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Performance and Techno-Economic Analysis of Optimal Hybrid Renewable Energy Systems for the Mining Industry in South Africa

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Abstract: This paper presents an exploration of the potential of hybrid renewable energy systems (HRESs), combining floating solar photovoltaics (FPV), wind turbines, and vanadium redox flow (VRF) battery energy storage systems (BESSs) to expedite the transition from conventional to renewable energy for the mining sector in South Africa. The feasibility study assesses how to enhance the overall efficiency and minimize greenhouse gas emissions from an economic standpoint by using the Hybrid Optimization of Multiple Energy Resources (HOMER) grid software version 1.11.1 and PVsyst version 7.4. Furthermore, the BESS Covariance Matrix Adaptation Evolution Strategy (CMA-ES) dispatch algorithm is proposed to make the most of the battery storage capacity and capability, aligning it with the dynamic energy demand and supply patterns of an HRES. The proposed HRES includes a highly efficient SFPV with a performance ratio of 0.855 and an annual energy production of 15,835 MWh; a wind turbine (WT) operating for 2977 h annually, achieving a 25% wind penetration rate; and a dynamic VRF-BESS with a 15,439 kWh life throughput and a 3 s dispatch response time. This HRES has a CapEx of R172 million, a 23.5% Internal Rate of Return (IRR), and an investment payback period of 4.9 years. It offers a low Levelized Cost of Energy (LCoE) at 4.27 R/kWh, a competitive Blended Cost of Energy (BCoE) at 1.91 R/kWh, and a positive net present cost (NPC), making it economically advantageous without external subsidies. Moreover, it annually reduces CO_2 emissions by 1,715,468 kg, SO_2 emissions by 7437 kg, and NOx emissions by 3637 kg, contributing to a significant environmental benefit.

Keywords: hybrid renewable energy systems; HOMER; techno-economic analysis; CMA-ES dispatch algorithm

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1. Introduction

The burgeoning South African population and rapid pace of industrial development are compounding the challenges associated with the nation's energy crisis [1]. Eskom, the state-owned power utility in the Republic of South Africa (RSA), is grappling with the formidable task of providing consistent and dependable electricity to not only residential areas but also to commercial, industrial, and crucially, mining sectors [2]. Unfortunately, these sectors are subjected to the adverse effects of load shedding and load curtailment, leading to significant revenue setbacks [3]. In response to these challenges, the mining sectors are actively seeking alternative renewable energy solutions. This strategic move aims to safeguard their operations from the disruptions caused by load shedding and load curtailment. By adopting renewable energy sources, such as solar, wind power, and BESSs, the mining sector can autonomously manage its energy supply [4]. This enables it to strategically dispatch energy according to its specific demand, thereby ensuring uninterrupted business operations even during instances of load shedding or load curtailment [5]. Another compelling reason for the mining sector to explore alternative renewable energy sources is its commitment to mitigating carbon emissions and aligning with global net-zero emissions initiatives [6]. By transitioning to cleaner and more sustainable energy options, such as renewables, the mining sector can significantly reduce its carbon footprint. This proactive approach not only contributes to local environmental goals but also aligns with the broader international efforts to achieve net-zero emissions, addressing the pressing challenges of climate change and promoting a greener future [7].

South Africa is committed to maintaining greenhouse gas emission levels within a fixed range of 398–510 MtCO2e by 2025 and further reduce them to a range of 350–420 MtCO2e by 2030 [8]. These commitments represent a noteworthy departure from its previous Nationally Determined Contribution (NDC), which had indicated emissions levels of 398 MtCO2e for 2025 and 614 MtCO2e for 2030 [9]. This heightened ambition underscores South Africa's commitment to addressing climate change via more robust emission reduction efforts, contributing to the global imperative of limiting temperature increases and their associated environmental consequences. In its revised NDC, South Africa has articulated an even more ambitious climate target by aiming to achieve net-zero greenhouse gas emissions by the year 2050, as outlined in its Low-Emission Development Strategy [10]. This commitment reflects a significant shift in the country's climate policy landscape, highlighting a long-term vision to reduce its carbon footprint substantially and align with global efforts to mitigate the impacts of climate change. South Africa's pledge to attain net-zero emissions by 2050 underscores its commitment to sustainable development and the imperative of transitioning toward a low-carbon economy in the coming decades.

It is noteworthy that coal-fired power stations continued to dominate the country's energy landscape, accounting for 80% of the total system load, whilst nuclear power contributes about 6% of energy [11]. At the same time, the contribution of renewable energy technologies, including wind, solar photovoltaics (PV), and concentrated solar power (CSP), had shown significant growth, with a total installed capacity of 6.2 gigawatts (GW) and contributing 7.3% to the overall energy mix [12]. This demonstrates a positive trend toward increasing the share of renewable energy in South Africa's energy generation, aligning with efforts to transition to cleaner and more sustainable energy sources while reducing the reliance on coal-fired power generation [13]. South Africa experiences an abundance of sunshine, with more than 300 sunny days annually, making solar energy generation an attractive option for various stakeholders. Furthermore, South Africa also boasts favorable conditions for wind energy generation, with its vast stretches of open land and coastal areas offering ample opportunities for harnessing wind power [14]. It is widely believed that the utilization of HRESs results in a substantial reduction in the cost of electricity generation. However, the efficient sizing and planning of an HRES necessitate meticulous consideration of the technical and economic facets. Oversizing HRES installations can incur excessive costs and result in an energy surplus, while undersizing may lead to unmet load demands. Addressing these intricacies involves judiciously employing BESSs, particularly batteries, to capture and efficiently manage excess energy. BESS deployment integrates advanced BESS dispatch algorithms, facilitating precise power allocation to optimize the load requirements and proficiently handle peak demand scenarios. Therefore, the meticulous selection of a dependable BESS plays a pivotal role in enhancing the reliability and cost-effectiveness of HRES frameworks. This strategic interplay of sizing, energy storage, and dispatch strategies underscores the imperative of meticulous HRES development to realize sustainable and technically optimized electrical energy solutions.

The design and implementation of grid-connected hybrid energy systems tailored to mining operations, as illustrated in Figure 1, involves a complex and comprehensive evaluation of the critical parameters. This evaluative process encompasses the identification of the most suitable system components, their appropriate sizing, and the strategic integration of efficient battery energy management techniques. These strategic decisions are contextualized within the framework of the system's geographic location and the precise energy demands imposed by the mining facility it serves.

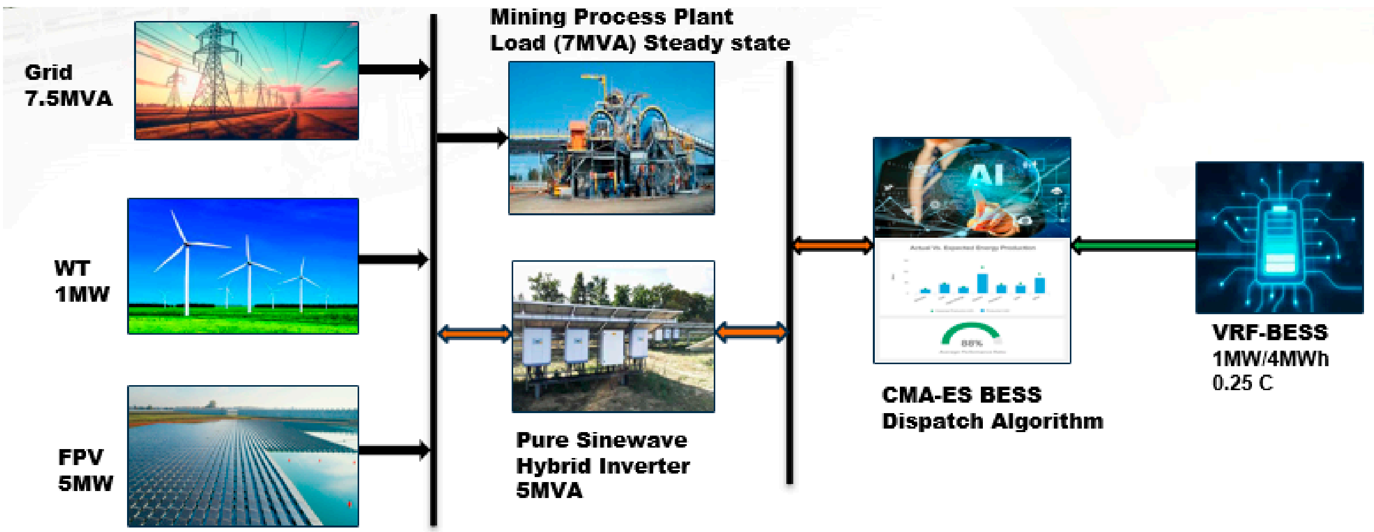


Figure 1. Proposed grid-connected HRES for the mining industry.

This research's primary aim is to conceptualize and simulate an HRES, integrating components such as a FPV system, WT system, VRF-BESS, and CMA-ES BESS dispatch algorithm. The fundamental contribution of this study is rooted in the methodical exploration and identification of efficacious HRES configurations. The HRES is designed with the overarching objective of augmenting the overall electrical efficiency of sustainable mining operations, simultaneously gauging its environmental footprint in the mitigation of greenhouse gas (GHG) emissions by integrating renewable energy sources into the national grid. The research contribution/objectives are as follows:

i. Design an optimal HRES (comprising solar, wind, BESS, and grid elements) to reduce reliance on the electrical grid for the mining power supply, thereby increasing revenue resilience during load curtailment periods.
ii. Analyze comprehensive data generated from simulations conducted using the HOMER version 1.11.1, PVsyst version 7.4, and MATLAB software version R2023b, encompassing power, economic, and environmental parameters, to assess the overall efficiency and delineate the optimal system configurations.
iii. Investigate the potential of the HRES, notably including FPV, a WT, and the integration of a VRF-BESS via modeling and simulations employing HOMER, PVsyst, and MATLAB.
iv. Propose a novel BESS CMA-ES dispatch algorithm to optimize the battery storage capacity utilization and align it with the dynamic energy demand and supply patterns inherent to the HRES.
v. Calculate vital financial metrics including the payback time, NPC, IRR, LCoE, and BCoE.
vi. Evaluate the environmental ramifications stemming from GHG emission reductions achieved via the implementation of the proposed optimal hybrid renewable energy configuration in mining operations.
vii. Recommendation on National Energy Regulator of South Africa's (NERSA's) registration procedure guidelines and grid code compliance for mining companies.
viii. Finally, the reliability assessment of the proposed HRES is analyzed using the Loss of Power Supply Probability (LPSP) approach.

The structure of this paper unfolds as follows: It commences with an introduction to the study in Section 1. Section 2 delves into an extensive literature review, laying the foundation for the research. Moving forward, Section 3 outlines the methodology employed and offers insights into the mining load profile under examination. Section 4 discusses the system setup of the proposed HRES and modeling parameters. Section 5 provides detailed results, discussions, and recommendations. Finally, Section 6 encapsulates the study with conclusive insights and takeaways.

2. Literature Review

This section analyzes the principal studies and documented sources that offer valuable insights and a deeper understanding of the application of an HRES composed of two or more renewable energy subsystems. The primary technical hurdle in the seamless integration and distribution of renewable energies lies in reconciling the supply and demand dynamics, primarily attributed to the sporadic nature of renewable energy sources. Nonetheless, the difficulty lies in identifying the ideal HRES with an intelligent BESS dispatch algorithm that strikes a balance between efficiency, cost-effectiveness, and reliability to offer effective solutions tailored to the unique energy needs of mining enterprises. In the pursuit of achieving an optimal balance between cost-efficiency and reliability for grid-tied systems, the design, optimization, and simulation of microgrids have garnered significant attention and interest within the scholarly literature.

Before introducing the literature survey, Table 1 provides an overview of the SWOT analysis conducted for mining companies relying exclusively on the Eskom grid in South Africa [15]. The principal purpose of conducting this analysis is to elucidate the inherent internal strengths and weaknesses of these mining entities, alongside external opportunities and threats that are context-specific. Such an analytical framework serves as an essential precursor to the literature review, as it offers a systematic and structured assessment of the critical factors shaping the operational landscape of mining companies in the RSA that are reliant on the Eskom grid.

Numerous research endeavors have focused on the challenge of integrating hybrid systems within microgrids, aiming to achieve economic goals by pioneering innovative energy management system strategies and enhancing the scalability of power generation and energy storage components. However, most researchers have focused on implementing HRESs at the residential, community, and commercial scale.

In the domain of optimization techniques being applied to system sizing, the work of Akbar Maleki and Alireza Askarzadeh [17] presents an intriguing case for academic consideration. Their investigation involved a comprehensive analysis of a PV/wind/diesel generator (DG) hybrid system, augmented by battery storage, geared toward addressing the electrification requirements of the remote off-grid village of Rafsanjan in Iran. Employing a discrete harmony-search-based optimization approach, their primary goal was to ascertain the ideal system configuration, with the total annual cost of the system serving as the primary objective function. Nevertheless, an apparent limitation in their study pertains to its singular focus on cost minimization, which may not account for the diverse and complex aspects inherent to renewable energy systems. The absence of a comprehensive analysis of performance and reliability considerations, such as system efficiency and resilience, represents a notable gap in the research. Future studies would benefit from a more holistic approach, considering a broader spectrum of objectives to encompass the system's multifaceted requirements and constraints, thereby offering a more robust and sustainable solution.

Nasser Yimen et al. [18] employed the HOMER software to analyze a stand-alone PV/wind/biogas/PHS hybrid system for electrifying Djoundé, a remote village in Northern Cameroon. The study considered diverse energy demands and a minimized NPC as the primary objective. The optimal system configuration included a 15 kW biogas generator and an 81.8 kW PV array, resulting in a cost of electricity (COE) of 0.256 EUR/kWh and an NPC of 370,426 EUR. However, the study's exclusive focus on cost optimization neglects the consideration of performance, resilience, and environmental sustainability, suggesting the need for a multi-objective approach in future rural electrification endeavors.

Table 1. SWOT analysis for mining companies relying solely on Eskom grid [16].

