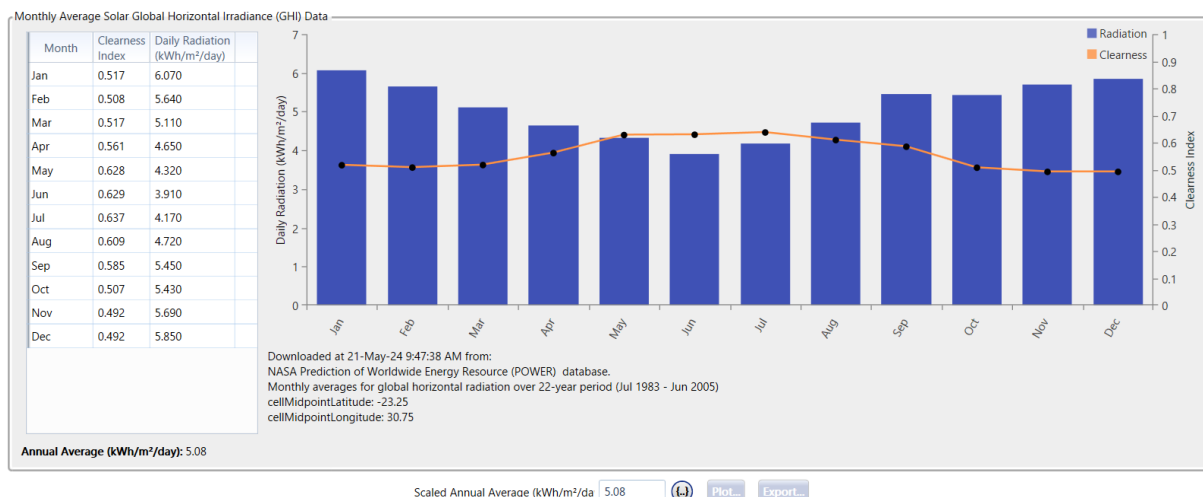


Figure A2. Monthly average solar global horizontal irradiance of Ka-Dzingidzingi.

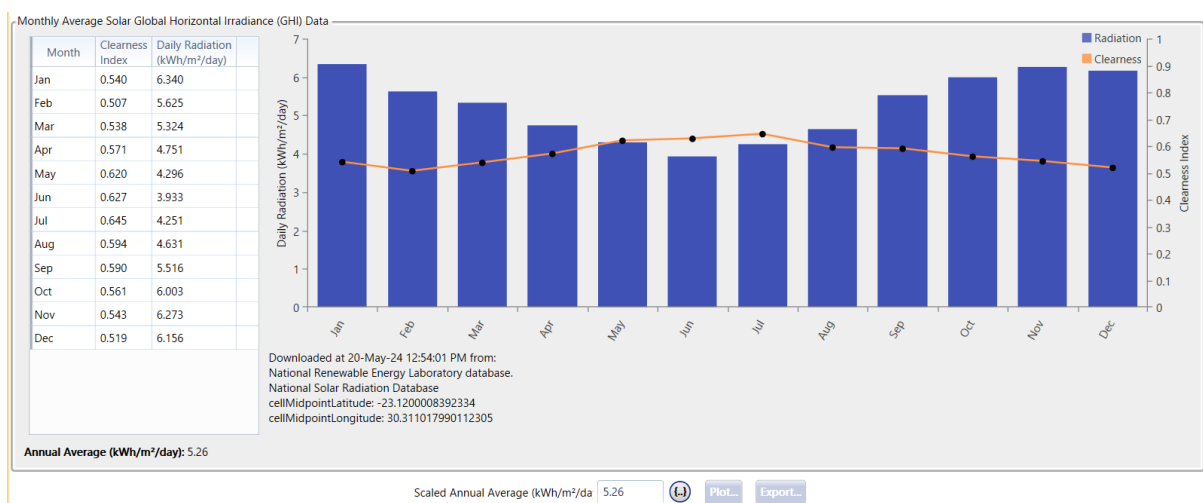


Figure A3. Monthly average solar global horizontal irradiance for Duthuni.

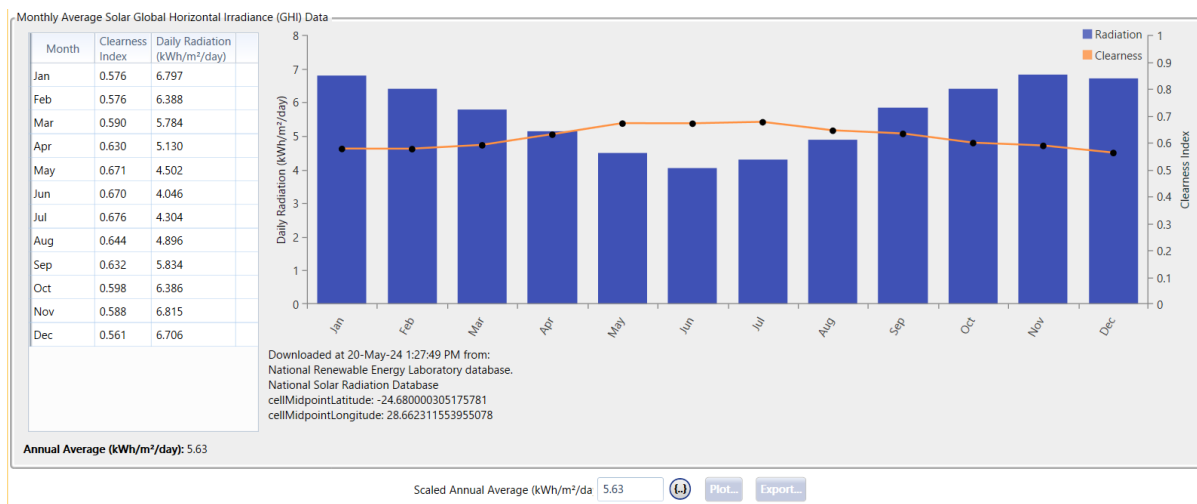


Figure A4. Monthly average solar global horizontal irradiance for Mookgopong NU.



Figure A5. Monthly average temperature data for Ga-Masekwa.



Figure A6. Monthly average temperature data for Ka-Dzingidzingi.



Figure A7. Monthly average temperature data for Duthuni.



Figure A8. Monthly average temperature data for Mookgopong NU.

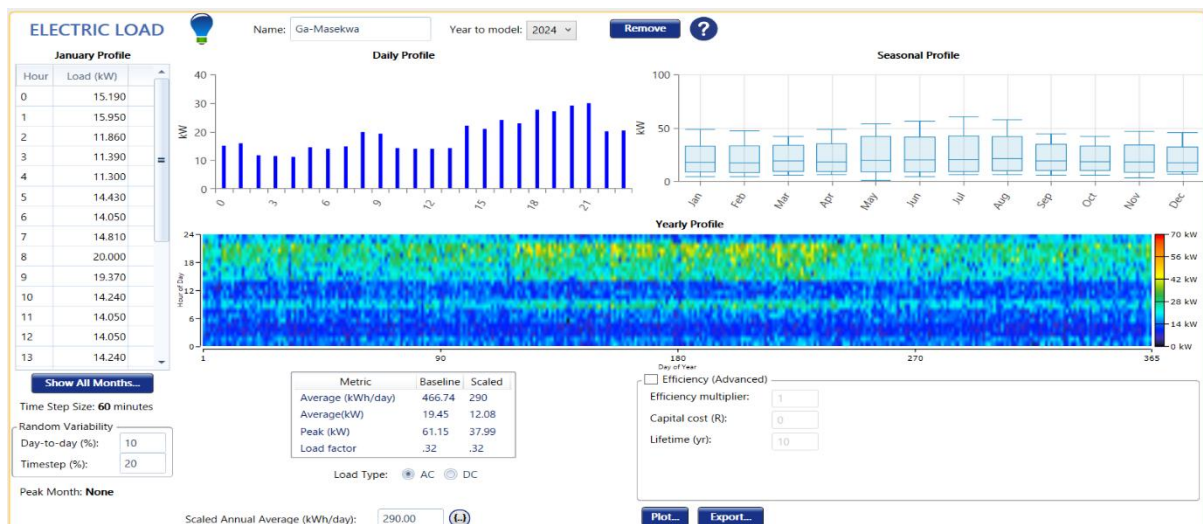


Figure A9. Electric load profile for Ga-Masekwa.

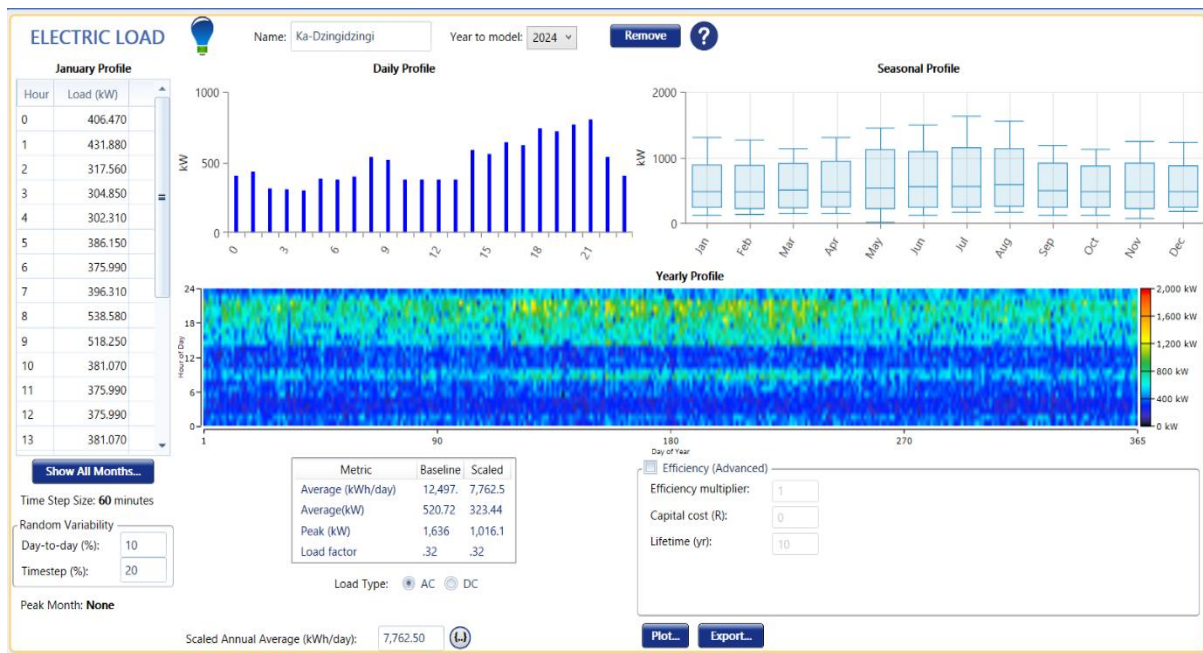


Figure A10. Electric load profile of Ka-Dzingidzingi.

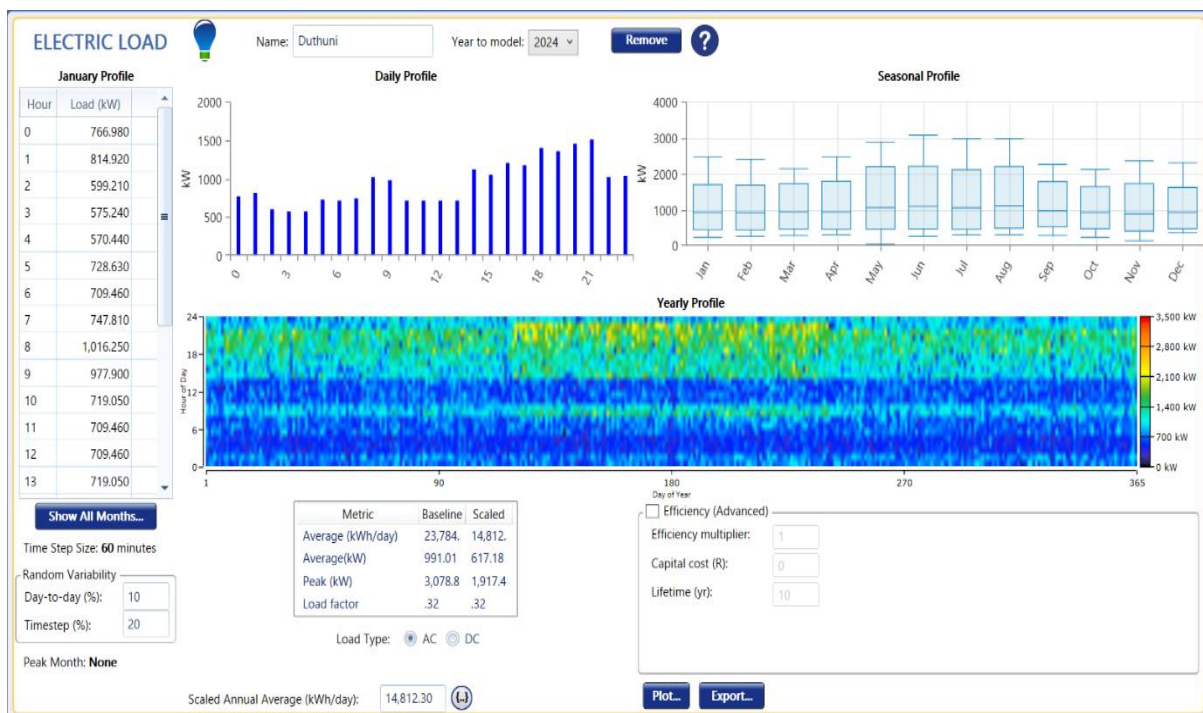


Figure A11. Electric load profile for Duthuni.