Strengths	Weaknesses
• Reliable Power Supply: Eskom, despite its challenges, has historically provided a relatively stable power supply to the mining industry in South Africa, allowing for consistent operations. • Established Infrastructure: Mines relying on the Eskom grid have existing infrastructure and systems in place that are designed to work with this power source. • Cost-Efficiency: Eskom's electricity rates have traditionally been lower compared to alternative sources, providing cost advantages to mining companies. • Access to National Grid: Being connected to the national grid provides access to electricity across the country, allowing for expansion and remote operations.	• Power Outages and Reliability Issues: Eskom has faced significant challenges with power generation and distribution, leading to frequent blackouts and supply interruptions, which can disrupt mining operations and cause production losses/revenue setback. • Tariff Increases: Eskom's tariffs have steadily increased due to financial and operational challenges, impacting the cost-effectiveness of using the Eskom grid. • Limited Control: Mining companies relying solely on Eskom have limited control over their power supply, making them vulnerable to Eskom's operational issues and regulatory decisions. • Environmental Concerns: Eskom's primary energy source is coal, which is a major contributor to greenhouse gas emissions, raising environmental concerns and potential regulatory challenges.
Opportunities	**Threats**
• Alternative Energy Sources: Exploring renewable energy sources, such as solar and wind, can reduce reliance on Eskom and provide a more sustainable energy mix. • Energy Efficiency: Investing in energy-efficient technologies and practices can reduce electricity consumption and lower costs. • Government Initiatives: The South African government may introduce incentives and policies to encourage renewable energy adoption, providing opportunities for mining companies to diversify their energy sources. • Grid Stabilization: Eskom may invest in improving grid stability and reliability, reducing the risk of power interruptions.	• Energy Supply Risks: Ongoing issues with Eskom's financial stability, aging infrastructure, and operational challenges pose a significant threat to mining companies relying on its grid. • Regulatory Changes: Changes in government regulations, emissions standards, or carbon taxes could increase operational costs and affect the competitiveness of mining operations. • Environmental Compliance: Stricter environmental regulations could require costly upgrades or force mines to reduce emissions, impacting profitability. • Competitive Disadvantage: Mining companies that do not adapt to more sustainable energy sources may face a competitive disadvantage as stakeholders and investors increasingly prioritize environmental and social responsibility.

The authors of [19], a comprehensive study, examined the effects of various operational strategies on an HRES incorporating PV, WTs, diesel generators, and hydro power in a rural area of India. The research findings indicated that the Combined Dispatch (CD) control strategy emerged as the most cost-effective, resulting in a remarkably low COE at \$0.31 per kilowatt-hour. Furthermore, the Load-Following strategy demonstrated superior renewable energy penetration when compared to alternative methods. Likewise, ref. [20] delved into a technoeconomic analysis of PV, WT, battery, and biogas generator systems, exploring different dispatch strategies. The results highlighted the cost-effectiveness of the CD approach in meeting the energy demand, particularly when the system comprised 0.5% biofuel, 12.7% wind energy, and 86.8% solar energy. However, both methods used conventional PV, which requires a large carbon footprint as compared to FPV. Furthermore, traditional batteries are utilized, which has safety and environmental concerns.

The researchers in [21] conducted a thorough analysis of the electrification options for the village of Fouay in the Republic of Benin, focusing on the techno-economic aspects. Their findings led them to recommend a hybrid PV–DG–battery system as the most advantageous solution for providing electricity to the village. This hybrid system not only exhibited the lowest net present cost and enhanced the reliability of the power supply but also effectively mitigated battery storage expenses by reducing the battery requirements to just 30% of what a standard PV–battery standalone system would necessitate. This approach boasted a remarkably short payback period of 3.45 years and an impressive 33.3% IRR, affirming its suitability for fulfilling the rural electrification objectives laid out in the country's master plan. However, it is important to acknowledge that the utilization of a DG in this hybrid system may have negative repercussions. DGs are associated with higher operational and maintenance costs, as well as a considerable environmental footprint due to the emission of greenhouse gases and air pollutants. Additionally, they introduce noise pollution to the local environment, which can have adverse effects on the well-being of the community.

Similarly, Kasaeian et al. [22] explored the feasibility of biomass energy utilization, emphasizing the influence of geographical location and the available raw materials. Their study centered on Bandar Dayyer, Iran, where they conducted a techno-economic assessment to identify the optimal HRES, combining PV, biomass, and a DG. Using the HOMER software for simulations, the results indicated that the combined systems generated a total of 470,176 kW of electricity, with 22,409 kW generated by a PV–biomass system and 447,767 kW generated by a PV–diesel–biomass system. The economic analysis underscored the cost-effectiveness of the PV–biomass system, with an NPC of USD 23,148.84, highlighting the advantages of adopting an HRES over a PV–diesel–biomass system. However, it us important to note that an off-grid system incorporating biomass and a diesel generator may raise environmental concerns due to the emissions associated with diesel combustion. This can lead to air pollution and contribute to greenhouse gas emissions, impacting both local air quality and global climate change.

In a recent study by Ansori and Yunitasari [23], they explored the electrification of rural areas using a hybrid power generation system that combines solar PV and biogas. Interestingly, despite their comprehensive investigation encompassing various sizing optimization strategies and state-of-the-art methodologies and software tools, there was a notable absence of a critical comparison of the effectiveness of standalone hybrid solar and wind systems for remote regions and islands. It is worth noting that the utilization of solar and biogas alone may not entirely fulfill the energy demands, including both electrical and thermal, in these areas. Moreover, the application of biogas and hybrid solar energy systems remains somewhat limited, despite their considerable potential. Therefore, it is imperative to assess the economic viability of these resources and their capacity to address specific needs and constraints, with the aim of facilitating their integration into rural energy planning and promoting wider adoption to unlock their full potential. HRESs hold promise, particularly for off-grid systems designed for remote and island locations, as well as grid-connected systems, addressing the challenges of unreliable national grids.

Recently, there is a growing emphasis on refining and the construction of hybrid renewable power facilities. Researchers are utilizing advanced software tools like HOMER to intricately weave energy storage solutions into electrification systems for remote regions, all while considering the potential for grid integration. Most researchers commonly utilized lead acid (LA) [24], lithium-ion (LI) [25] and nickel–iron (IN) [26] battery technologies. However, these battery technologies have disadvantages, which are unpacked as follows:

- LI batteries are known for their high cost and potential fire hazard due to thermal runaway.
- LA batteries are heavy, have a limited cycle life, and pose environmental concerns due to the toxic nature of lead.
- NI batteries are relatively less energy-dense and have higher self-discharge rates, making them less suitable for certain applications.

HOMER's optimization capabilities are instrumental in pinpointing the most suitable system sizes, and these results are concisely presented in Table 2 in summary.

The utilization of LI, LA, and NI battery technologies in HRESs is impeded by various constraints, resulting in elevated COEs and prolonged payback periods. To address these limitations, the integration of VRF-BESSs and CMA-ES energy dispatch algorithms is proposed. These innovative solutions aim to mitigate the drawbacks associated with existing battery technologies, thereby enhancing the overall economic feasibility and reliability of HRESs.

Table 2. Review of existing HRESs with different BESS technologies.

HRES	Ref	Location	On-/Off-Grid	BESS Technology	Design Constraints	Analysis
PV/WT/BESS	[27]	India	Off-Grid	LI Battery	Distribution of energy supply–demand planning	0.470 USD/kWh COE
PV/WT/DG/BESS	[28]	Namibia	Off-Grid	LA Battery	Socio-economic studies required	0.388 USD/kWh COE
PV/WT/biogas/BESS	[18]	Cameroon	Off-Grid	Pumped Hydro	Reliability and operational constraints	0.28 USD/kWh COE
PV/WT/DG/BESS	[29]	Malawi	Off-Grid	LI Battery	Power balance and budget	0.12 USD/kWh COE
PV/WT/BESS	[30]	Kenya	Off-Grid	LI Battery	Power balance and techno-economics	0.519 USD/kWh COE
PV/WT/DG/BESS	[31]	Nigeria	Off- and On-Grid	LA and LI Batteries	Reliability and operational constraints	0.218 USD/kWh COE
WT/BESS	[32]	Italy	Off- and On-Grid	NI Battery	Required electrical load and the techno-economic feasibility	0.09 USD/kWh COE
PV/WT/biogas/DG/BESS	[33]	India	Off Grid	LA Battery	Reliability and operational constraints	0.17 USD/kWh COE
PV/WT/BESS/DG	[34]	Bangladesh	Off-Grid	LI Battery	Power balance and techno-economics	0.72 USD/kWh COE

3. Methodology

This investigation encompasses a comprehensive examination of HRES performance, environmental, and techno-economic dimensions, to assess the reliability and suitability of the proposed system. The research approach entailed the development of a structured framework designed to enhance the electrical energy efficiency while concurrently curbing the greenhouse gas emissions stemming from conventional fossil-fuel-based electricity generation. This paradigm shift is achieved via the deployment of an HRES, a multifaceted amalgamation of renewable energy technologies, such as solar, wind power, and a BESS, in stark contrast to conventional energy sources dependent on fossil fuels for mining companies. The configuration of FPV + WT + BESS was chosen because FPV systems optimize water and land resources for solar energy capture, reducing the carbon footprint. BESSs play a crucial role in enhancing the grid stability, bolstering resilience, and efficiently managing peak energy demands within the context of renewable energy scenarios. Wind turbines provide a sustainable and environmentally friendly source of electricity, reducing the overall greenhouse gas emissions. This transformative adaptation propels an HRES-powered facility on the path to becoming an environmentally sustainable structure. The study involved the collection of data pertaining to electricity consumption patterns, renewable energy resources, and the quantification of greenhouse gas emissions.

The study employed the HOMER Pro software for conducting the techno-economic analysis simulation. HOMER Pro is a powerful microgrid simulation tool that generates a comprehensive set of practical system configurations encompassing various equipment types. What distinguishes HOMER Pro is its ability to identify and optimize the most cost-effective microgrid solution. This choice of utilizing the HOMER software proves to be more advantageous for this project compared to a mathematical model, as it excels in optimizing complex input parameters, including outage scenarios and load data, with a primary focus on economic efficiency. Furthermore, the performance evaluation of the proposed hybrid FPV, WT, and BESS dispatch algorithm involves the utilization of the PVsyst and MATLAB software tools. These software platforms are instrumental in conducting a comprehensive analysis and assessment of the system's effectiveness and efficiency. PVsyst is employed for assessing the photovoltaic system's performance, while MATLAB SIMULINK facilitates the evaluation of the WT and BESS dispatch algorithm's performance across all components, allowing for a thorough examination of the integrated renewable energy system's functionality. The core of this proposed framework revolves mainly around the four stages depicted in Figure 2.

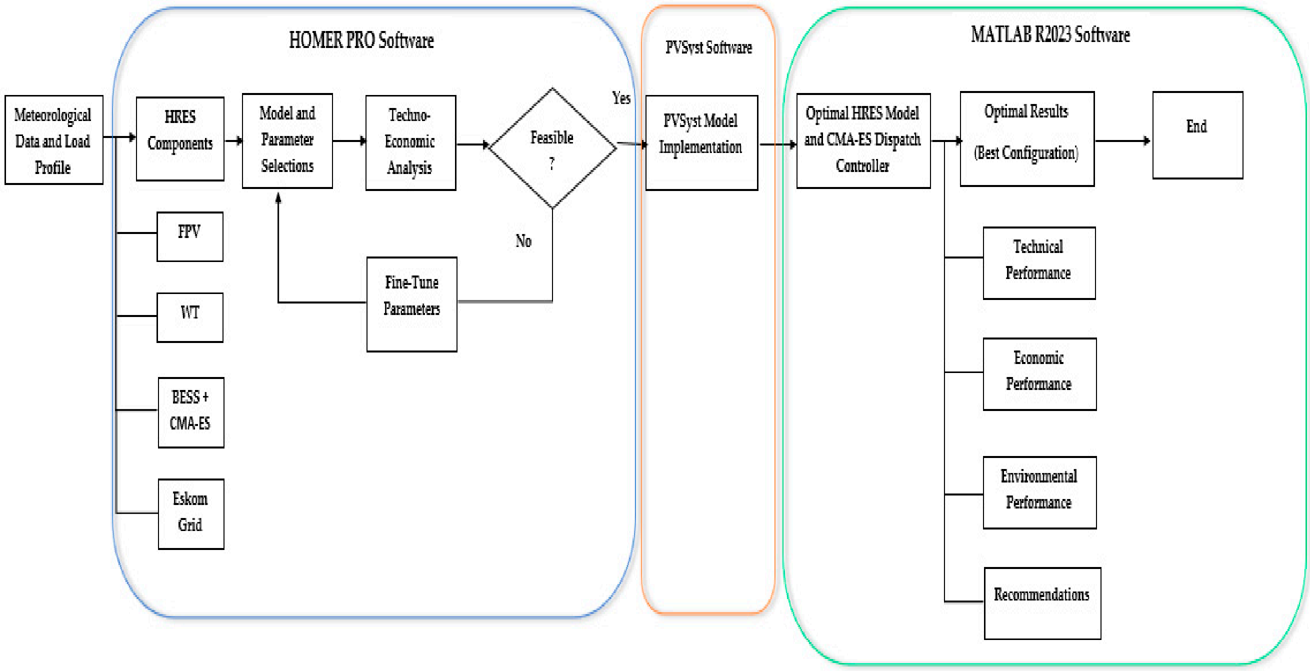


Figure 2. A proposed systematic structure for achieving the best and most effective HRES configuration.

3.1. Site Selection and Resources

3.1.1. Meteorological Data

The techno-economic assessment of implementing an HRES within the mining sector has been undertaken with a specific focus on the Driekop region, situated in the Limpopo province of South Africa, adjacent to Burgersfort town. This location was chosen due to its pronounced prominence in mining activities, housing a diverse array of mineral commodities including gold, platinum, chrome, vanadium, coal, and platinum group metals (PGMs), all of which rely on Eskom for their substantial power needs. Figure 1, provided herewith, illustrates the selected site for the proposed HRES system, emphasizing its strategic selection predicated on the rich solar and wind energy resources available, thus exemplifying its suitability for the integration of renewable energy solutions. This study endeavors to comprehensively evaluate the economic feasibility and operational viability of introducing an HRES system within Driekop's mining sector, thereby contributing to sustainable energy practices in this resource-intensive industrial landscape (Figure 3).

3.1.2. Load Profile

The load profile of the mining processing plant is defined by an average power demand of 8000 kW during its peak operational periods. This peak load encompasses the simultaneous operation of critical components within the facility, such as the crushing circuit, milling machinery, flotation processes, thickener units, and product-handling circuits. In addition to the peak power demand, the plant has an average daily power consumption of 189,750 kilowatt-hours (kWh/day). This daily energy usage provides a comprehensive view of the plant's continuous energy requirements, accounting for variations in demand throughout the day but culminating in the highest power demand observed during peak operations. Figures 4 and 5 demonstrate the daily load profile and base load profile of the mining company in a year. The historical standard load profile for the metallurgical processing plant equipment was determined, considering the utilization of typical equipment loads each month, accounting for low, standard, and peak seasons [35].

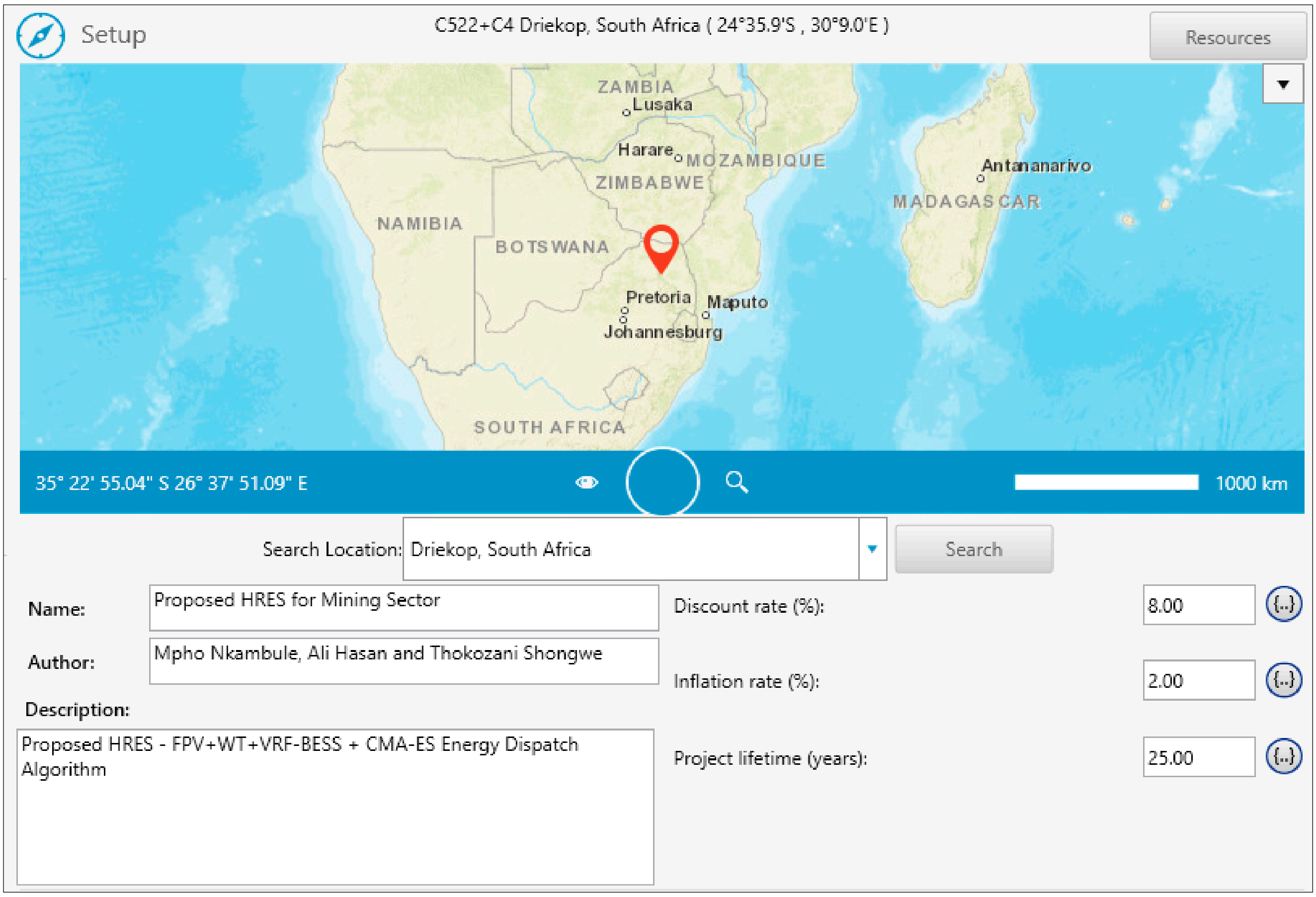


Figure 3. The proposed site location of Driekop mining complex.

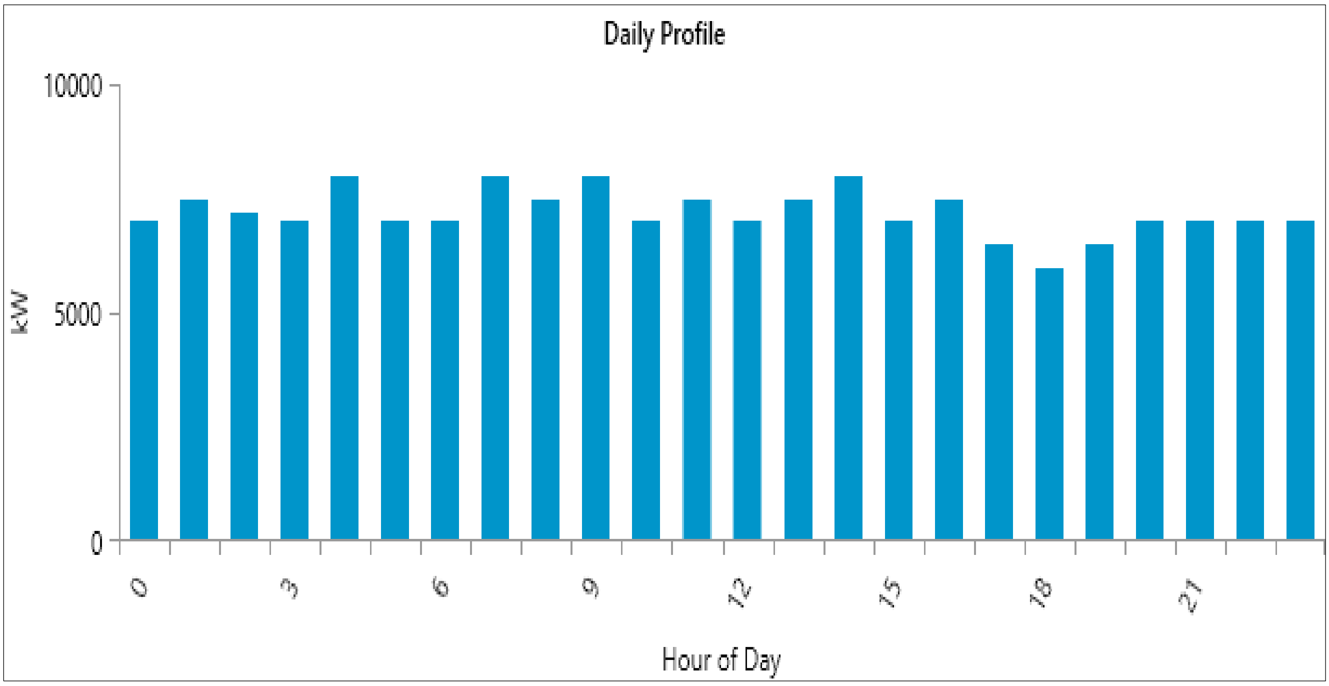


Figure 4. Daily load profile for mining processing plant.

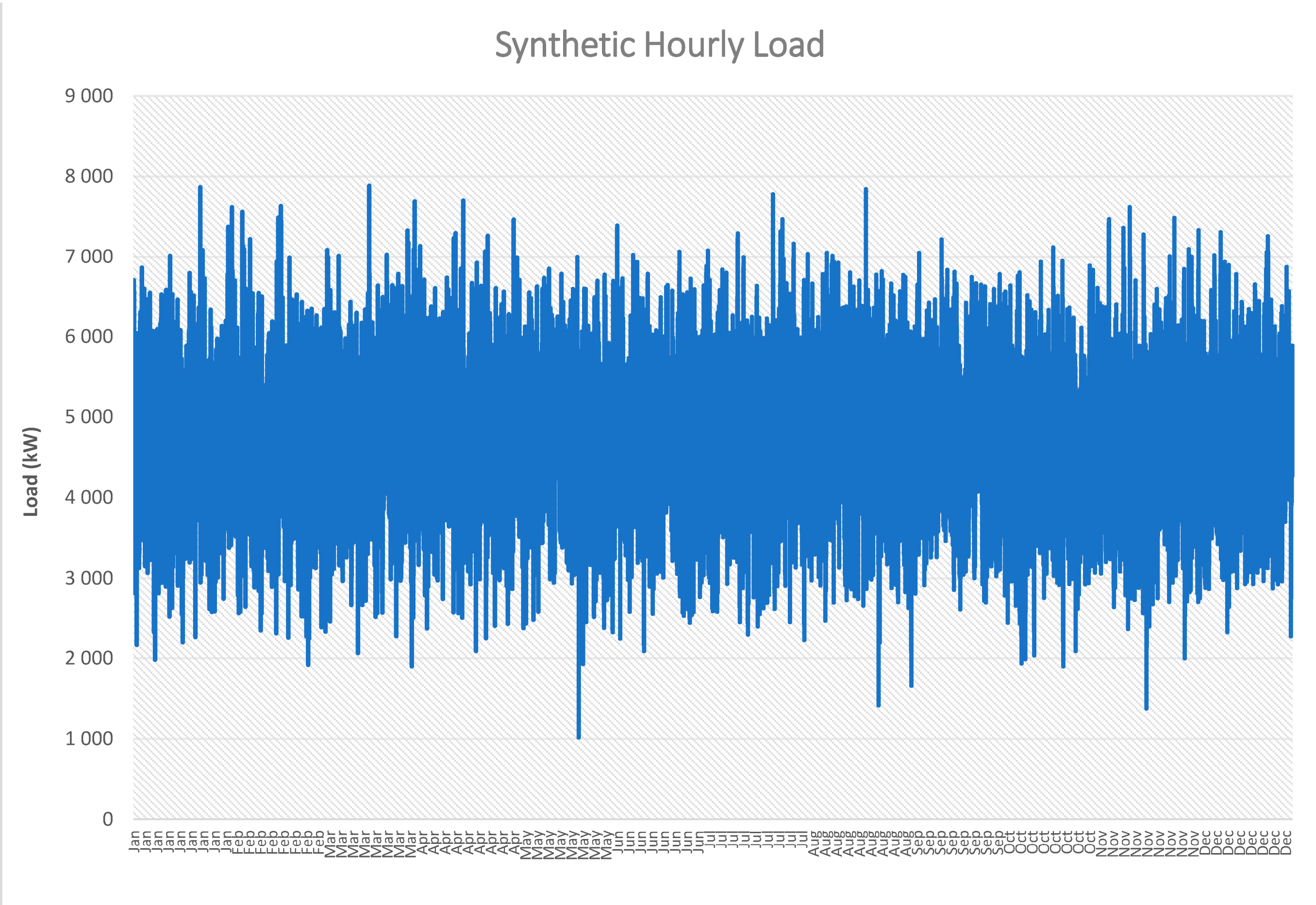


Figure 5. Baseline load profile for mining processing plant.

The power demand per equipment component within the mining processing plant varies, reflecting the diverse energy requirements of each operational unit, as shown in Table 3. The crushing circuit and milling circuit both have a demand of 1500 kW, highlighting their substantial energy consumption during processing activities. The flotation circuit follows closely with a power demand of 2000 kW, underscoring its importance in the mineral separation process. The thickener circuit, responsible for the separation of solids and liquids, operates at a demand of 1000 kW, while the product-handling circuit, which plays a crucial role in material transport and logistics, requires 2000 kW of power. These individual power demands collectively contribute to the plant's overall peak power demand of 8000 kW during simultaneous operation. Understanding these specific energy needs for each equipment component is vital for efficient energy management, process optimization, and cost-effective operation within the mining processing plant. Figure 6 demonstrates a typical mining processing plant and equipment 3D model.

Table 3. Power demand per mining processing plant equipment component.

Equipment	Load (kW)
Crushing Circuit	1500
Milling Circuit	1500
Flotation Circuit	2000
Thickener Circuit	1000
Product-Handling Circuit	2000

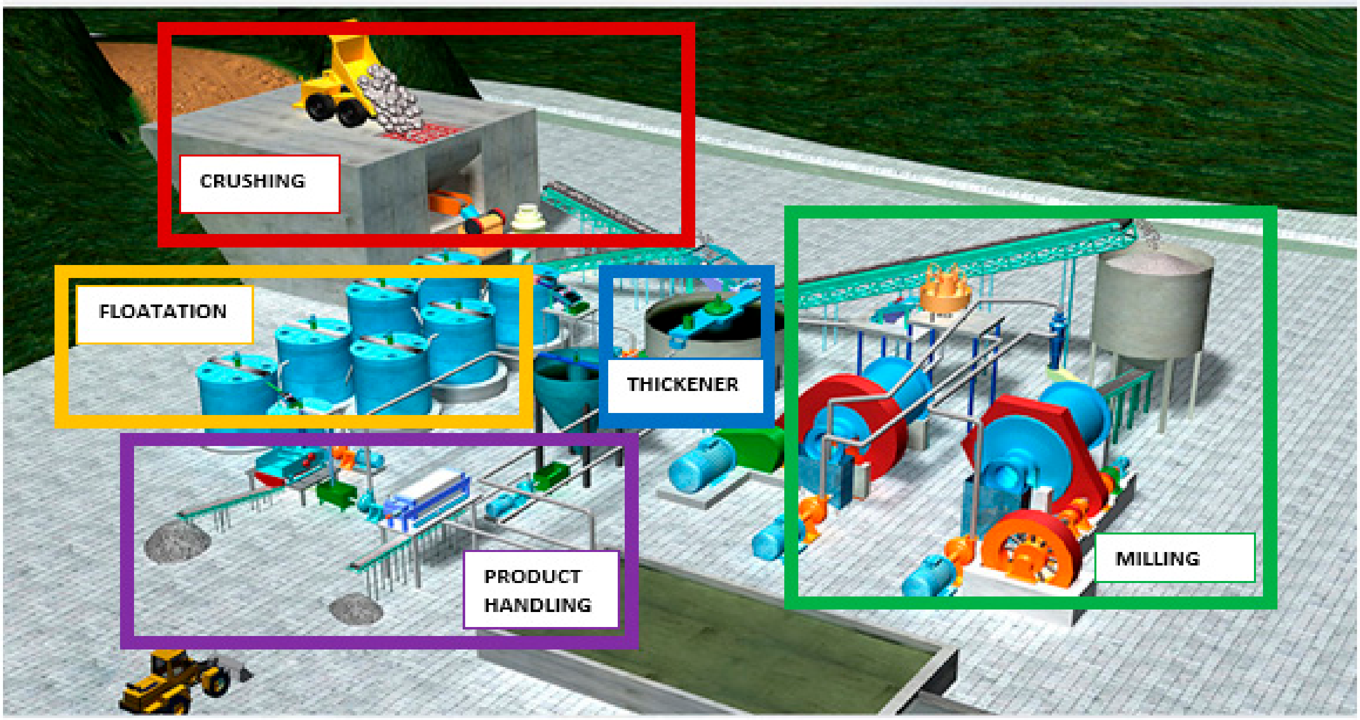


Figure 6. 3D model of a typical mining processing plant [36].