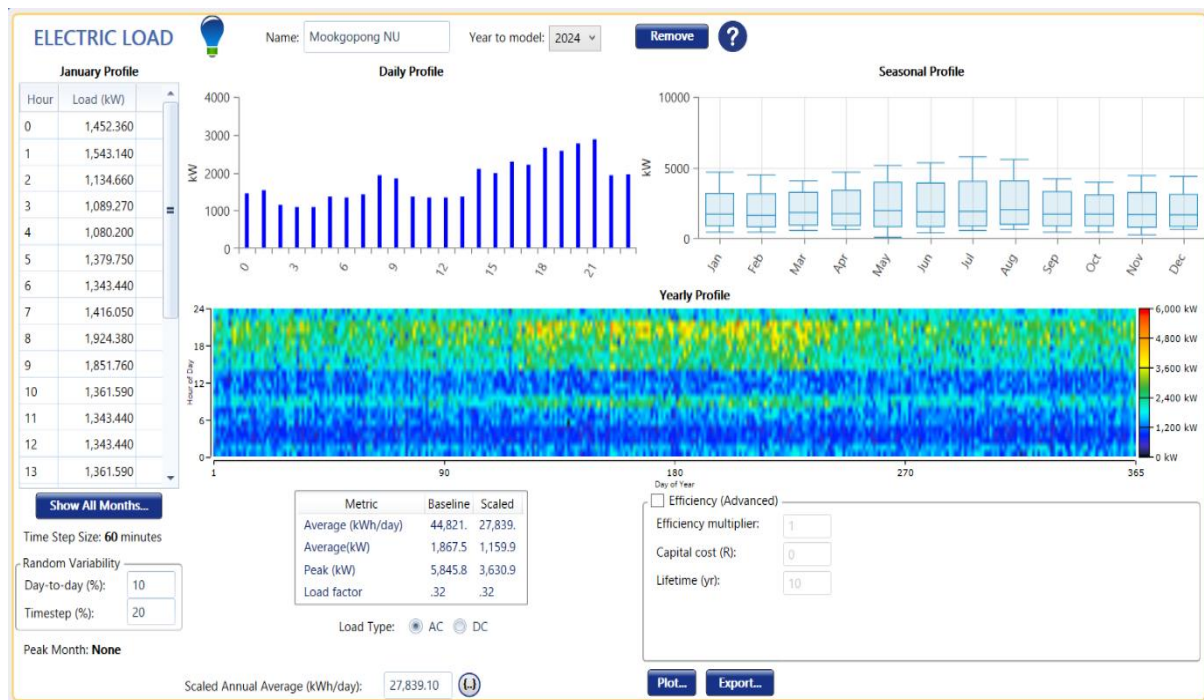


Figure A12. Electric load profile for Mookgopong NU.

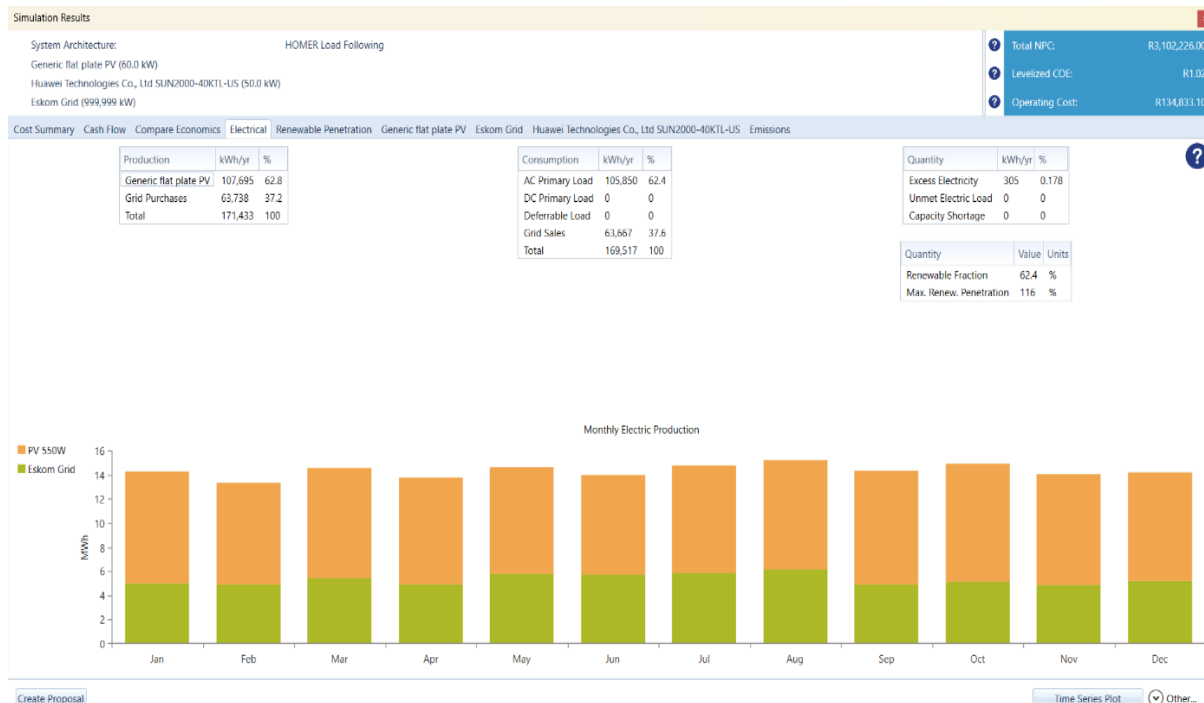


Figure A13. Electrical results data for PV/Grid for Ga-Masekwa.

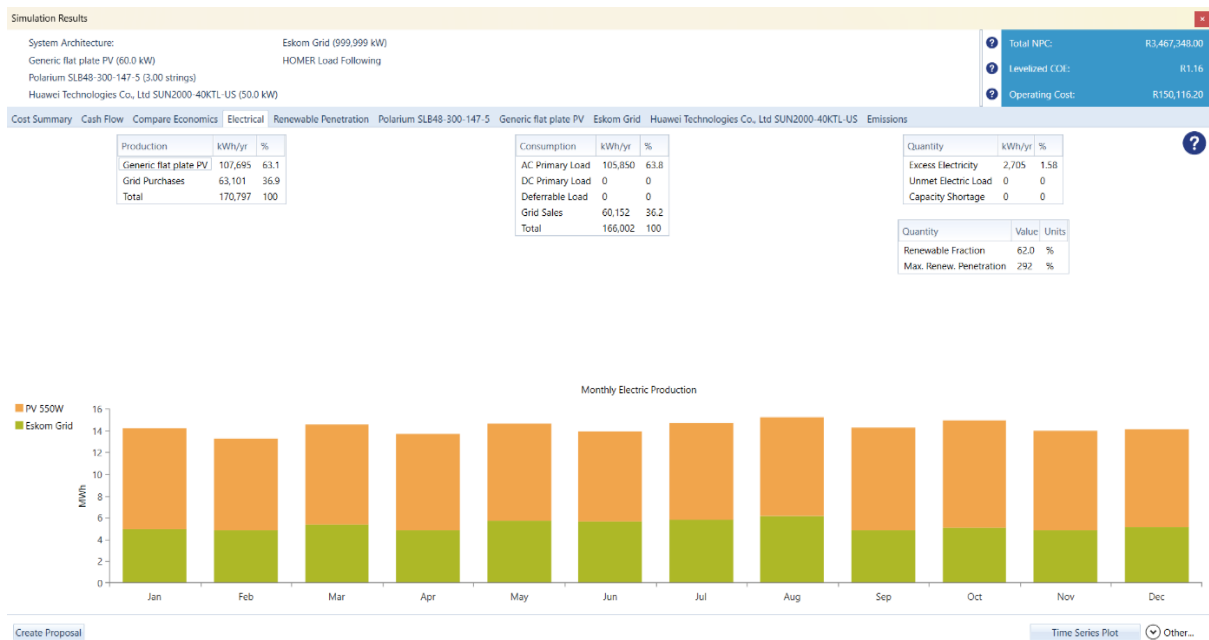


Figure A14. Electrical results data for PV/BES/Grid for Masekwa.

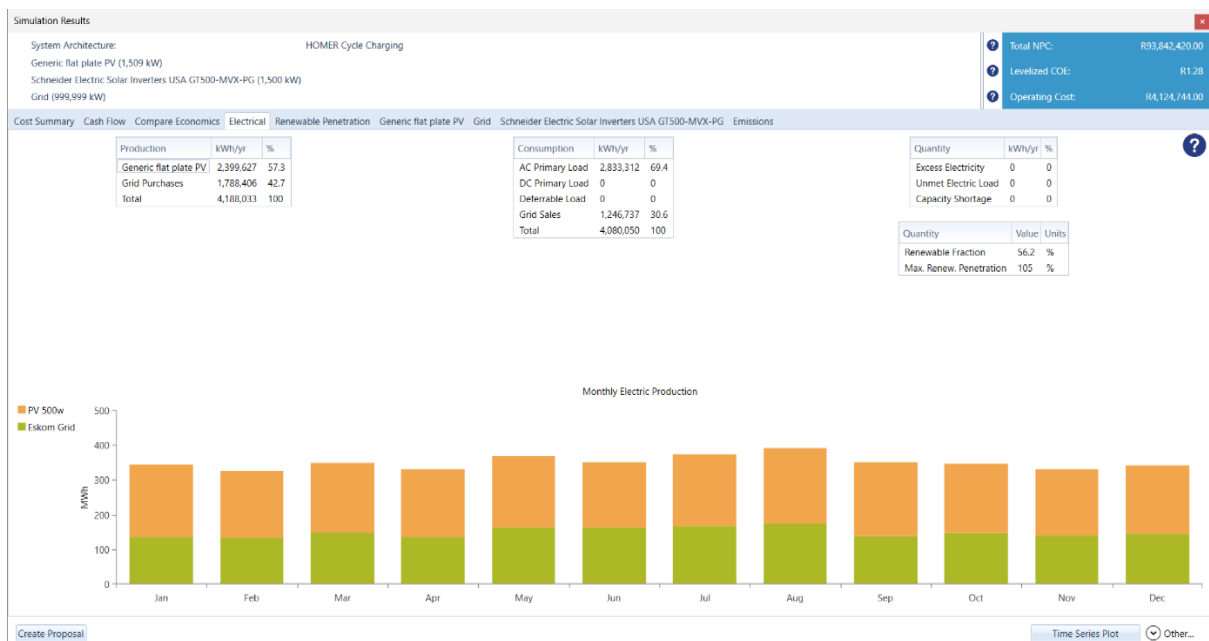


Figure A15. Electrical results data for PV/Grid for Ka-Dzingidzingi.

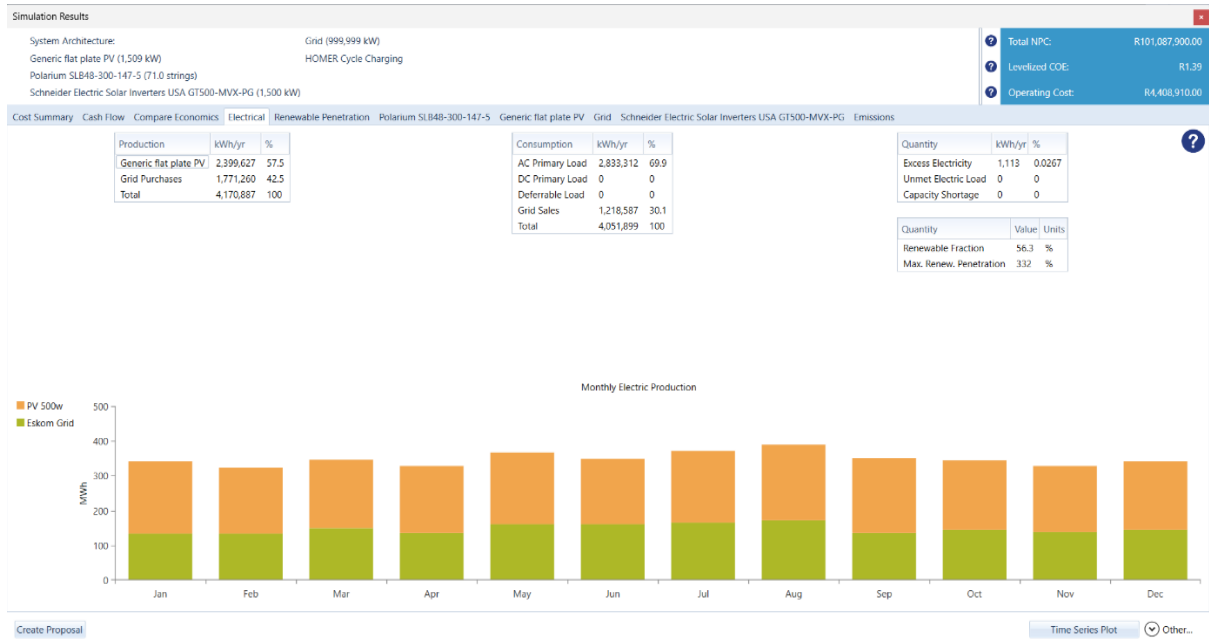


Figure A16. Electrical results data for PV/BES/Grid for Ka-Dzingidzingi.