3.2. HOMER PRO Software

The HOMER PRO software is utilized for the proposed system to assess the technical, economic, and environmental aspects for implementing the winning HRES system for the mining companies. HOMER Pro is a powerful software tool used for optimizing and analyzing microgrids, distributed energy resources (DERs), and other renewable energy systems. Developed by HOMER Energy, the software is widely utilized in the fields of energy planning, renewable energy integration, and microgrid design. HOMER Pro enables users to model various energy generation sources, such as solar panels, wind turbines, batteries, and conventional generators, to find the most cost-effective and efficient combination for a given energy project. The software has parameter fine-tuning capabilities to enable researchers and designers to select the feasible and best HRES strategies [37].

The key features of HOMER Pro include:

- Simulation and Optimization: HOMER Pro uses advanced simulation and optimization algorithms to evaluate different system configurations and determine the best combination of energy sources and storage options to meet the specific energy needs while minimizing costs.
- Renewable Energy Integration: It allows users to model and assess the integration of renewable energy sources into existing grids or off-grid systems, taking into account factors like resource availability and grid constraints.
- Financial Analysis: HOMER Pro provides detailed financial analysis tools, helping users assess the economic feasibility of their projects by calculating various financial metrics such as the NPC, IRR, and payback period.
- Load Profiles: Users can input load profiles, electricity demand patterns, and other consumption data to customize simulations and optimize system design for specific applications.
- Sensitivity Analysis: The software allows for sensitivity analysis, enabling users to explore how changes in key parameters (e.g., fuel costs, renewable resource variability) impact the performance and economics of their energy systems.
- Exportable Results: HOMER Pro generates detailed reports and exportable results, making it easier to communicate project findings and results to stakeholders.

- Integration with Geographic Information Systems (GIS): It can be integrated with GIS data to incorporate geographic and spatial information into energy system modeling.

HOMER Pro is widely used by energy professionals, researchers, and organizations to design and analyze renewable energy projects, microgrids, and distributed energy systems, ultimately helping to optimize energy generation, reduce costs, and enhance sustainability.

3.2.1. HRES Components

In the pursuit of a sustainable energy transition, an HRES has been meticulously devised, incorporating the synergy of FPV arrays, wind turbines, and vanadium redox flow batteries for energy storage. This integrated system has been engineered to operate efficiently for a projected lifespan of 20 years. Notably, the choice of interconnection with the Eskom grid, which boasts scheduled electricity rates and monthly net purchase calculations, is deliberate. The Eskom grid serves a dual role, providing power to meet the load demands while absorbing excess energy when available. The pricing structure has been defined, with the grid supplying power at a rate of R 6.42 per kWh on a Megaflex tariff, and the FPV–grid system allowing for power sales back to the grid at a rate of R 1.24 per kWh [38]. Importantly, the grid system has been seamlessly integrated into all facets of simulation and optimization efforts. Furthermore, the emission profiles of the grid have been quantified, with values set at 38,754,240 kg/year for carbon dioxide, 168,017 kg/year for sulfur dioxide, and 82,169 kg/year for nitrogen oxides, as shown in Table 4. These emissions have significant environmental consequences. They contribute to climate change and air pollution, and can harm both ecosystems and human health, hence the need for the proposed HRES for mitigating their negative impacts and promoting a cleaner, healthier environment.

Table 4. Emissions generated by the existing system.

Quantity	Value	Units
Carbon dioxide (CO_2)	38,754,240	kg/year
Sulfur dioxide (SO_2)	168,017	kg/year
Nitrogen oxides (NOx)	82,169	kg/year

This comprehensive approach embodies a strategic commitment to reducing the reliance on conventional energy sources, embracing renewable alternatives, and managing grid interactions with precision. The parameters of electricity pricing, environmental impact, and long-term viability have been intricately balanced to ensure the HRES system's effectiveness in facilitating the transition toward sustainable energy solutions while maintaining economic feasibility for mining companies.

3.2.2. Wind Resources

The Driekop location exhibits favorable wind resources, as evidenced by its average windspeed of 6.08 m per second (m/s) at a height of 100 m above ground level, as shown in Figure 7. This wind speed measurement signifies a robust and consistent wind resource, which is a crucial factor in assessing the suitability of an area for wind energy generation. The relatively high wind speed suggests that the Driekop region has the potential to harness wind energy efficiently. Wind turbines typically require a minimum threshold (3 to 4 m/s) of wind speed to generate electricity effectively, and the measured speed of 6.08 m/s comfortably exceeds that threshold as shown in Figure 7. Therefore, Driekop's wind resource is indeed well suited for wind energy generation, presenting a valuable opportunity to diversify the region's energy mix, enhance energy security, and contribute to renewable energy sustainability while reducing carbon emissions. Wind energy projects in such locations have the potential for a significant positive impact on the local and regional energy landscape while aligning with the broader renewable energy goals. The wind turbine's production of electrical energy can be determined using Equation (1) [39].

$$P_{WTG} = \left[\frac{\rho}{\rho o}\right] P_{WTG,\ STC} \tag{1}$$

where "ρ" stands for the current air density, "ρo" represents the air density under the standard test conditions, and "$P_{WTG,\ STC}$" denotes the wind turbine's power output when assessed under standardized test conditions (STC).

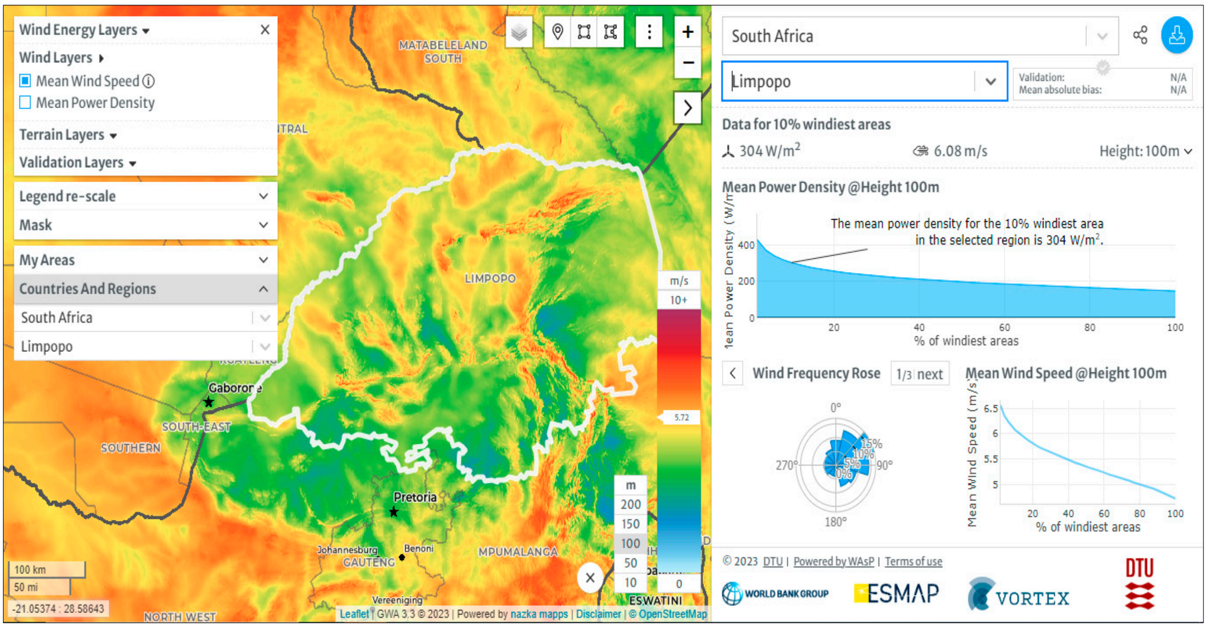


Figure 7. Driekop wind resources.

The HOMER software uses historical and forecasted weather data for the project location, including wind speed patterns over time. In uncertainty, the BESS acts as a crucial buffer by storing excess energy during high wind conditions. During periods of low wind power generation, the stored energy from the BESS is discharged to compensate for the shortfall, ensuring a continuous and stable power supply. This strategy not only mitigates the impact of intermittent wind resources but also contributes to grid stability by smoothing out fluctuations, enhancing system reliability, and providing a reliable power source during unfavorable weather conditions. Additionally, the proposed CMA-ES BESS algorithm proactively adjusts and optimizes the use of stored energy based on the anticipated variations in wind power.

3.3. PVsyst Software Modeling and Solar Resources

The SFPV energy production is a critical component of renewable energy project planning and optimization, and it is accomplished via the utilization of the PVsyst software. PVsyst is a sophisticated and specialized tool designed specifically for the in-depth analysis of photovoltaic systems. This software offers a comprehensive suite of features, allowing for a meticulous assessment of FPV generation potential. PVsyst considers a multitude of factors, including solar irradiance levels, photovoltaic panel efficiency, the shading effects caused by surrounding structures or natural features, and prevailing environmental conditions, such as temperature and humidity. By integrating these parameters into its calculations and simulations, PVsyst provides a highly accurate estimate of FPV energy production. The system supports integration with weather forecasting data to provide short- to long-term predictions of solar radiation. The solar energy during suboptimal conditions is managed by storing surplus energy during periods of optimal sunlight.

The precise evaluation of the FPV energy output is invaluable in several ways. It aids in the optimization of system design by determining the most suitable configuration of solar panels, their orientation, and the choice of equipment. Furthermore, it enables accurate predictions of energy yields, assisting project developers and investors in assessing the economic viability of FPV installations. Additionally, PVsyst helps ensure the efficient utilization of renewable energy resources, facilitating the transition toward sustainable and clean energy generation. In essence, PVsyst plays a pivotal role in informed decision-making for FPV projects, contributing to the overall success and effectiveness of renewable energy initiatives.

The Driekop location is endowed with favorable solar resources, making it an ideal candidate for solar PV energy generation. The region boasts an anticipated annual Global Horizontal Irradiation of 2061 kWh per square meter, signifying abundant sunlight exposure, as shown in Figure 8. Furthermore, the expected specific production of over 1821 kWh per kWp capacity suggests a robust energy yield from solar PV installations. Preliminary yield calculations also indicate a promising capacity factor (CF) of 30%, underlining the efficient utilization of solar energy resources throughout the year. In light of these factors, it is evident that the Driekop area offers optimal conditions for solar PV energy generation, presenting a compelling opportunity to harness renewable energy and contribute to sustainable power generation in the region. The electrical power generated by a solar photovoltaic (PV) array can be calculated using Equation (2).

$$P_{PV} = Y_{PV} F_{PV} \left[\frac{\overline{G_T}}{G_{T,STC}} \right] [1 + \alpha p (T_c - T_{c,\,STC})] \quad (2)$$

where Y_{PV} stands for the solar PV array's rated capacity, while F_{PV} represents the derating factor of the solar PV array. $\overline{G_T}$ and $G_{T,STC}$ denote the amount of sunlight hitting the array under current conditions and during standard test conditions, respectively. Additionally, αp, T_c, and $T_{c,\,STC}$ refer to the temperature coefficient, solar cell temperature during current conditions, and the solar cell temperature during standard test conditions, respectively.

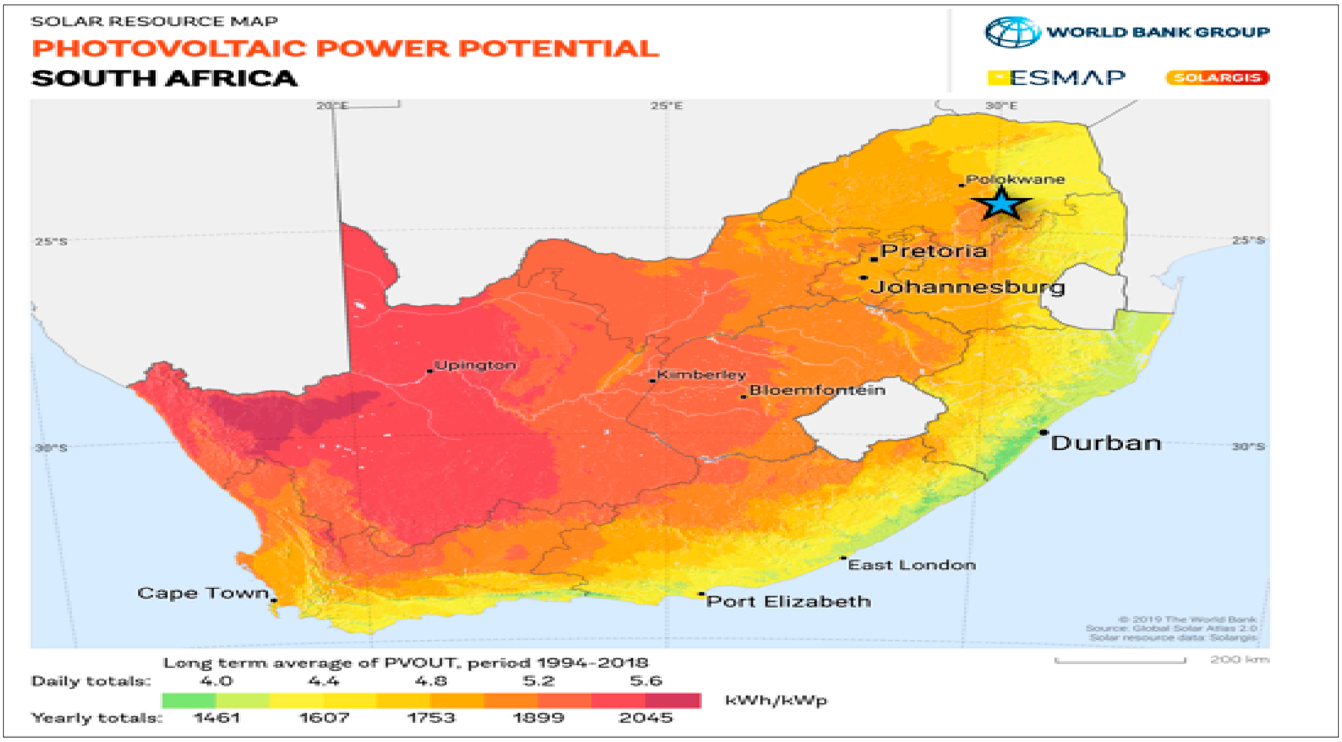


Figure 8. Driekop solar resources [40].

3.4. MATLAB Software Modeling

The MATLAB software serves as a pivotal tool in the configuration and integration of the innovative BESS dispatch strategy, called the CMA-ES, within the broader HRES model for comprehensive optimization. This utilization of MATLAB facilitates a multi-faceted evaluation, encompassing performance assessment, techno-economic analysis, and environmental impact assessment, with a particular focus on carbon emission reduction.

The configurability and flexibility of MATLAB empowers engineers and researchers to fine-tune and refine the BESS dispatch strategy, optimizing its performance within the context of the HRES. This dynamic approach ensures the efficient utilization of energy resources, thus contributing to the economic feasibility and sustainability of the entire system. Furthermore, MATLAB enables a rigorous techno-economic analysis, allowing stakeholders to assess the financial viability and potential return on investment for the proposed HRES model, critical considerations in the transition to renewable energy systems.

Crucially, MATLAB aids in the environmental assessment aspect by providing tools to quantitatively analyze the reduction in carbon emissions achieved by the integrated HRES. This comprehensive evaluation is instrumental in demonstrating the environmental benefits of the renewable energy solution, aligning with broader sustainability goals and regulatory requirements. In essence, MATLAB's versatility and computational capabilities play an indispensable role in the holistic evaluation of the proposed HRES model, supporting informed decision-making in the pursuit of clean and efficient energy solutions.

CMA-ES Algorithm

The Covariance Matrix Adaptation Evolution Strategy (CMA-ES) is an advanced evolutionary algorithm designed for optimizing complex, high-dimensional, and non-linear problems. It operates by iteratively improving a population of candidate solutions to find the optimal solution. CMA-ES starts with an initial guess at the solution, represented by a mean vector (μ), and a covariance matrix (C) that captures the relationships between variables. In each iteration, a population of candidate solutions is sampled from a multivariate normal distribution with parameters μ and C. These candidates are then evaluated using the objective function. The top-performing solutions are selected, and their information is used to update μ, C, and the other algorithm parameters, such as the step size σ. This adaptation process allows CMA-ES to effectively explore and exploit the search space, gradually converging toward an optimal solution. By automatically adjusting the search distribution based on the problem's characteristics, CMA-ES excels at solving complex optimization problems without requiring prior knowledge of the objective function's shape or properties [41].

CMA-ES maintains a delicate balance between exploration and exploitation. The covariance matrix C plays a crucial role in adapting the search distribution. When successful candidate solutions spread out in the search space, C enlarges to encourage exploration. Conversely, when candidates converge toward promising regions, C contracts to favor exploitation. The mean vector μ evolves toward better solutions based on the fitness of the selected candidates. This adaptive mechanism allows CMA-ES to efficiently navigate complex landscapes with multiple local optima, making it suitable for a wide range of applications, including parameter tuning in machine learning, structural optimization in engineering, and many other fields. Researchers and practitioners often customize CMA-ES by adjusting its parameters to tackle specific optimization challenges, ensuring its versatility and effectiveness across various domains.

CMA-ES is an exceptionally well-suited algorithm for VRF-BESS dispatch optimization for several compelling reasons. First and foremost, CMA-ES excels in high-dimensional and non-linear optimization problems, which are common characteristics of BESS dispatch optimization. BESS systems often involve numerous decision variables, including charging and discharging rates, state-of-charge (SoC) limits, and time intervals for decisions. CMA-ES can efficiently explore this high-dimensional solution space, adapt its search distribution to navigate complex landscapes, and converge to optimal solutions without requiring explicit knowledge of the problem's mathematical structure. Furthermore, CMA-ES offers adaptability and robustness, two critical attributes in BESS dispatch. Energy management scenarios can change rapidly due to fluctuations in energy prices, grid conditions, and renewable energy availability. CMA-ES's ability to dynamically adjust the search distribution via its covariance matrix adaptation allows it to respond effectively to evolving conditions [42]. It can balance the trade-off between exploration and exploitation, ensuring that the BESS dispatch strategy remains efficient and effective under various circumstances. CMA-ES stands out as the best algorithm for BESS energy dispatch optimization due to its capacity to handle high-dimensional, non-linear problems, adaptability to changing energy landscapes, and efficient exploration–exploitation balance. It enables BESS systems to make data-driven, real-time decisions that optimize energy usage, reduce costs, enhance grid stability, and facilitate the integration of renewable energy sources, all of which are critical in today's dynamic and sustainable energy environments.

3.5. Financial and Economic Metrics

Financial and economic metrics such as the NPC, IRR, LCoE, and BCoE are indispensable tools in investment and project evaluation [43]. They aid decision-makers in determining the project viability, assessing risks, allocating capital efficiently, and optimizing resource allocation. These metrics are vital for budgeting, monitoring project performance, and facilitating transparent communication with stakeholders. They also enable comparative analysis, ensuring the selection of the most favorable investment opportunities and compliance with regulatory standards. Ultimately, financial, and economic metrics contribute to informed decision-making, financial sustainability, and long-term success across various sectors and industries.

3.5.1. NPC

The NPC represents the total cost of the project over its lifetime, including capital costs (CapEx), operating and maintenance expenses, and any other relevant costs (OpEx), all adjusted for the time value of money. The NPC is crucial for assessing the total financial commitment required for a renewable energy project. It allows decision-makers to understand the comprehensive costs involved over the project's lifetime, aiding in budgeting, resource allocation, and financial planning. By considering the time value for money, it provides a realistic view of the project's financial impact. The NPC can be determined using Equation (3) [43]:

$$NPC = \Sigma\left[(Ct + OMt)/(1+r)^t\right] \tag{3}$$

where:

NPC = Net present cost
Ct = CapEx at time t
OMt = OpEx at time t
r = Discount rate (usually the CapEx)
t = Time period

3.5.2. IRR

The IRR is a financial metric that indicates the discount rate at which the NPC of cash flows from a renewable energy project becomes zero. In other words, it represents the project's rate of return. The IRR is a vital metric for assessing the financial attractiveness of a renewable energy project. It helps determine whether the project's expected return on investment meets or exceeds the required rate of return or cost of capital. A higher IRR indicates a more financially appealing project, while a lower IRR may suggest potential financial challenges. The IRR is determined using Equation (4) [43]:

$$0 = \Sigma\left[(CFt - OMt)/(1+IRR)^t\right] - Ct \tag{4}$$

where:

0 = represents the condition that the NPC of cash flows is zero at the IRR.
Σ = denotes the summation over time periods from t = 1 to some final time period.
CFt = represents the cash at time t, which includes revenues or savings and expenses.
OMt = OpEx at time t.
Ct = CapEx at t = 0.

3.5.3. LCoE

The Levelized Cost of Energy (LCoE) is the per-unit cost of generating electricity from a renewable energy project over its lifetime. It includes all costs (capital, operating, and maintenance) and is expressed in terms of dollars per megawatt-hour (MWh) or kilowatt-hour (kWh). The LCoE is a crucial metric for comparing the cost competitiveness of renewable energy technologies and projects. It allows decision-makers to assess the economic feasibility of different energy sources and technologies, making it easier to select the most cost-effective option and promote renewable energy adoption. The LCoE is determined using Equation (5) [43]:

$$LCoE = (NPC/E) \tag{5}$$

where:

LCoE = Levelized Cost of Energy
NPC = Net present cost
E = Total energy generated over the project's lifetime

3.5.4. BCoE

The BCoE is a variation of the LCoE that takes into account the costs of multiple renewable energy sources integrated into a hybrid system. It calculates the cost per unit of electricity generated when two or more renewable sources are combined. The BCoE provides insights into the overall cost-effectiveness of the system. It helps evaluate the synergy and trade-offs between different components, allowing for the optimization of the hybrid system's design and operation. The BCoE is computed using Equation (6) [43]:

$$BCoE = (\Sigma(NPCi)/\Sigma(Ei)) \tag{6}$$

where:

BCoE = Blended Cost of Energy
NPCi = Net present cost of each energy source/component
Ei = Total energy generated by each energy source/component

3.5.5. Payback Time

Payback time, often referred to as the payback period, is a financial metric used to determine the timeframe in which an investment or project is expected to generate sufficient cash flows to recover its initial capital outlay or investment cost. Typically measured in years, the payback time signifies the duration required for the cumulative cash inflows, which may include profits, savings, or revenues, to equal or exceed the initial cash investment. This metric is valuable for assessing the risk associated with an investment, prioritizing projects, and making informed decisions about resource allocation. A shorter payback time indicates a quicker return on investment, which can enhance liquidity, reduce risk exposure, and bolster investor confidence, making it an essential tool in financial analysis and project evaluation. The payback time is determined using Equation (7) [43]:

$$Payback\ Time = \frac{Initial\ capital\ investment}{Total\ savings\ per\ year} \tag{7}$$

3.6. Environmental Analysis

Employing an HRES to diminish the carbon footprint in the mining sector, in lieu of relying solely on Eskom's coal-fired power station grid, is a vital step toward meeting global emission targets. The environmental assessment for this transition will employ a comprehensive methodology to gauge the feasibility and environmental impacts. Initially, a meticulous baseline assessment will quantify the mining operation's existing carbon emissions, encompassing energy consumption and emissions sources, and contrast it with the emissions associated with Eskom's coal-fired grid electricity. Subsequent to this baseline, a feasibility study will assess the suitability of integrating renewable energy sources such as solar, wind, and energy storage systems into the mining infrastructure. This assessment will include an economic analysis to ensure its cost-effectiveness and financial viability. An environmental impact assessment will evaluate the potential benefits, such as significant reductions in greenhouse gas emissions and reduced air and water pollution, while also considering potential drawbacks related to land use, habitat disruption, and resource extraction. Furthermore, a lifecycle analysis will scrutinize the overall sustainability of the HRES, considering factors such as the environmental impact of the manufacturing, deployment, and decommissioning of renewable energy equipment. Ongoing stakeholder engagement, compliance with environmental regulations, and robust monitoring and reporting mechanisms will be integrated throughout the implementation to guarantee the project's success. By transitioning to HRESs in the mining sector, we not only curtail carbon emissions but also endorse more environmentally responsible mining practices that align with global emissions reduction goals while reducing the dependency on coal-fired power stations like Eskom.

Recommendations being provided for the optimal HRES solution in the mining sector is essential to benefit mines, energy specialists, and the broader engineering research community. A well-informed winning solution should encompass customized feasibility studies, system designs tailored to specific mining operations, integration of energy storage, and a focus on efficiency optimization. It is crucial to prioritize environmental impact mitigation and reliability in HRES implementation. Knowledge sharing and educational initiatives will empower mine personnel, while adherence to regulatory compliance and the exploration of financial incentives can facilitate the transition. Ongoing research and development efforts are pivotal, fostering innovation and collaboration within the field of engineering as a whole, ultimately driving the successful adoption of HRES in mining.

3.7. Reliability Analysis Using the LPSP Approach

Loss of Power Supply Probability (LPSP) is a pivotal metric in the domain of power systems and reliability analysis, quantifying the likelihood of a power system or its components experiencing a disruption in electrical supply. This parameter is instrumental for engineers, planners, and operators as it provides a quantitative measure of the system's robustness and resilience. Loss of Power Supply Probability (LPSP) serves as a fundamental metric for assessing the adequacy of hybrid energy systems in meeting energy demands [44].

This probability, ranging from 0 to 1, provides a quantitative measure of the system's reliability in fulfilling energy requirements. A lower LPSP value, closer to 0, signifies a higher probability that the energy supply from the hybrid system will meet or exceed the energy demand. In contrast, as the LPSP approaches 1, there is an increased likelihood that the energy supply falls short of satisfying the energy demand. Mathematically, this relationship can be expressed using Equation (8) [45]:

$$LPSP - 1 - \frac{Energy\ Supply}{Energy\ Demand} \tag{8}$$

The LPSP is derived by subtracting the ratio of the actual energy supply to the energy demand from 1. When the LPSP equals 0, it indicates a perfect match between energy supply and demand, reflecting a scenario where the system reliably meets all energy requirements.

Conversely, an LPSP of 1 signals a complete mismatch, implying that the energy supply fails to meet the energy demand. This mathematical representation underlines the critical role LPSP plays in quantifying the reliability and adequacy of hybrid energy systems, providing a robust analytical tool for engineers and planners to optimize system design and operation for enhanced performance.

The LPSP also assesses the likelihood of a disruption in electrical supply within this integrated framework, encompassing the intricate interactions and dependencies among the diverse components. This can be determined using Equation (9) [46]:

$$LPSP - 1 - \Pi_{i-1}^{n}(1 - P_i) \quad (9)$$

where $LPSP$ denotes the Loss of Power Supply Probability, n represents the number of independent failure events, and P_i signifies the probability of the ith failure event. This formula enables a comprehensive evaluation by considering the combined impact of various factors, including the reliability of SFPV modules, the WT, BESS components, and their associated control systems.

To delve into the specifics of a hybrid RES, each constituent element's LPSP can be delineated with more granularity. For instance, the LPSP of the solar PV subsystem ($LPSP_{PV}$) can be modeled as [46]:

$$LPSP_{PV} - 1 - \left(1 - P_{PV}\right)^{N_{PV}} \quad (10)$$

where P_{PV} represents the probability of module failure, and N_{PV} denotes the number of PV modules in the system. Similarly, the LPSP for the wind turbine subsystem ($LPSP_{WT}$) can be expressed using Equation (11) [46]:

$$LPSP_{WT} - 1 - \left(1 - P_{WT}\right)^{N_{WT}} \quad (11)$$

where P_{WT} denotes the probability of a generator failure, and N_{WT} is the number of wind turbines. Analogously, the LPSP for the BESS ($LPSP_{BESS}$) may be defined as Equation (12) [46]:

$$LPSP_{BESS} - 1 - \left(1 - P_{BESS}\right)^{N_{BESS}} \quad (12)$$

Here, P_{BESS} captures the failure probability of the storage system, and N_{BESS} represents the number of BESS units. The overall LPSP for the hybrid RES then integrates these individual probabilities using the overarching formula. The overall LPSP of the hybrid RES is then determined by the joint probability of these independent failure events.