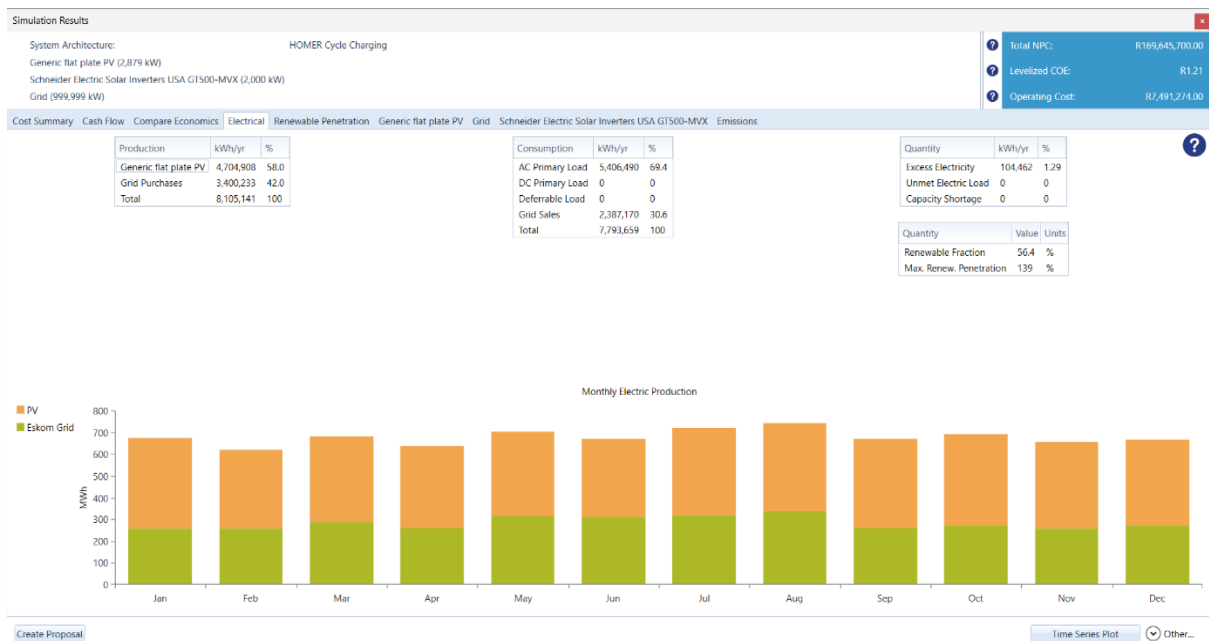


Figure A17. Electrical results data for PV/Grid for Duthuni.

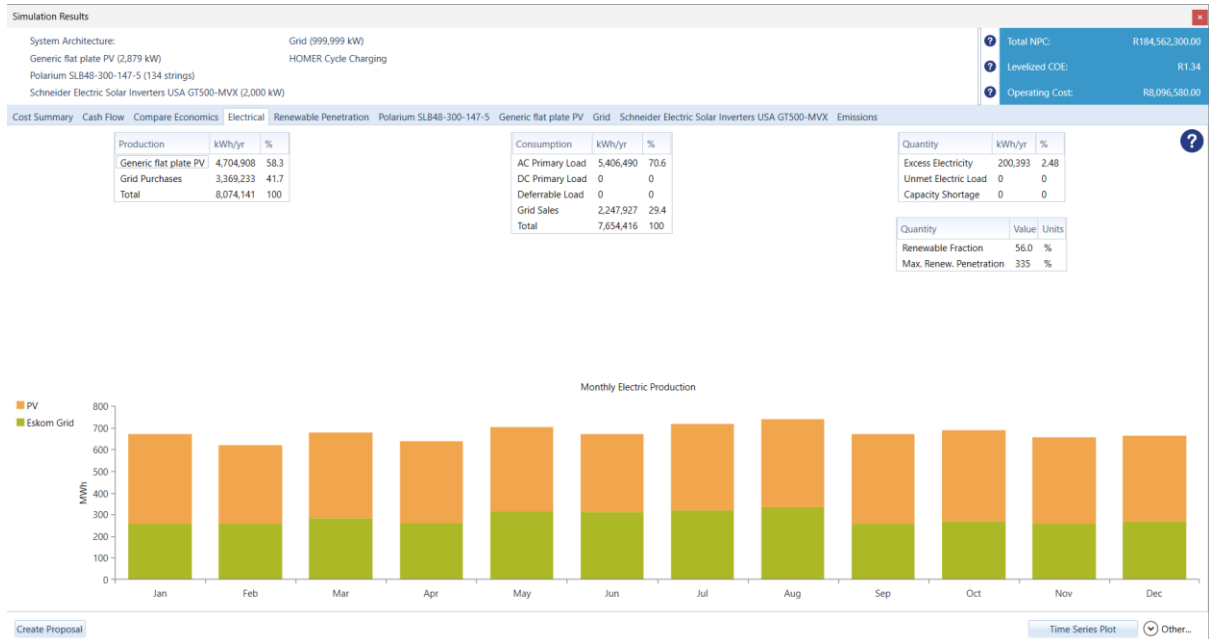


Figure A18. Electrical results data for PV/BES/Grid for Duthuni.

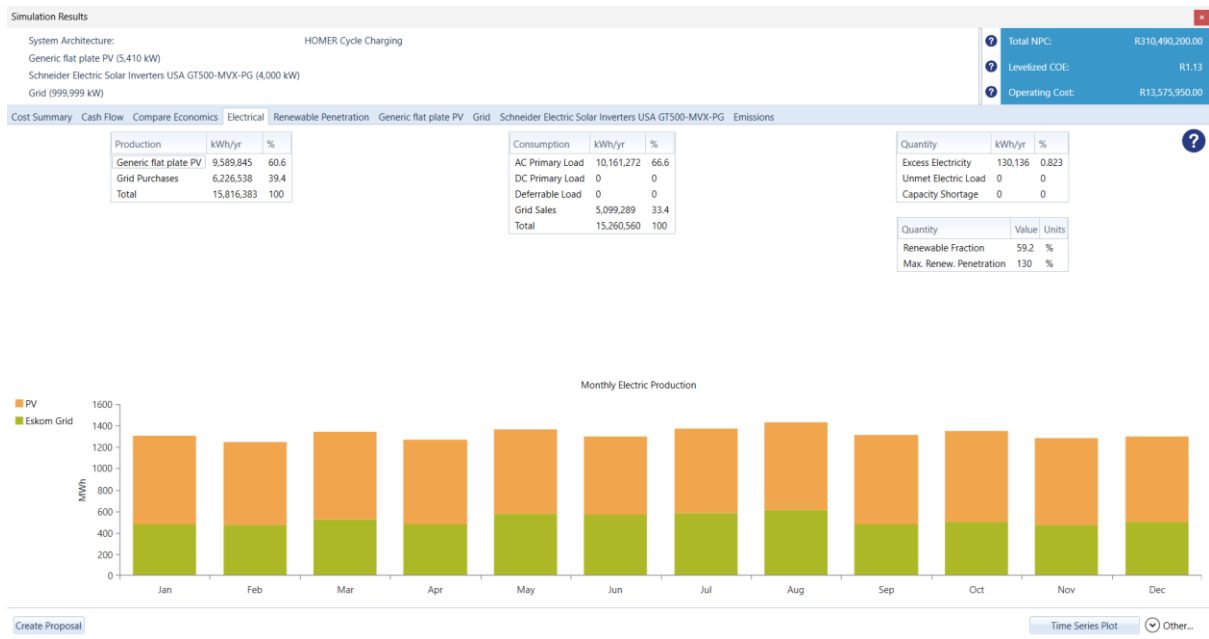


Figure A19. Electrical results data for PV/Grid for Mookgopong NU.

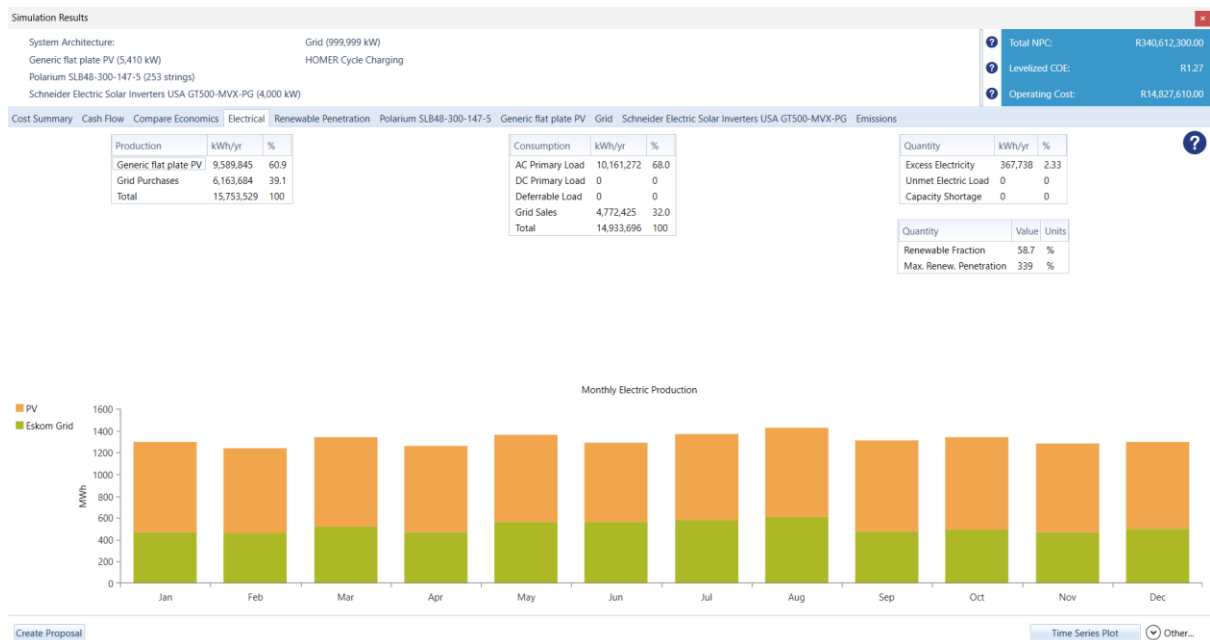


Figure A20. Electrical results data for PV/BES/Grid for Mookgopong NU.

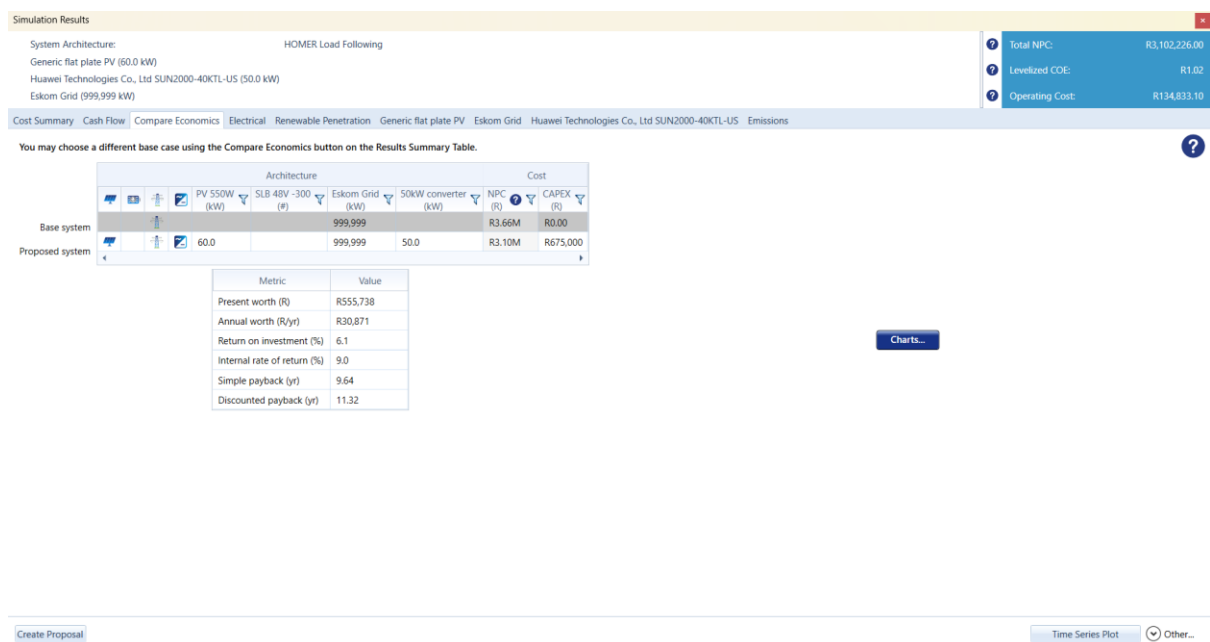


Figure A21. Economic performances and metrics for PV/Grid for Ga-Masekwa.

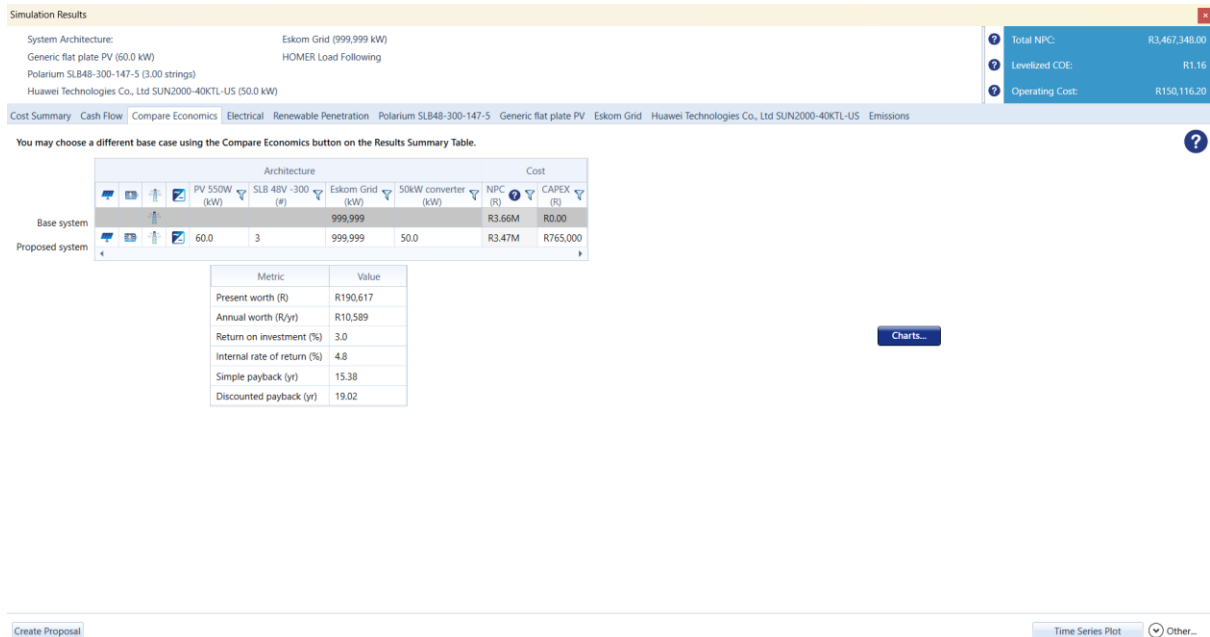


Figure A22. Economic performances and metrics for PV/BES/Grid for Ga-Masekwa.

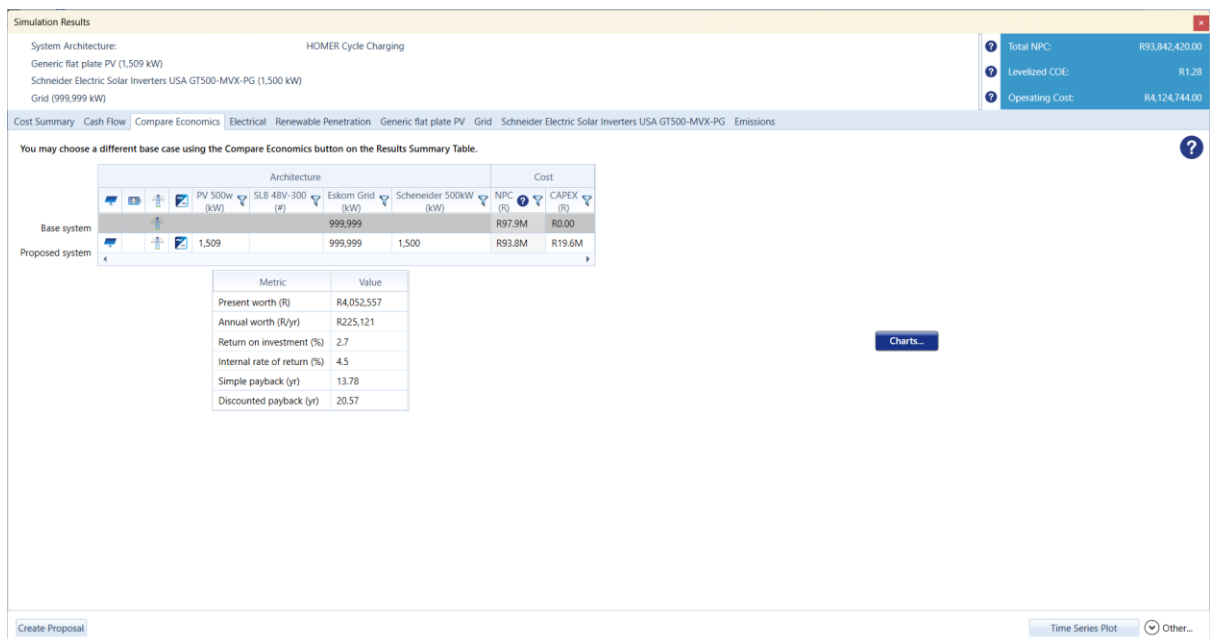


Figure A23. Economic performances and metrics for PV/Grid for Ka-Dzingidzingi.

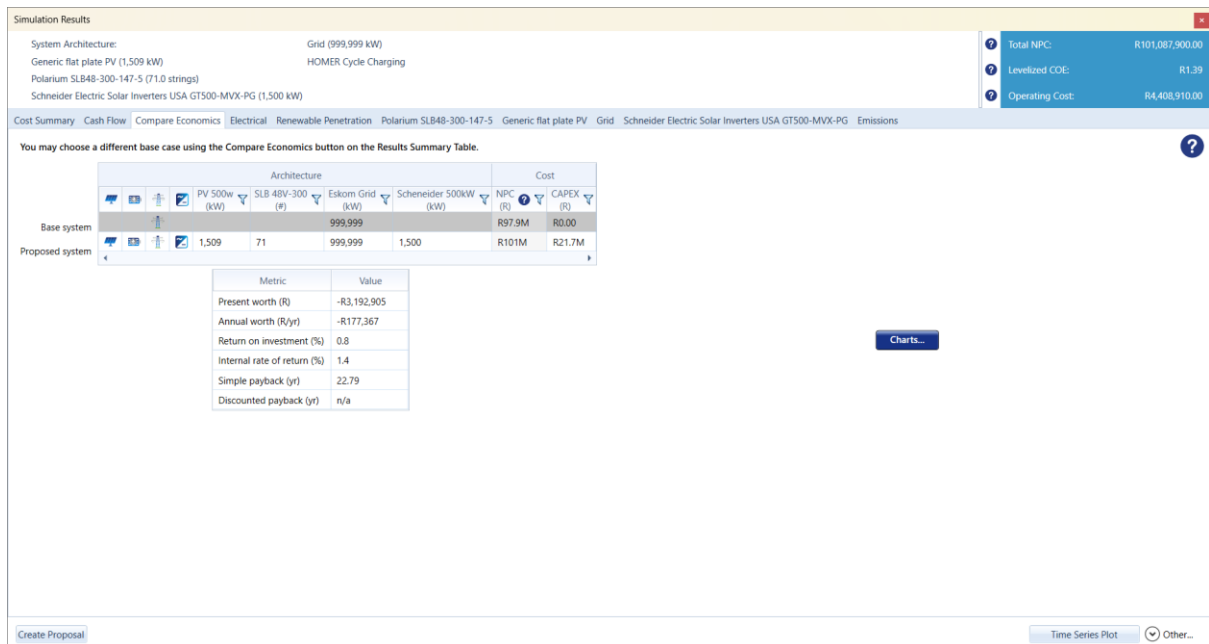


Figure A24. Economic performances and metrics for PV/BES/Grid for Ka-Dzingidingi.

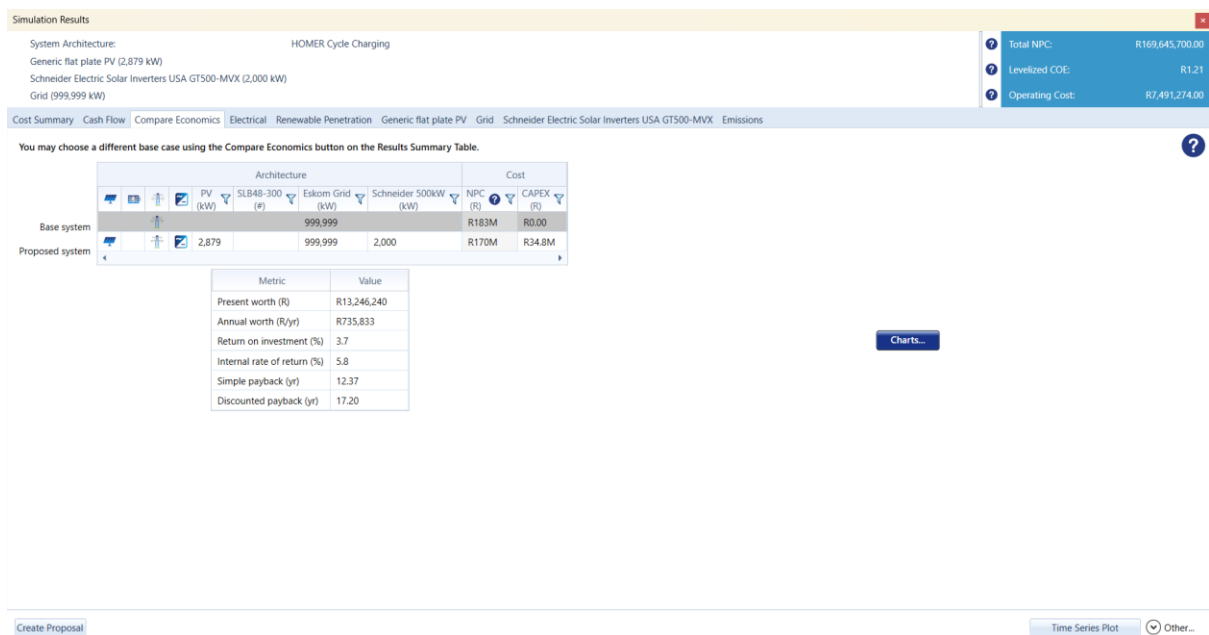


Figure A25. Economic performances and metrics for PV/Grid for Duthuni.

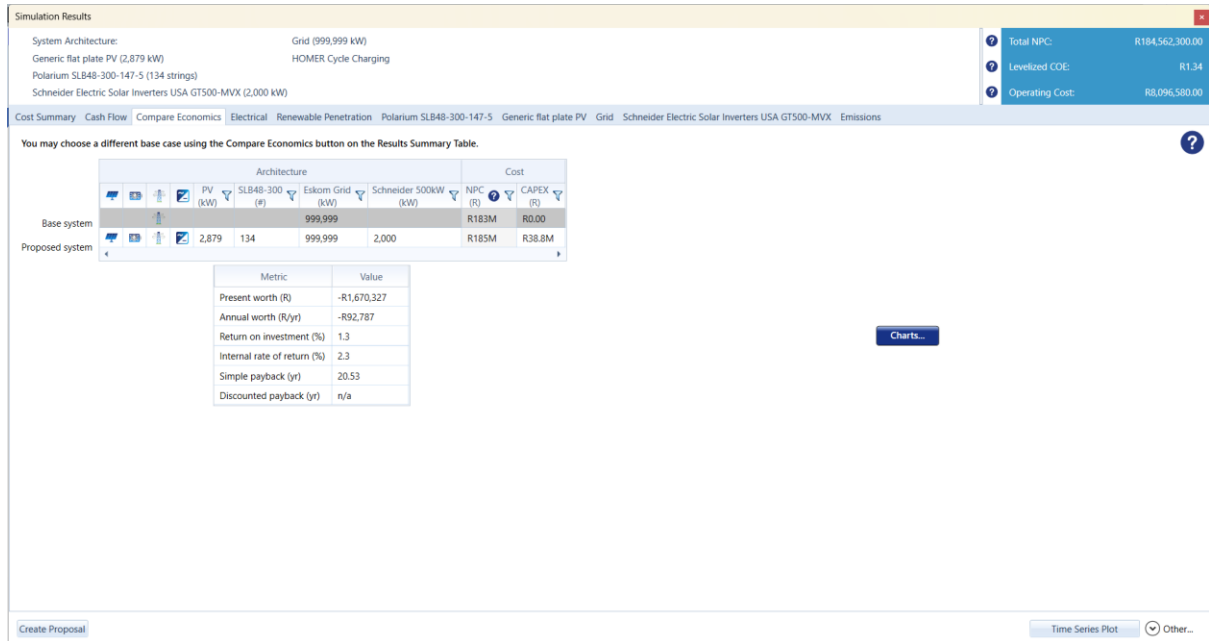


Figure A26. Economic performances and metrics for PV/BES/Grid for Duthuni.