The comprehensive methodology for testing the proposed HRES unfolds in a series of interconnected steps. Commencing with data acquisition and monitoring, real-time performance data are meticulously collected from each renewable energy source, concurrently monitoring system parameters and documenting any failure or outage events via the utilization of the HOMER, PVsyst, and MATLAB software. Subsequently, the focus shifts to reliability assessment and modeling, where the failure probabilities of individual components, considering factors such as module degradation rates, generator failure probabilities, and the reliability of the BESS, are meticulously assessed. This leads to the subsequent stage of failure probability assessment, where the failure probability of each component is determined based on historical performance data and known failure modes. Moving forward, LPSP calculation and analysis ensue, employing the ascertained failure probabilities to quantify the overall LPSP. This stage incorporates the intricate integration of mathematical models to account for the interdependence of components within the HRES. The final stride involves LPSP results and interpretation, encompassing a comprehensive understanding of the implications for the HRES. This step culminates in the identification of specific areas requiring improvement in either system design or maintenance practices, thereby enhancing the overall resilience and efficiency of the hybrid energy system.

4. System Setup

This section will provide the system setup and specification of the proposed HRES for the techno-economic feasibility study.

4.1. Proposed SFPV System

In this study, the distinct type of PV panel known as the JA Solar JAM72S30 525-550W-MR flat plate module is used. These panels are characterized by their 550 W rated capacity, impressive 21.1% efficiency, and a specified operational lifespan of 25 years. Notably, these PV panels exhibit a degradation factor (DF) of 90%, indicating a gradual performance decrease over time, and possess a nominal operating cell temperature (NOCT) of 45 degrees Celsius. A distinctive aspect of these panels is their fixed horizontal installation at a 20-degree slope, with the absence of a maximum power point tracking system, signifying their operation without dynamic power optimization in response to varying environmental conditions.

These panels will be installed in a return water dam using a floating system in a fixed tilt configuration. The installation of the PV panels within the mine return water dam presents several advantages, primarily centered around land reuse and environmental benefits. By repurposing the dam for PV panel deployment, we can optimize the land utilization and minimize the need for additional space, thereby reducing the environmental footprint. This dual-purpose approach enables us to harness solar energy efficiently while concurrently utilizing previously disturbed or otherwise underutilized land, promoting sustainability and responsible land management within the mining facility. Table 5 demonstrates the FPV system design data.

Table 5. SFPV system specification.

Parameters	Value
Nominal DC capacity at STC (kWP)	5500
DC/AC nominal ratio	1.29
PV module specification	JA Solar JAM72S30 525-550W-MR
Number of PV modules	10,000
Number of modules per string	25
Number of strings	400
Inverter specification	Growatt MAX250KTL-3 HV
Number of inverters	17
PV structure type	FPV fixed tilt
Tracking angle	20
Backtracking control	Yes
Pitch (distance between row centers)	5.5
Ground coverage ratio	41%
Ground albedo	0.2
Inverter power factor	0.99

4.2. Proposed WT System

The wind turbine, known as the ELKRAFT Avedøre 1000 model, is able to produce enough power from wind motion to meet the load requirements, whether during the daytime or nighttime. This particular turbine has a rated capacity of 1000 kW, a hub height of 80 m, and an expected operational lifespan of 20 years. Table 6 shows the specification of the proposed WT.

Table 6. WT system specification.

Parameters	Value
Supplier	ELKRAFT Avedøre
Model	Avedøre-1000
Rated power output	1 MW
Rotor diameter	70 m
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Rated wind speed	6 m/s
Rotor number of blades	3
Blade length	35 m
Type	Turbula Steel Tower
Hub height	80 m
Rated voltage	690 Vac
Frequency	50 Hz
Efficiency	30–40%
Swept area	3848 square meters

4.3. BESS and CMA-ES Dispatch Algorithm

4.3.1. BESS

The 1 MW/4 MWh BESS with 0.25 C vanadium redox flow (VRF) batteries is employed to efficiently store energy the generated by the HRES. This stored energy can then be strategically dispatched to power the mine, especially during periods of load curtailment or power outages. The VRF batteries are selected because of their benefits, such as:

- Long Cycle Life: VRFBs have a long cycle life, typically exceeding 10,000 charge–discharge cycles. This makes them a durable and reliable energy storage solution for long-term applications.
- Scalability: VRFBs are highly scalable, allowing for easy adjustment of their capacity by simply increasing or decreasing the size of the electrolyte tanks. This scalability makes them suitable for a wide range of applications, from small-scale residential systems to large utility-scale installations.
- Deep Discharge Capability: VRFBs can be discharged to very low states of charge without causing damage to the battery. This deep discharge capability ensures that a significant portion of the stored energy can be utilized.
- Safety: VRFBs are considered to be relatively safe due to their non-flammable and non-toxic vanadium electrolyte. They do not pose the same fire and safety risks as some other battery chemistries.
- High Efficiency: VRFBs can achieve high round-trip efficiency, often exceeding 80%. This means that the energy stored in the battery can be efficiently retrieved when needed.
- Fast Response Time: VRFBs have a fast response time, making them suitable for applications requiring rapid changes in power output or frequency regulation, such as grid stabilization.
- Low Self-Discharge: VRFBs have a low self-discharge rate, which means that they can store energy for extended periods without significant loss.
- Maintenance-Friendly: VRFBs are relatively easy to maintain. The electrolyte can be replaced without affecting the rest of the battery components, extending the system's life.
- Environmental Friendliness: Vanadium is abundant, and VRFBs are considered more environmentally friendly than some other battery chemistries due to the recyclability of the vanadium electrolyte.
- Decoupled Energy and Power: VRFBs have a unique advantage in that their energy storage capacity and power output can be independently scaled. This flexibility allows for the optimization of energy and power delivery based on specific application requirements.

- Long Shelf Life: VRFBs can have a long shelf life, making them suitable for backup power applications where the battery may sit idle for extended periods before being used.

Table 7 below presents the key design data for the VRF-BESS:

Table 7. BESS design specification.

Parameters	Value
BESS Capacity	4000 kWh (4 MWh)
Rated Power Output	1000 kW (1 MW)
Battery Type	0.25 C VRF
Battery Chemistry	Vanadium Redox Flow
Efficiency (Round-Trip)	Up to 95%
Operating Temperature Range	−20 °C to 50 °C
Voltage Range (DC)	400 V–800 V
Cycle Life	>5000 cycles (80% DoD)
Response Time	<20 ms
Grid Ancillary Service Support	Yes
Frequency Regulation Support	Yes
Voltage Support	Yes

4.3.2. CMA-ES Algorithm Design

The battery energy benefit during the charge time Δt1 can be calculated by considering the change in the state of charge (SoC) of the battery over that time period. The energy benefit is essentially the difference between the energy stored in the battery at the end of Δt1 and the energy stored at the beginning of Δt1. This can be expressed using Equation (13):

$$\Delta E\_benefit(\Delta t1) = E\_b(\Delta t1) - E\_b(0) \tag{13}$$

where:

$\Delta E\_benefit(\Delta t1)$ is the energy benefit during the charge time Δt1.
$E\_b(\Delta t1)$ is the energy stored in the battery at the end of Δt1.
$E\_b(0)$ is the energy stored in the battery at the beginning of Δt1.

The energy stored in the battery at any time (E_b) can be calculated as the integral of the power flowing into or out of the battery over time. Assuming $Pcharger(t)$ represents the power being supplied to charge the battery, and $Pp(t)$, $Pw(t)$, and $PL(t)$ represent the power from the PV, wind, and load, respectively, the energy stored in the battery can be computed using Equation (14):

$$E\_b(t) = \int [0,\ t]\ (Pcharger(\tau) - (Pp(\tau) + Pw(\tau) - PL(\tau)))\ d\tau \tag{14}$$

Now, to calculate the energy benefit during Δt1, the equation is integrated over the time interval $[0,\ \Delta t1]$:

$$\Delta E\_benefit(\Delta t1) = \int [0,\ \Delta t1]\ (Pcharger(\tau) - (Pp(\tau) + Pw(\tau) - PL(\tau)))\ d\tau \tag{15}$$

This shall provide the energy benefit during the charge time $\Delta t1$, taking into account the power supplied by the charger, the power from PV and wind, and the load power over that time interval.

Determining the SoC of a battery is essential for the safe management of its charging and discharging processes. Accurately estimating the SoC is crucial in safeguarding the battery against potential issues like overcharging and deep discharging, which, in turn, promotes a longer lifespan for the battery. The SoC is carefully regulated to remain within a specified range:

$$SoCmin \leq SoC \leq SoCmax$$

The battery's state of charge, denoted as SoC, must be maintained between a lower limit known as $SoCmin$ and an upper limit referred to as $SoCmax$.

As illustrated in Figure 9, the CMA-ES BESS dispatch algorithm is integrated with the power management system, which monitors various parameters, including the grid power, PV power, WT power, load demand, and the state of charge of the BESS. In cases where the grid power falls short of meeting the load demand (resulting in a load curtailed condition), the algorithm will initiate the dispatch of energy from the hybrid renewable energy system (HRES) while assuming favorable conditions such as solar and wind energy availability. Simultaneously, the battery will be charged. In situations where the power generated by the HRES is insufficient to meet the load demand, a strategic energy dispatch operation from the BESS will be employed to ensure a balanced match between the energy supply and the load requirement.

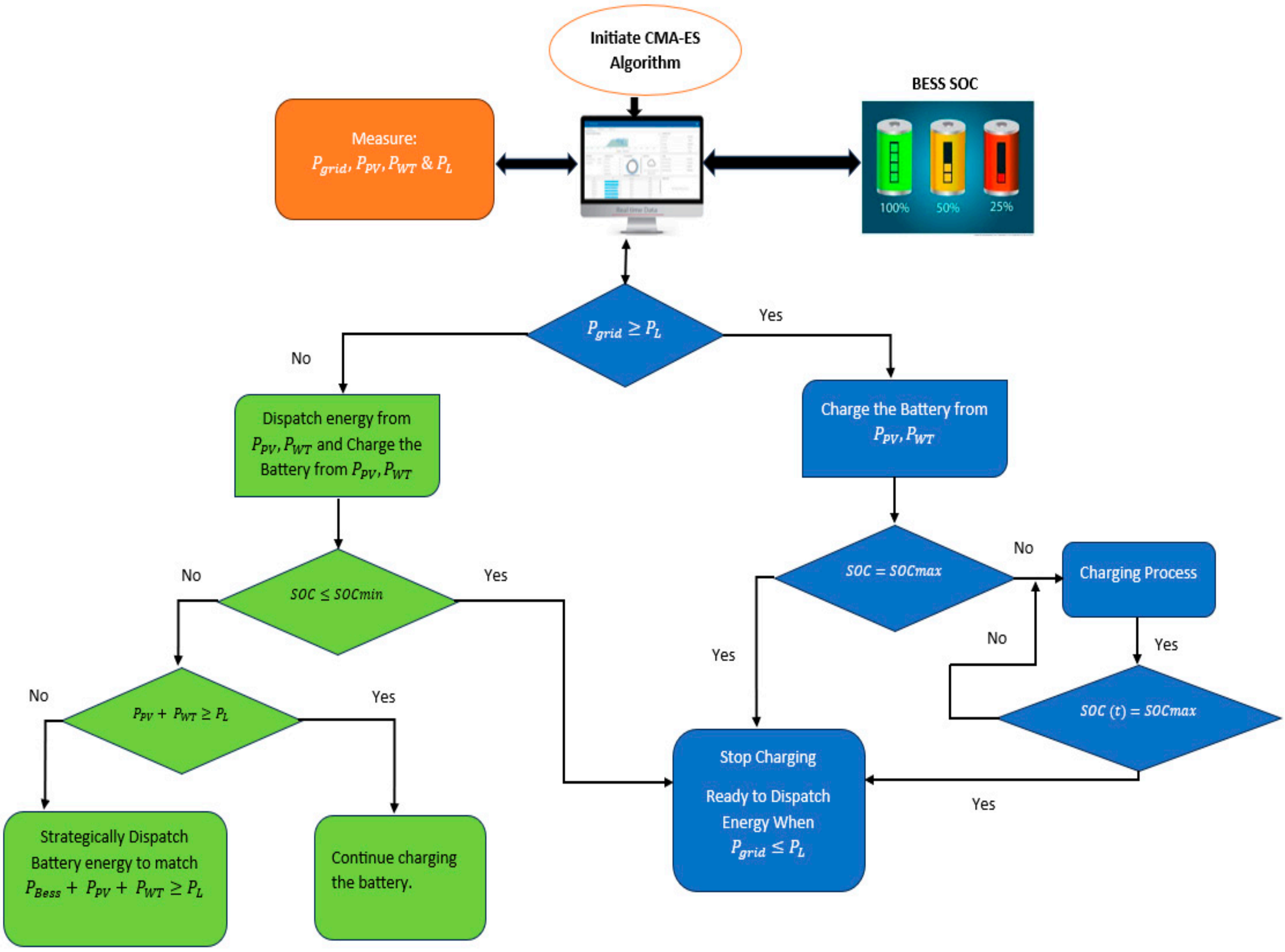


Figure 9. CMA-ES BESS dispatch algorithm functional flow diagram.

In the optimization study, the proposed CMA-ES hyperparameters were carefully chosen, as shown in Table 8. A population size (λ) of 32 individuals was utilized in each generation, ensuring a balance between the exploration and exploitation of the search space. By selecting a parent fraction (μ) of 10, the top-performing 10 individuals were employed as parents for the subsequent generation, promoting the convergence of the algorithm. The initial mean (μ_0) was determined based on the problem's characteristics, ensuring the algorithm commenced its search from an informed starting point. Additionally, the initial covariance matrix (C_0) was configured as a diagonal matrix with small values to establish a conservative exploration space. The step size (σ) was set to 0.2, effectively controlling the magnitude of steps taken during the search. To facilitate a well-structured and resource-efficient optimization process, stopping criteria that included a maximum of 10,000 function evaluations were introduced. The termination criteria dictated that the optimization process would cease if the best fitness value remained stagnant for 500 consecutive iterations. To denote algorithmic convergence, a condition was imposed, requiring the step size (σ) to fall below 0.001. The selection of these values was motivated by the need to strike a balance between exploration and exploitation, ensure sufficient computational resources, and achieve convergence within reasonable timeframes, thus promoting the effective and efficient optimization of complex problems.