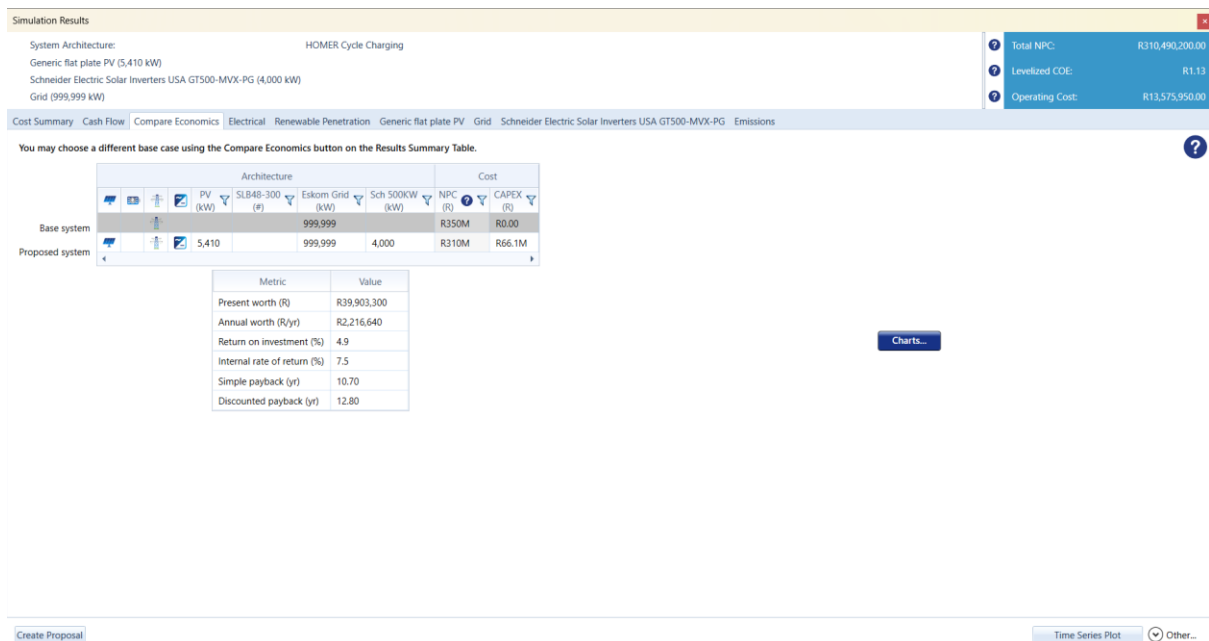


Figure A27. Economic performances and metrics for PV/Grid for Mookgopong NU.

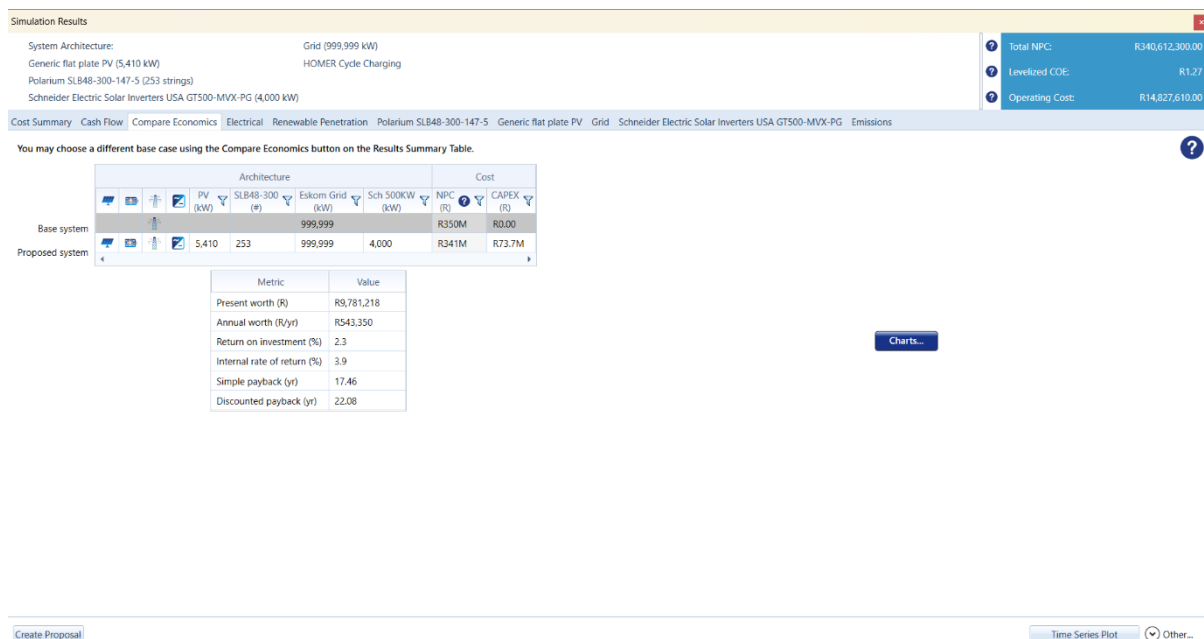


Figure A28. Economic performances and metrics for PV/BES/Grid for Mookgopong NU.

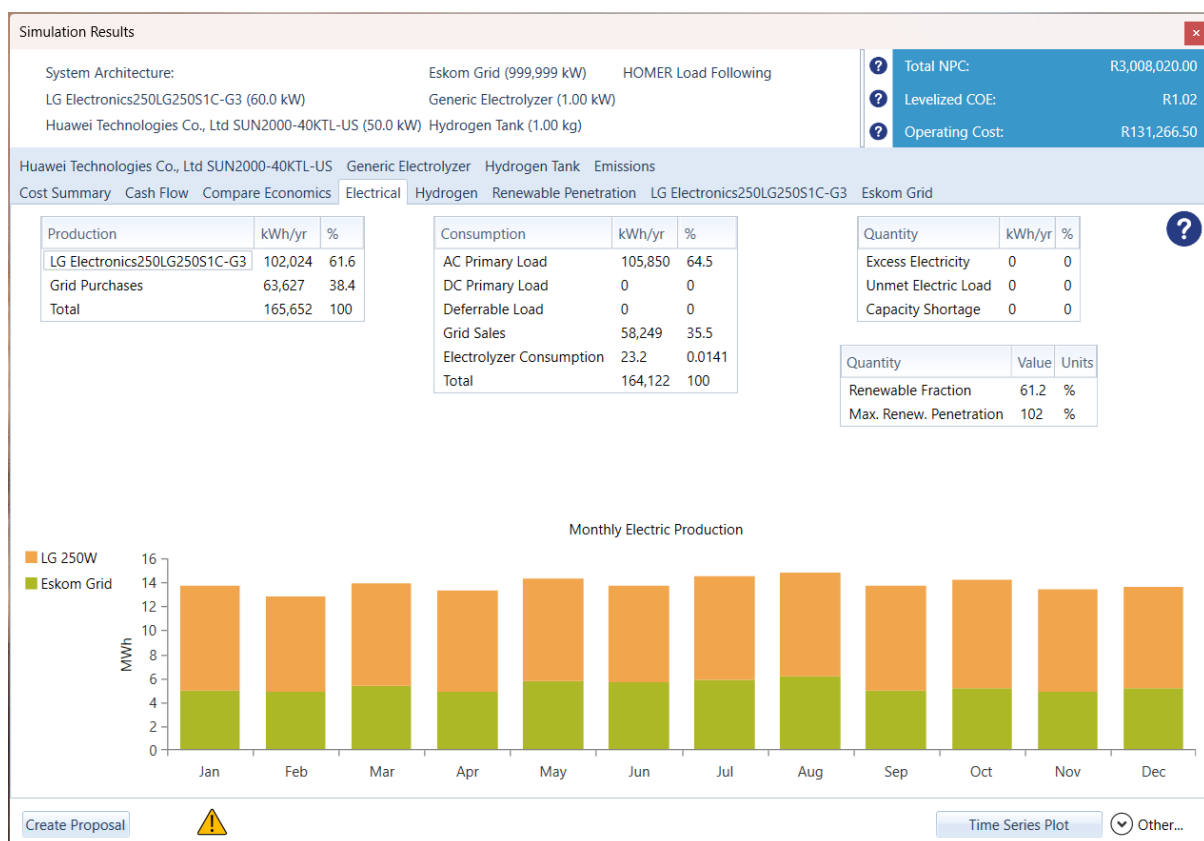


Figure A29. Electrical data for 250W module for PV/H₂/Grid configuration for Ga-Masekwa hydrogen production.

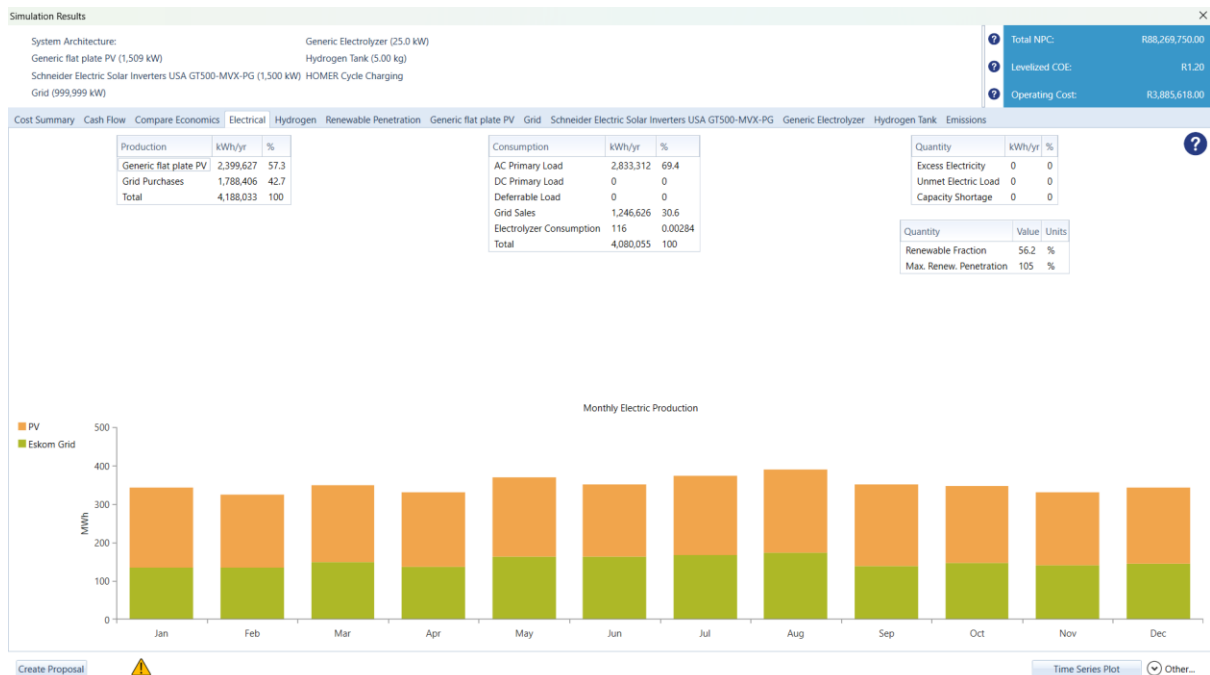


Figure A30. Electrical data for 250W module for PV/H₂/Grid configuration for Ka-Dzingidzingi hydrogen production.