Table 8. CMA-ESS BESS dispatch algorithm specification.

Hyperparameter	Description	Selected Value
Population Size (λ)	Number of candidate solutions in each generation	32
Parent Fraction (μ)	Number of top-performing individuals as parents	10
Initial Mean (μ_0)	Initial guess for the mean of the distribution	Randomly generated based on the problem
Step Size (σ)	Standard deviation of the normal distribution	0.3
Convergence Thresholds	Criteria for convergence of the algorithm	Convergence of step size (σ) below 0.001
Restart Strategies	Strategies for escaping local optima	σ-self-adaptation
Covariance Update Parameters	Parameters for covariance matrix adaptation	Learning rates
Stopping Criteria	Termination condition(s) for stopping the algorithm	Max. function evaluations: 10,000

4.4. Eskom Grid Parameters

The Eskom power grid infrastructure described in Table 9 comprises a generation capacity of 10 MVA, operating at a transmission voltage level of 132 kV and distributing electricity at 11 kV. The system adheres to a standard grid frequency of 50 Hz. Spanning a length of 20 km, this transmission network encounters challenges in terms of grid reliability, characterized by low uptime and frequent grid interruptions. Such disruptions, given the documented frequency, can result in adverse consequences on the stability and continuity of power supply. Therefore, mitigating strategies and investments in HRESs and redundancy are pivotal to ensure the consistent delivery of electricity services in the face of such reliability issues. These conditions emphasize the importance of the design and implementation of an HRES with an intelligent BESS dispatch algorithm to reduce interruptions, ultimately providing a more dependable power supply for consumers and industries.

Table 9. Eskom grid parameters.

Parameters	Value
Generation Capacity	10 MVA
Transmission Voltage Levels	132 kV
Distribution Voltage Levels	11 kV
Grid Frequency	50 Hz
Transmission Line Length	20 km
Grid Reliability	Low uptime
Grid Interruptions	Often

5. Results and Discussion

5.1. Optimization Results—HOMER Pro

The research employed the use of the HOMER Pro software to facilitate the optimal sizing of components, as illustrated in Figure 10, for the proposed HRES microgrid. In the ensuing discussion, the performance of the HRES is thoroughly examined, encompassing a comprehensive analysis of the economic indicators and environmental impact. Additionally, the study provides insightful recommendations pertaining to NERSA applications and grid compliance, underscoring the significance of aligning the microgrid project with regulatory standards and sustainable energy practices. This multifaceted evaluation not only offers an in-depth understanding of the HRES's operational efficiency and cost-effectiveness but also underscores its crucial role in advancing renewable energy integration within the broader energy landscape.

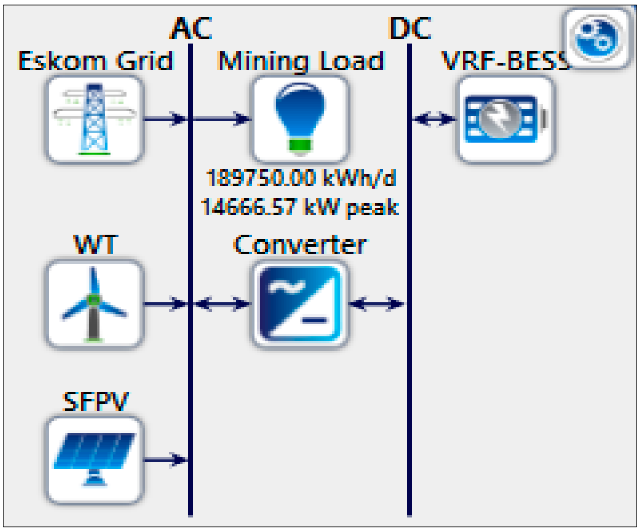


Figure 10. Proposed HRES in HOMER Pro.

5.2. SFPV Performance—PVsyst

The performance results for the SFPV system its demonstrate robust and efficient operation throughout the year. With a performance ratio (PR) of 0.855 per year depicted in Figure 11, the system maintains a high level of efficiency, indicating that it effectively converts incident solar energy into electricity. The system's total annual energy production is substantial, generating 15,835 MWh (megawatt-hours), which is a significant contribution to the energy supply.

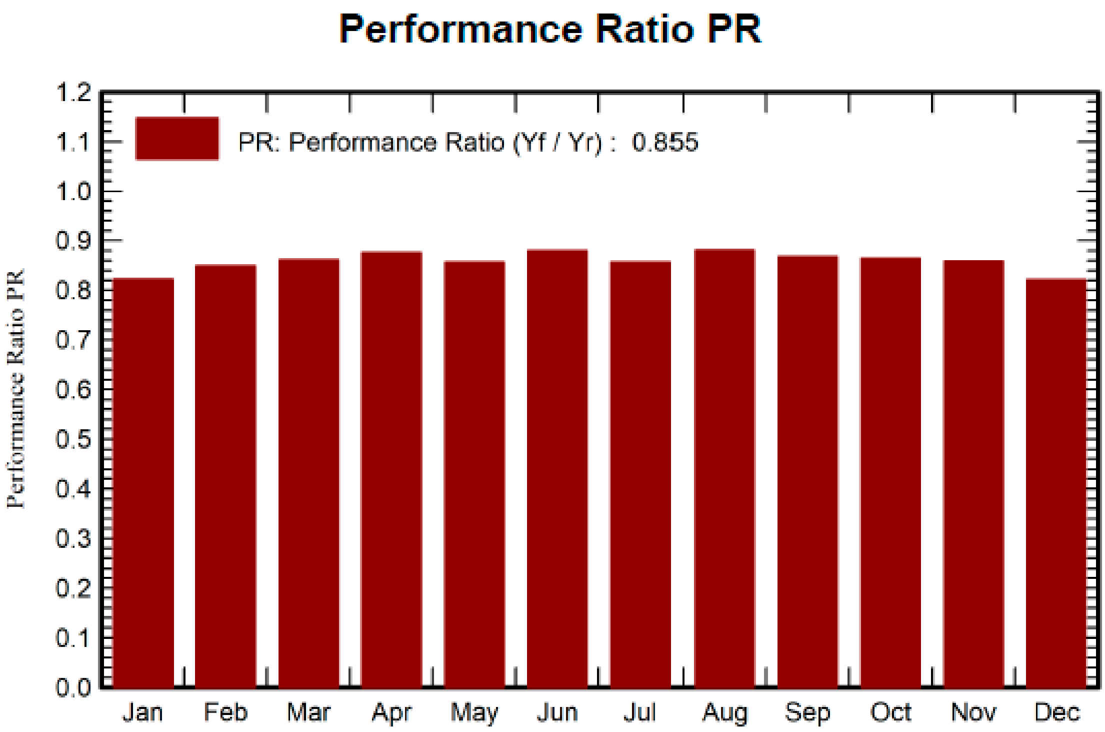


Figure 11. SFPV performance ratio.

The annual solar irradiance values provide further insights into the system's performance. The Global Horizontal Irradiance (GlobHor) is 2257 kWh/m^2 per year, showcasing the consistent availability of solar energy in the region where the PV system is installed. The Diffuse Horizontal Irradiance (DiffHor) at 560 kWh/m^2 per year suggests that even in less optimal lighting conditions, the system continues to capture and convert a substantial amount of solar energy. Moreover, the Global Incident Solar Energy (GlobInc) at 2980 kWh/m^2 per year and Global Efficiency (GlobEff) at 2840 kWh/m^2 per year indicate the system's ability to effectively harness the available solar resources, with only a minimal loss during the energy conversion process. This high efficiency contributes to the impressive energy output mentioned earlier.

In summary, these results suggest that the proposed FPV is performing admirably, efficiently converting solar energy into electricity with a PR of 0.855 and an annual energy production of 15,835 MWh, as shown in Table 10. The consistency in the solar irradiance values further underscores its reliability and effectiveness, making it a valuable and sustainable source of clean energy in the region. These findings could be instrumental in evaluating the system's long-term economic and environmental benefits and potentially inform decisions for expanding or replicating similar solar PV installations in the future.

Table 10. FPV normalized performance.

Month	GlobHor kWh/m^2	DiffHor kWh/m^2	T_Amb °C	GlobInc kWh/m^2	GlobEff kWh/m^2	EArray MWh	PR Ratio
January	241	73	23	310	297	1623	0.83
February	207	56	23	271	260	1419	0.85
March	119.2	56	22	260	249	1380	0.86
April	165.5	37	19	220	211	1187	0.87
May	147.2	29	17	200	190	1084	0.86
June	128	21	14	180	168	971	0.88
July	139	24	14	193	185	1050	0.86
August	166	26	16	226	216	1024	0.88
September	185	42	19	243	233	1304	0.87
October	214	60	21	278	266	1479	0.86
November	223	71	21	287	175	1520	0.86
December	238	67	21	307	294	1610	0.82
Per Year	2257	560	19	2980	2840	158,280	0.855

The presented yield statistics in Figure 12, including a P50 yield of 15,280 MWh, P90 yield of 14,876 MWh, and P95 yield of 14,763 MWh, offer valuable insights into the expected energy production from a given system under varying scenarios. These metrics are essential in risk assessment and financial modeling for renewable energy projects. The P50 yield represents the median or most likely annual energy production, which can serve as a basis for revenue projections and financial planning. The P90 yield, on the other hand, represents a more conservative estimate, indicating that there is a 10% probability of achieving a higher energy production than this value. Finally, the P95 yield reflects a more extreme case, with a 5% probability of exceeding this production level. These figures are crucial for project developers, investors, and other stakeholders in quantifying the potential variability and risks associated with energy generation, thus aiding in making informed decisions regarding resource allocation, revenue expectations, and risk management in the context of renewable energy projects.

5.3. WT Performance Metrix

Table 11 demonstrates the operational and performance metrics of a wind power generation facility to glean insights into its efficiency and productivity. The mean output of 19,701 kW conveys the average electricity generation capacity of the facility, while the capacity factor of 26% reveals that it is operating at its optimal maximum capacity, indicative of significantly high performance. The total annual production of 172,580,718 kWh reflects the aggregate energy output over the course of a year, which is contingent on the capacity factor and the hours of operation. The wind turbine's maximum output capacity, standing at 134,870 kW, underscores its significant potential to harness and contribute substantial electricity to the grid, signifying its pivotal role in bolstering renewable energy generation, as depicted in Figure 13. Furthermore, with a wind penetration of 25% and 2977 h of operation per year, this wind power generation facility demonstrates a commendable contribution to the overall energy mix while maintaining sufficient availability for the BESS during the year, signifying its potential to offer reliable and sustainable power generation. This balance of wind energy integration and operational duration is a promising model for achieving a resilient and consistent supply of renewable energy.

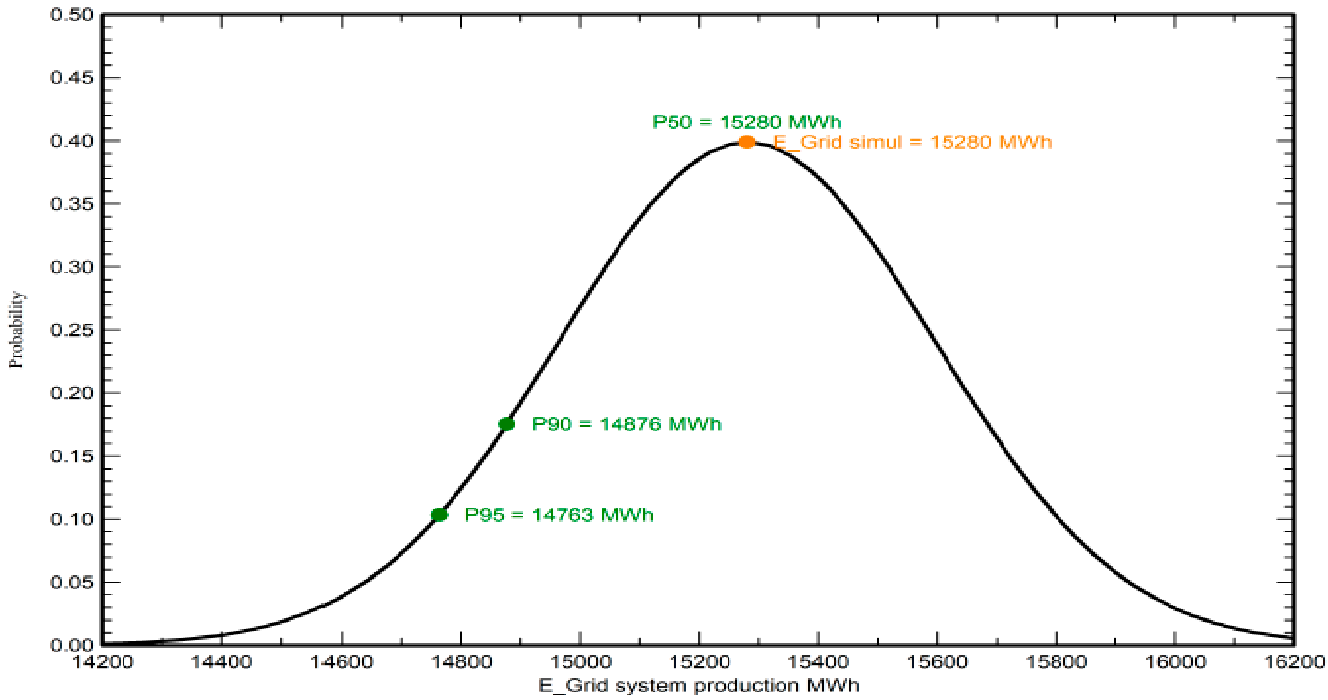


Figure 12. Probability distribution curve.

Table 11. WT performance results.

Parameter	Value	Units
Mean Output	19,701	kW
Capacity Factor	26.6	%
Total Production	172,580,718	kWh/Year
Maximum Output	134,870	kW
Wind Penetration	25	%
Hours of Operation	4977	Hours/Year

5.4. BESS and CMA-ES Algorithm Performance Metrix

Table 12 and Figure 14a,b show a heatmap of the hourly state of charge for a 1 MW/4 MWh VRF-BESS over the first year of operation. The autonomy of 4 h signifies the duration for which the system can sustain its output independently, implying its capacity to provide a reliable energy supply during brief grid interruptions or fluctuations. The BESS state of charge demonstrates an energy shifting and renewable energy smoothing dispatch scenario with an estimated life throughput of 15,439 kWh, which highlights the cumulative energy processed by the system over its operational lifespan. Comparing the energy in (1085 kWh/year) and energy out (976 kWh/year) values provides insights into the system's efficiency, with a small discrepancy suggesting minimal energy losses during the charge–discharge cycle. The algorithm response time of 3 s underlines the system's rapid decision-making capabilities in responding to grid demands. Lastly, the annual throughput of 1029 kWh/year indicates the amount of energy transferred into and out of the system on an annual basis. These metrics collectively reflect the BESS's operational and efficiency characteristics, contributing to a more comprehensive understanding of its performance in a grid support and energy management context. Further analysis and comparison with industry standards would be valuable to gauge its effectiveness in specific applications and grid stabilization scenarios.