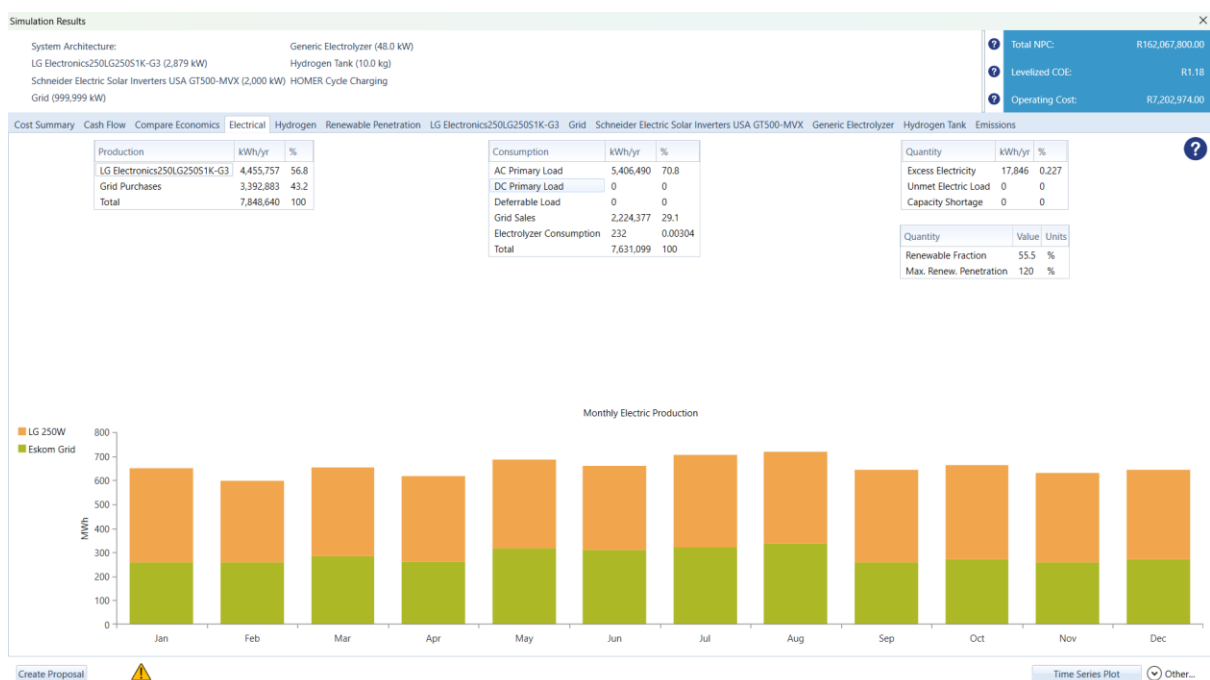


Figure A31. Electrical data for 250W module for PV/H₂/Grid configuration for Duthuni hydrogen production.

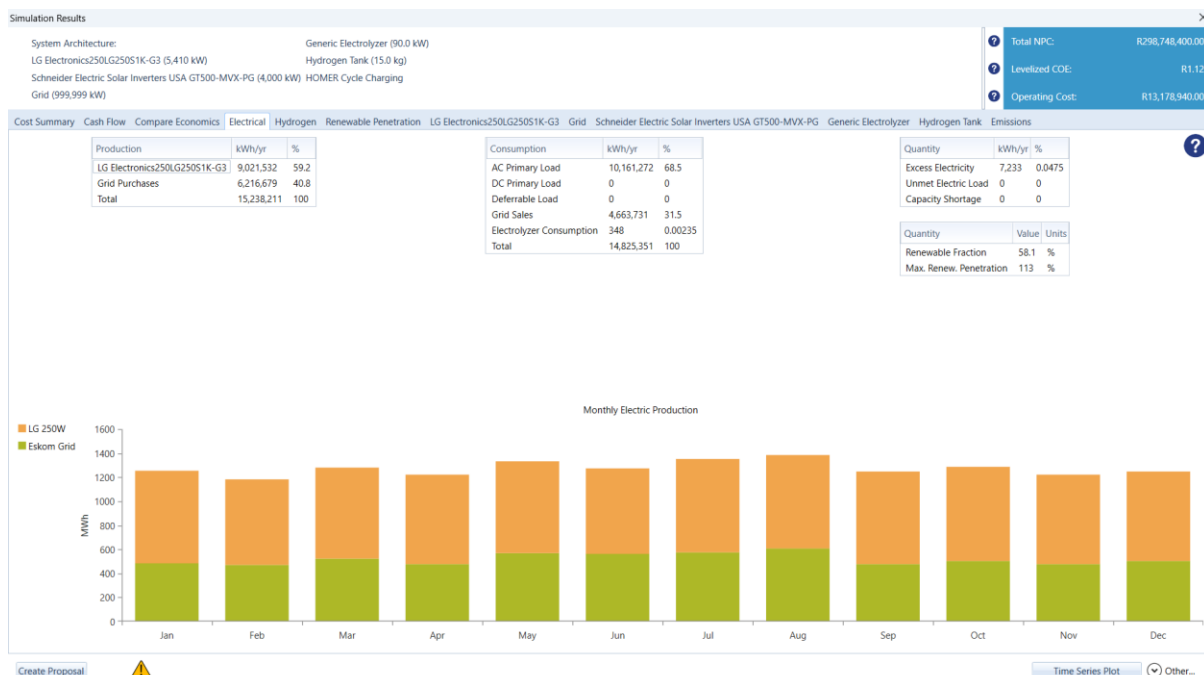


Figure A32. Electrical data for 250W module for PV/H₂/Grid configuration for Mookgopong NU hydrogen production.

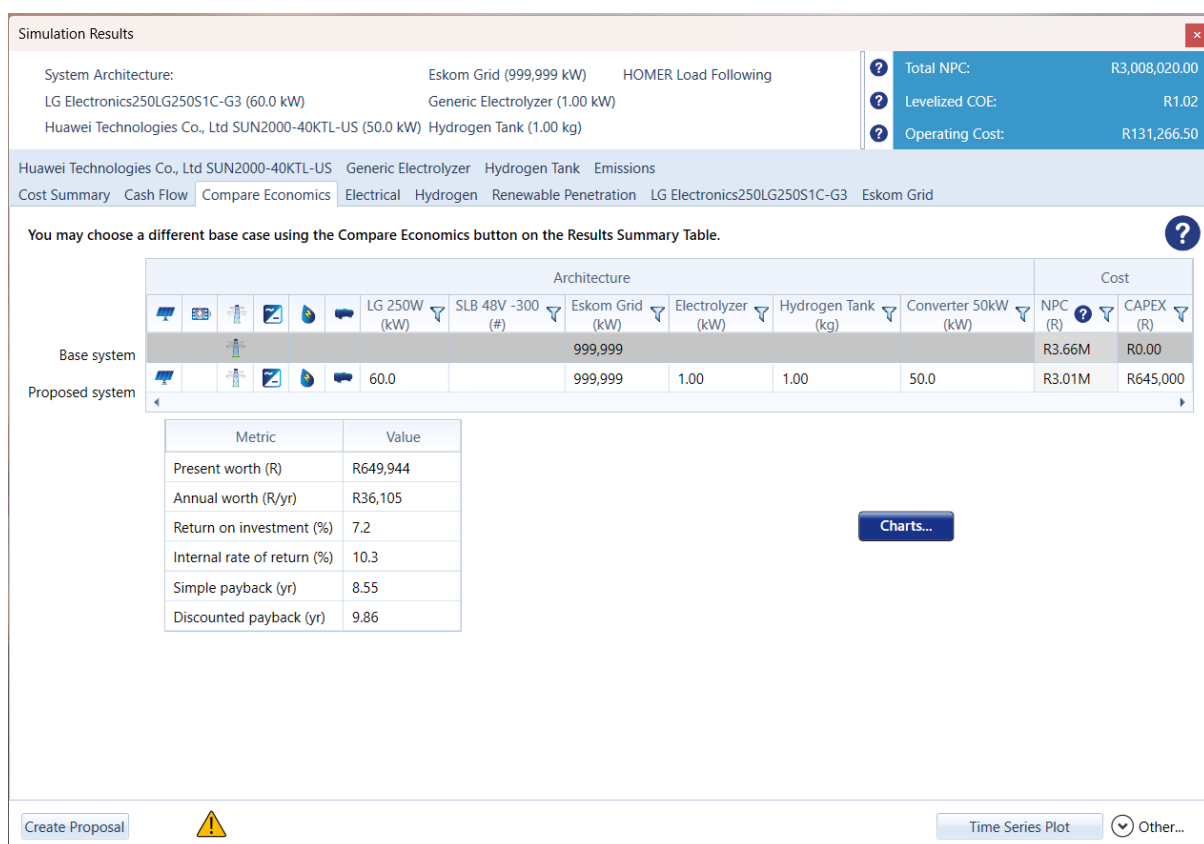


Figure A33. Economic metrics simulation results for Ga-Masekwa for a 250W module.

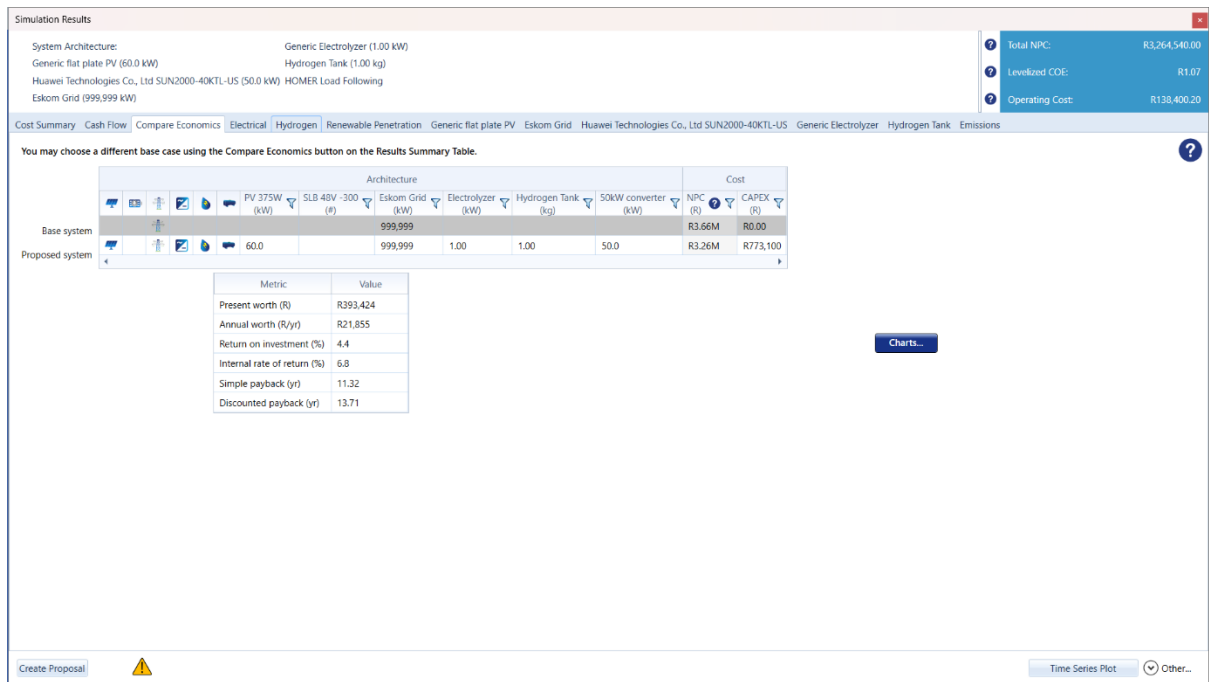


Figure A34. Economic metrics simulation results for Ga-Masekwa for a 375W module.

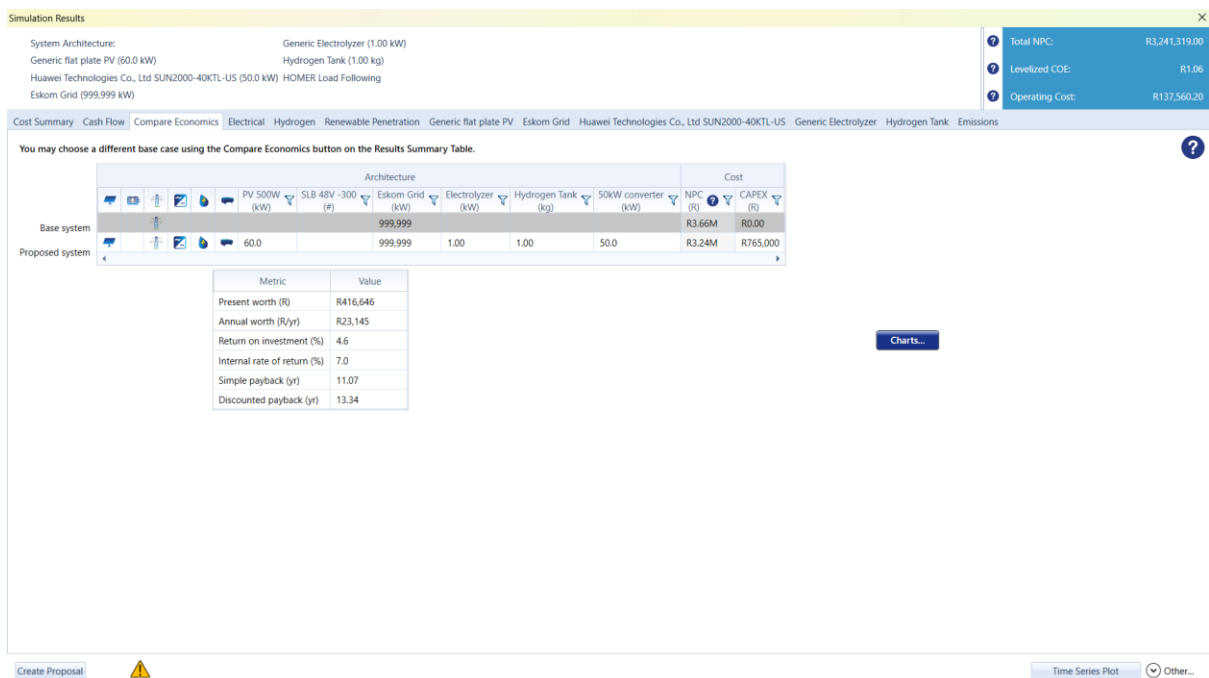


Figure A35. Economic metrics simulation results for Ga-Masekwa for a 500W module.

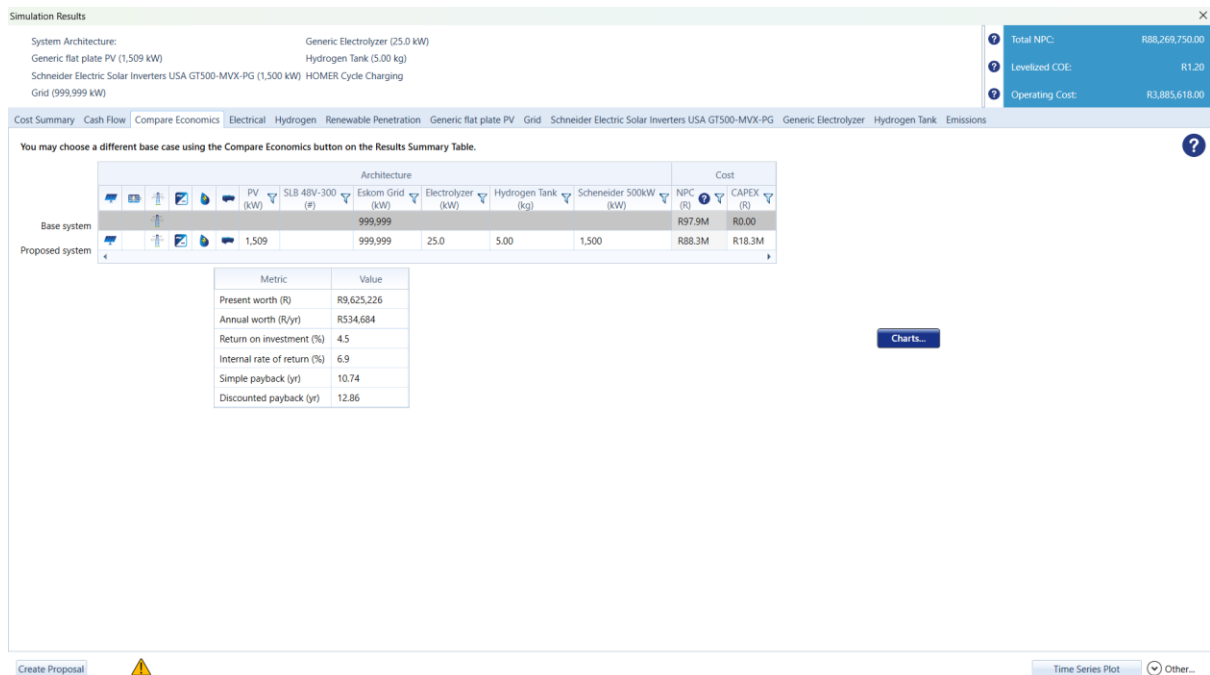


Figure A36. Economic metrics simulation results for Ka-Dzingidzingi for a 250W module

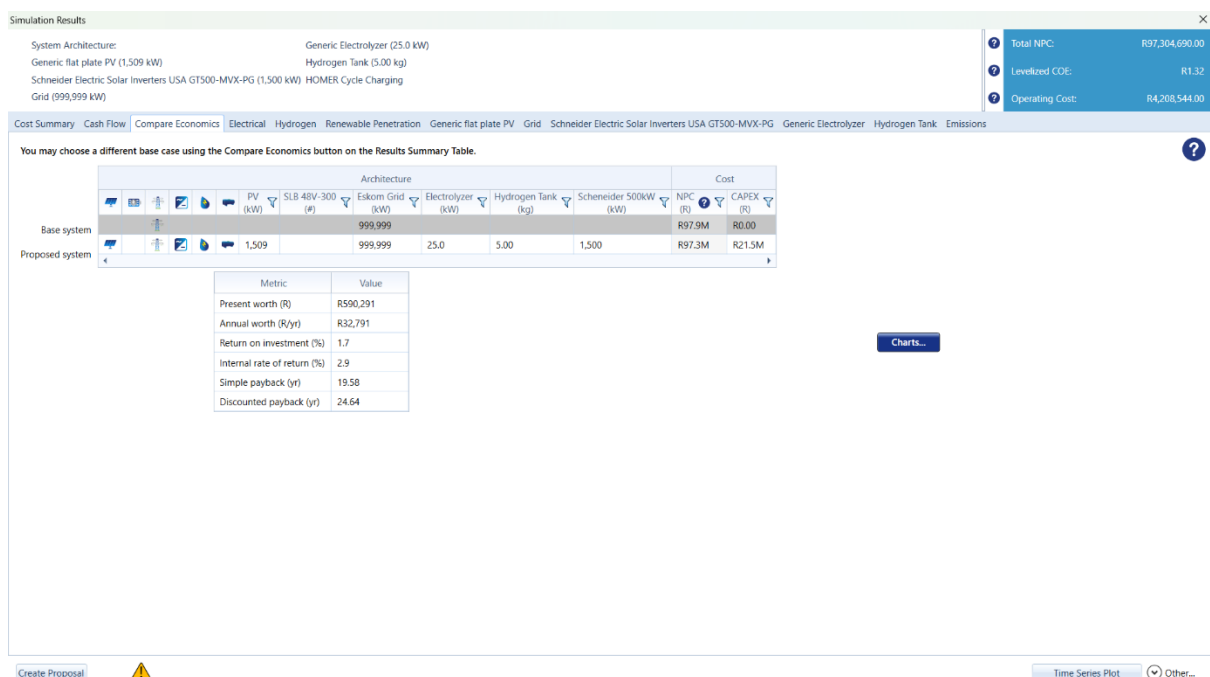


Figure A37. Economic metrics simulation results for Ka-Dzingidzingi for a 375W module

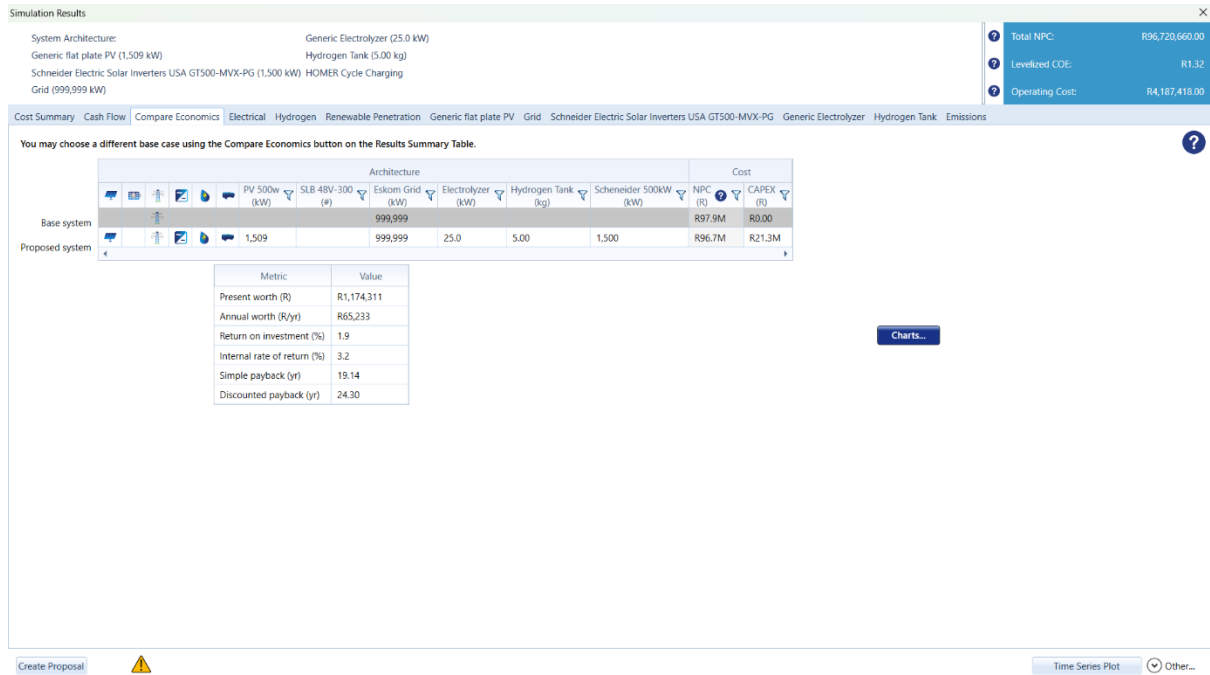


Figure A38. Economic metrics simulation results for Ka-Dzingidzingi for a 500W module

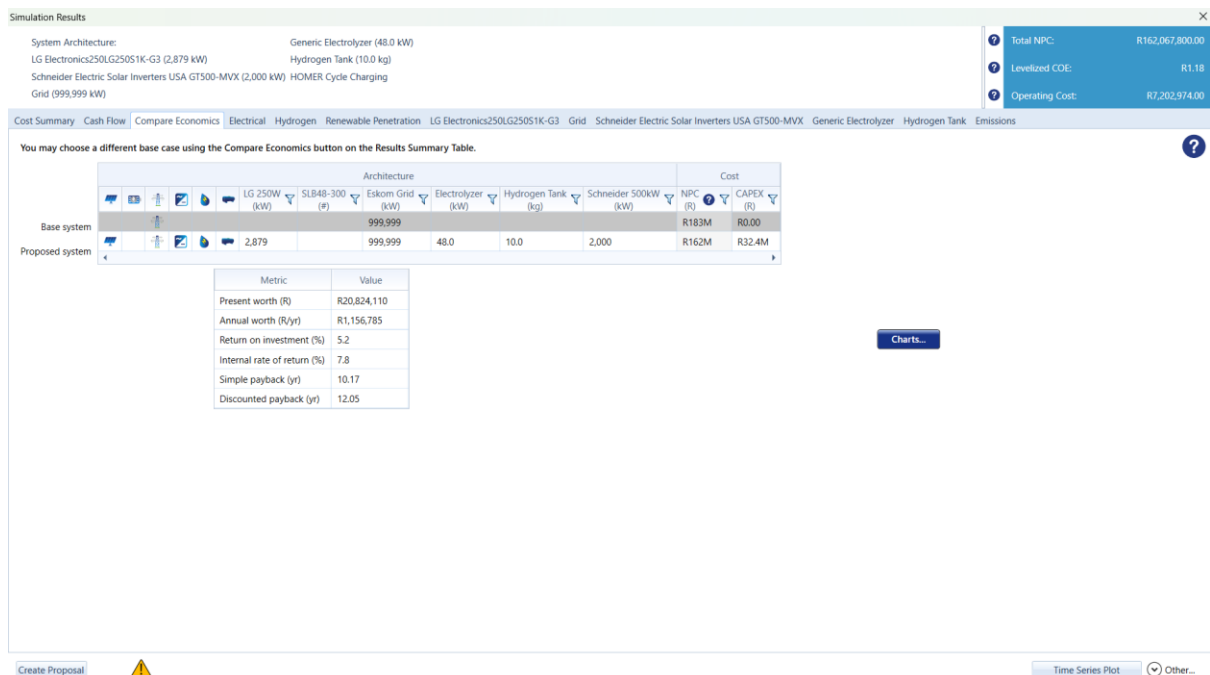


Figure A39. Economic metrics simulation results for Duthuni for a 250W module.

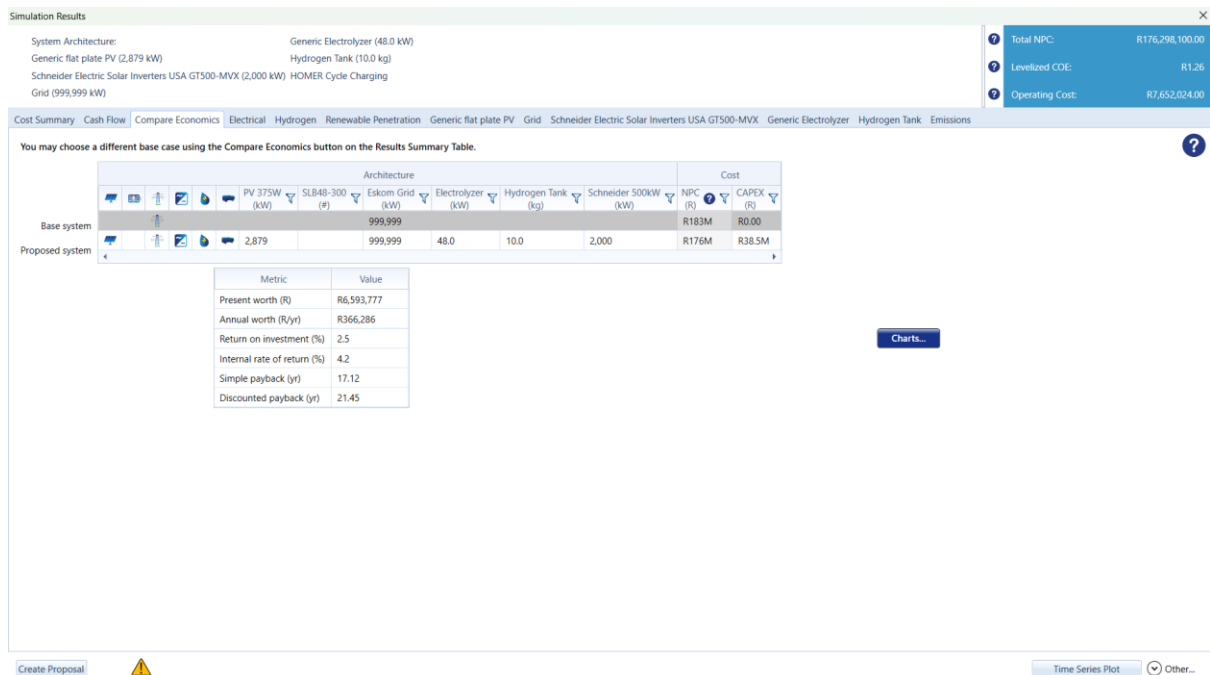


Figure A40. Economic metrics simulation results for Duthuni for a 375W module.

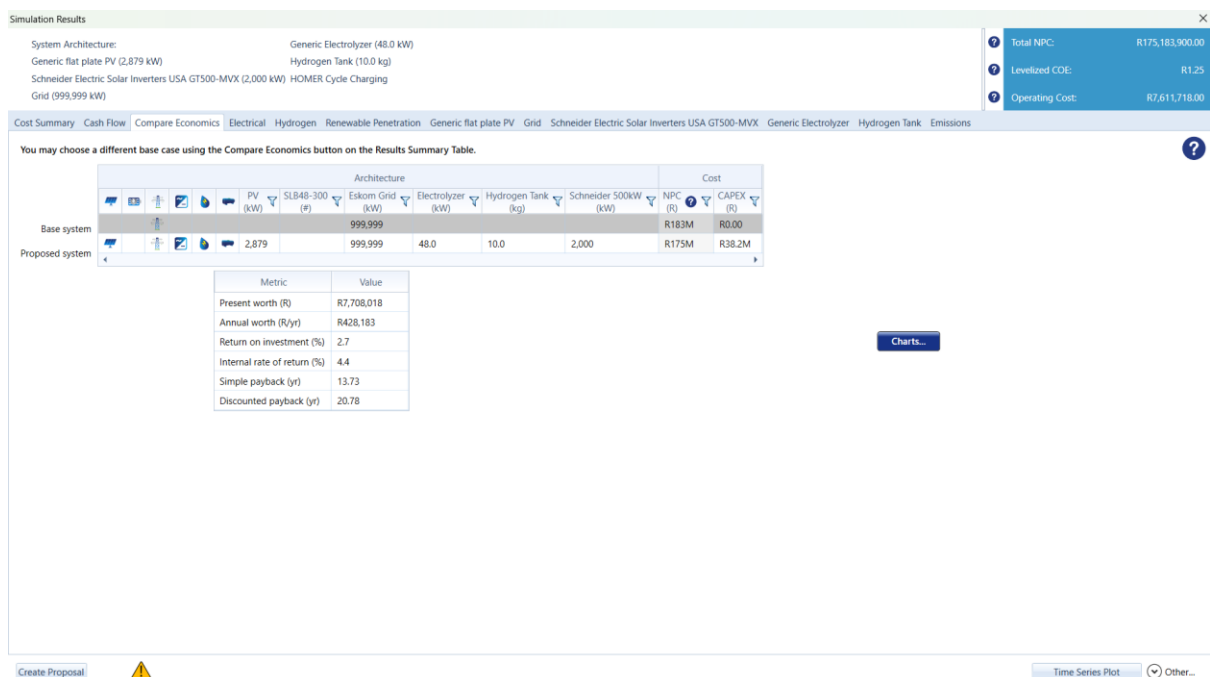


Figure A41. Economic metrics simulation results for Duthuni for a 500W module.

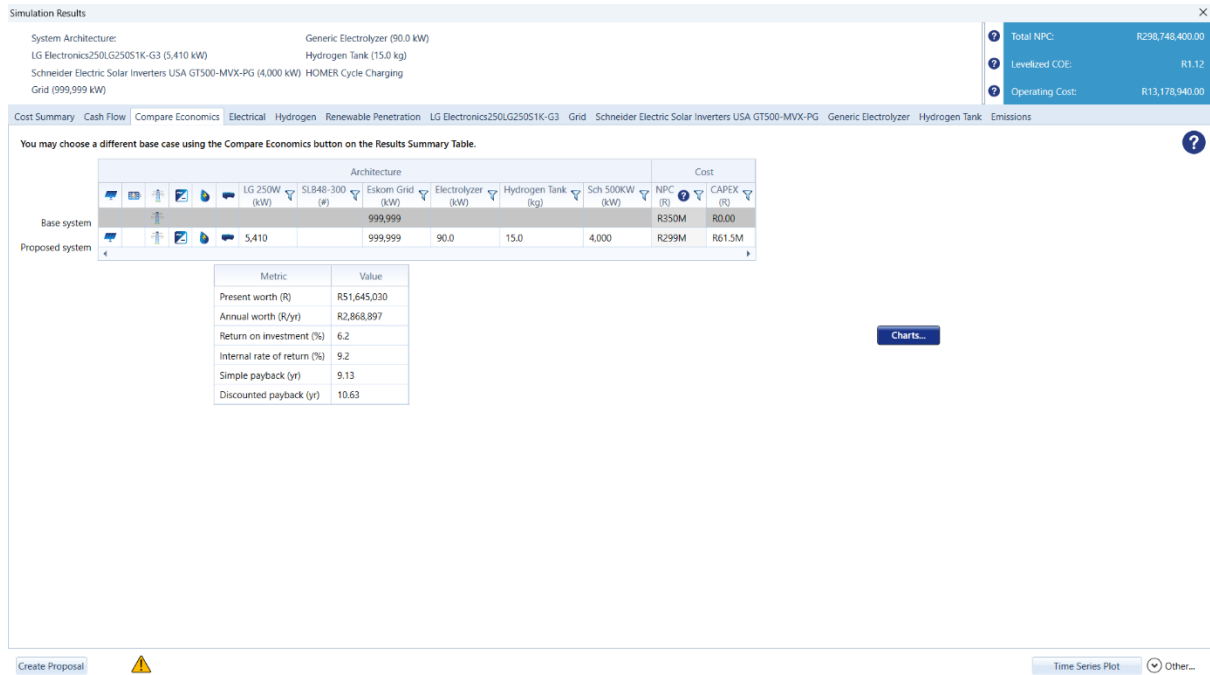


Figure A42. Economic metrics simulation results for Mookgopong NU for a 250W module.

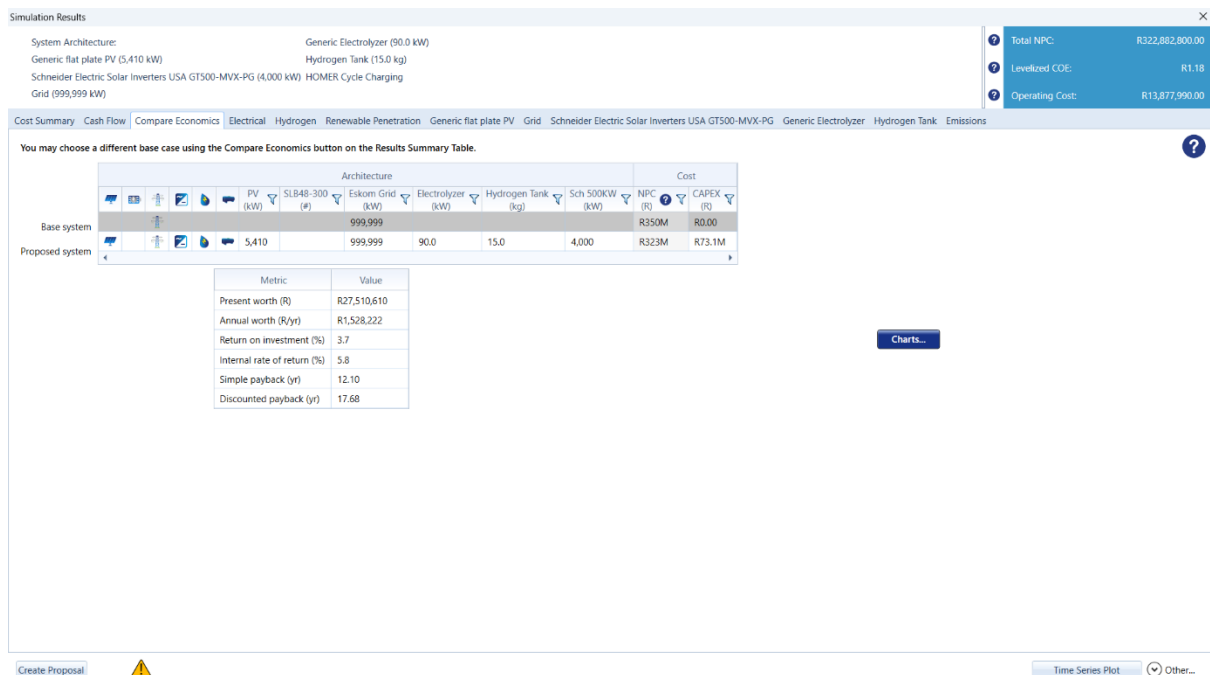


Figure A43. Economic metrics simulation results for Mookgopong NU for a 375W module.

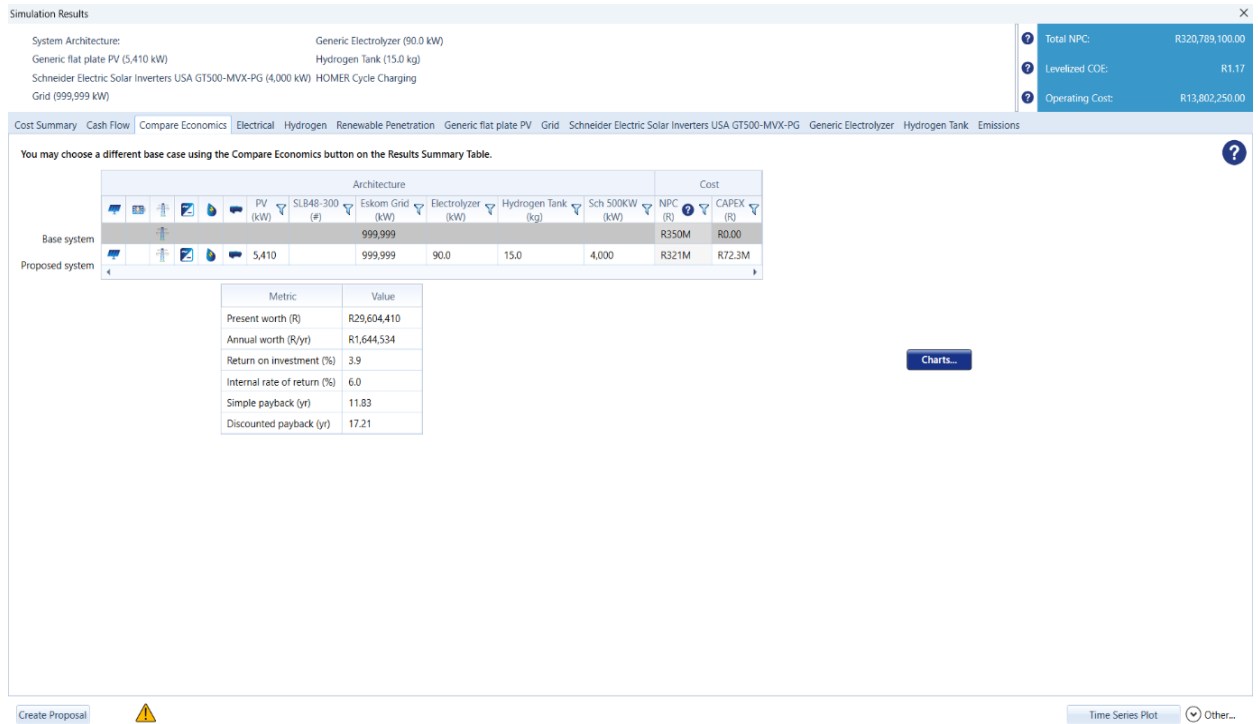


Figure A45. Economic metrics simulation results for Mookgopong NU for a 500W module.