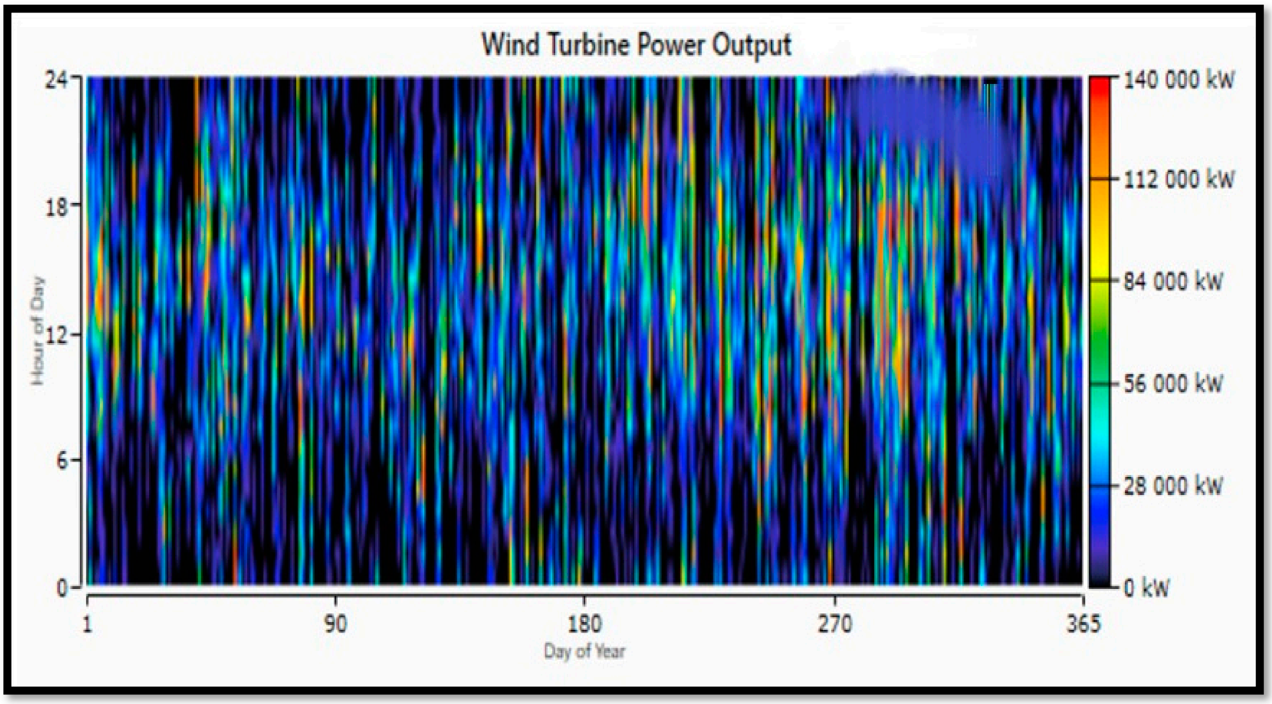


Figure 13. WT power output.

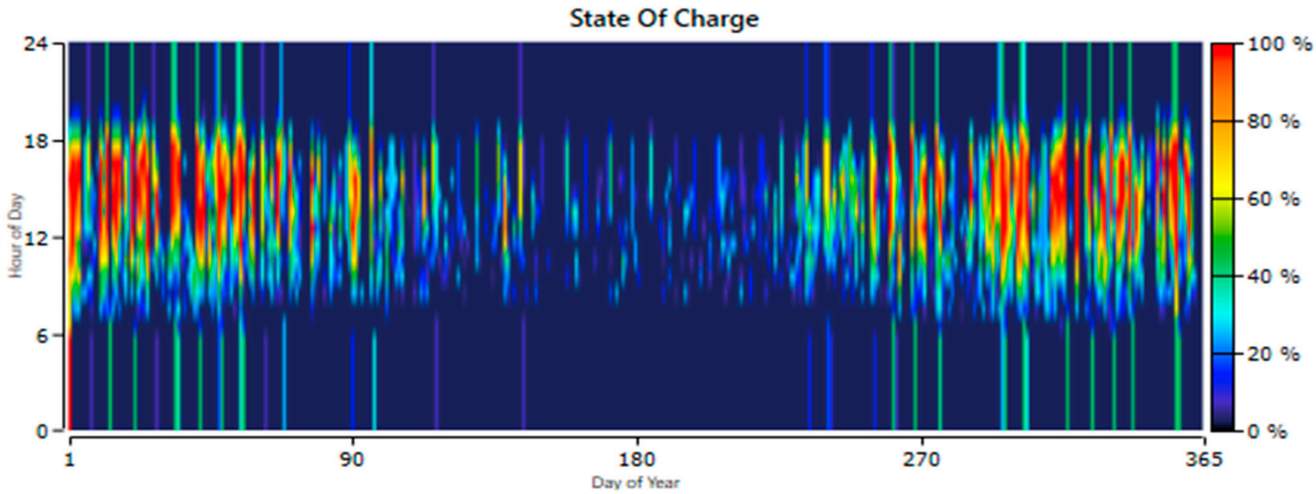
Table 12. BESS and CMA-ES algorithm performance results.

Parameter	Value	Units
Autonomy	4	Hours
Lifetime Throughput	15,439	kWh
Energy In	1085	kWh/Year
Energy Out	976	kWh/Year
Algorithm Response Time	3	Seconds
Annual Throughput	1029	kWh/Year

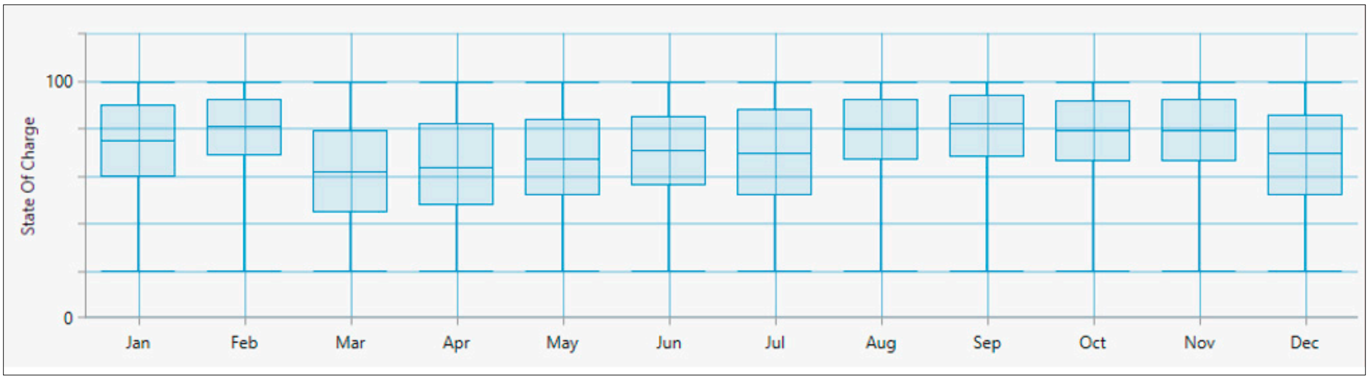
5.5. Economic Performance Indicators

5.5.1. CapEx and Cash Flow

Table 13 serves as a cornerstone in the financial assessment of the HRES microgrid project, offering a comprehensive and meticulously detailed breakdown of the investment profile. With a total CapEx commitment of R172 million, this table underscores the substantial financial undertaking associated with the project, which includes costs related to infrastructure development, equipment procurement, and system installation. The nuances of this financial commitment are further elucidated in Figure 15, which provides a dynamic and multi-faceted representation of the annual savings and cash flow patterns resulting from the implementation of the HRES. This financial roadmap is precisely tailored to cater to the distinctive energy demands of the mining company, thereby accounting for variations in energy consumption and the seasonal nature of mining operations. Figure 15 functions as a pivotal visual aid, offering a nuanced representation of not only the expected cost savings but also the intricacies of revenue generation over time. The figure, supported by meticulous data analysis, provides a holistic view of the HRES solution's financial performance within the unique context of the mining industry, which considers elements such as operational costs, depreciation, potential revenue streams, and the sustainability of the project over its lifecycle. As such, this comprehensive financial analysis ensures that all stakeholders have access to the essential insights necessary to make informed decisions regarding the HRES microgrid project's economic viability and long-term success in the mining sector.



(**a**)



(**b**)

Figure 14. (**a**,**b**) Proposed 1 MW/4 MWh VRF-BESS state of charge heatmap.

Table 13. HRES microgrid CapEx.

Parameter	Capital Cost (R 'Million)	Life Span (Years)
SFPV	35	25
Inverters	10	25
WT	30	25
1 MW/4 MWh VRF-BESS	60	15
Supporting Engineering	30	1
OpEx	4	25

5.5.2. Sensitivity Analysis

Table 14 offers comprehensive insights into the economic viability and performance of the proposed HRES microgrid project. For the base case, the Eskom service, demand, and energy charges are expected to increase with an annual inflation of 9.61%. The IRR of 23.5% is indicative of the project's attractiveness, as it exceeds the typical discount rates in most financial markets, implying a strong potential for generating positive returns on investment, as depicted in Figure 16. The payback time of 4.9 years, which drops to 4.5 years when discounted, is an essential metric, indicating the period required for the project to recover its initial investment. This shorter period signifies a relatively quicker return on investment, enhancing the project's economic attractiveness.

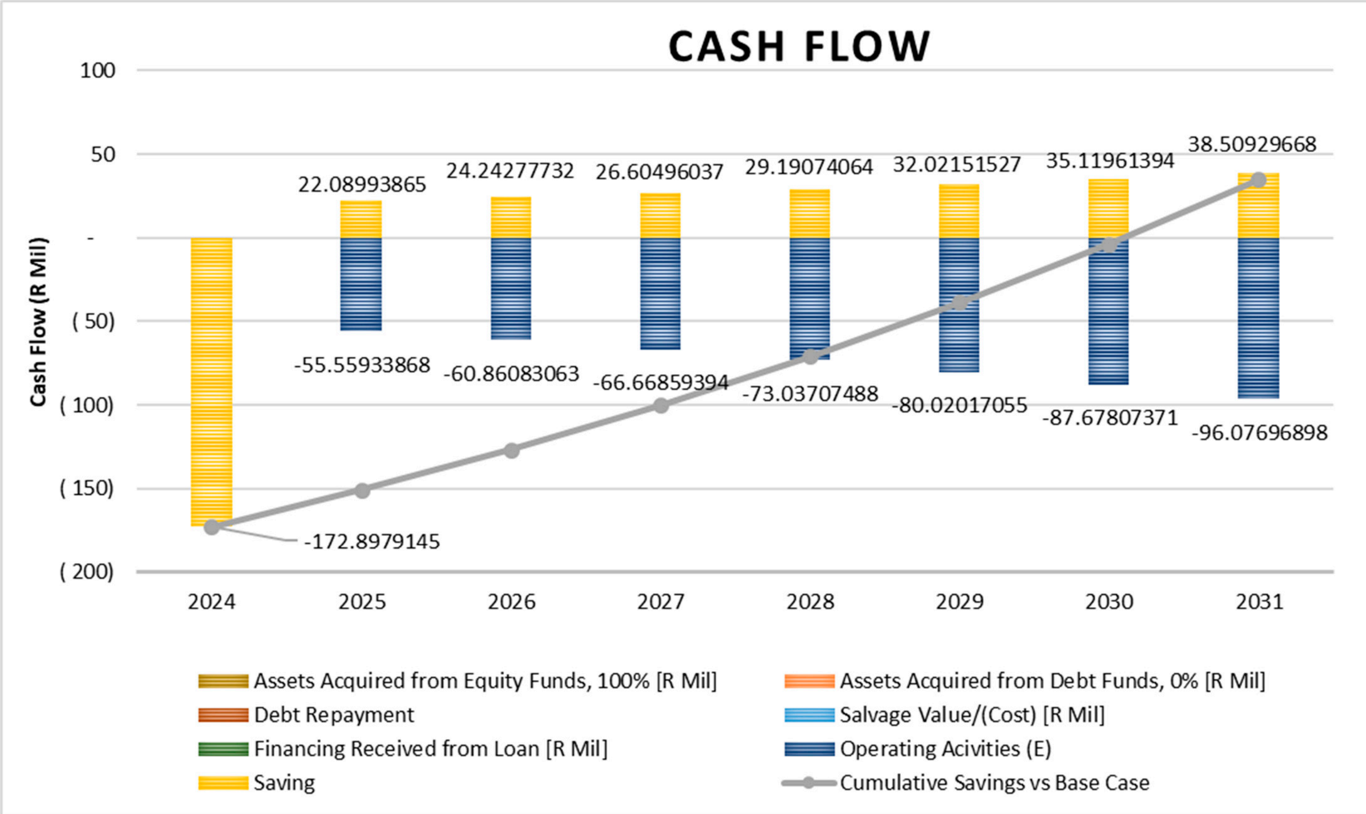


Figure 15. Cash flow for the first eight years.

Table 14. Sensitivity analysis.

Financial Metrix	Value	Units
IRR	23.5	%
LCoE	4.27	R/kWh
BCoE	1.91	R/kWh
Payback time	4.9	Years
Discounted payback time	4.5	Years
NPC	752	R' Million

The LCoE at 4.27 R/kWh and the BCoE at 1.91 R/kWh are crucial indicators of the project's cost-efficiency, as shown in Figures 17 and 18, respectively. The relatively low LCoE suggests that the project can produce electricity at a competitive rate when compared to conventional sources, which enhances its appeal from a cost-effectiveness standpoint. The BCoE, even lower, signifies that the project can provide electricity at a low cost without subsidies or incentives. Lastly, the NPC of R752 million reflects the total present value of the project's costs and benefits over its lifetime. This metric is vital in determining the overall financial feasibility of the project, with a positive NPC indicating that the project is financially sound.

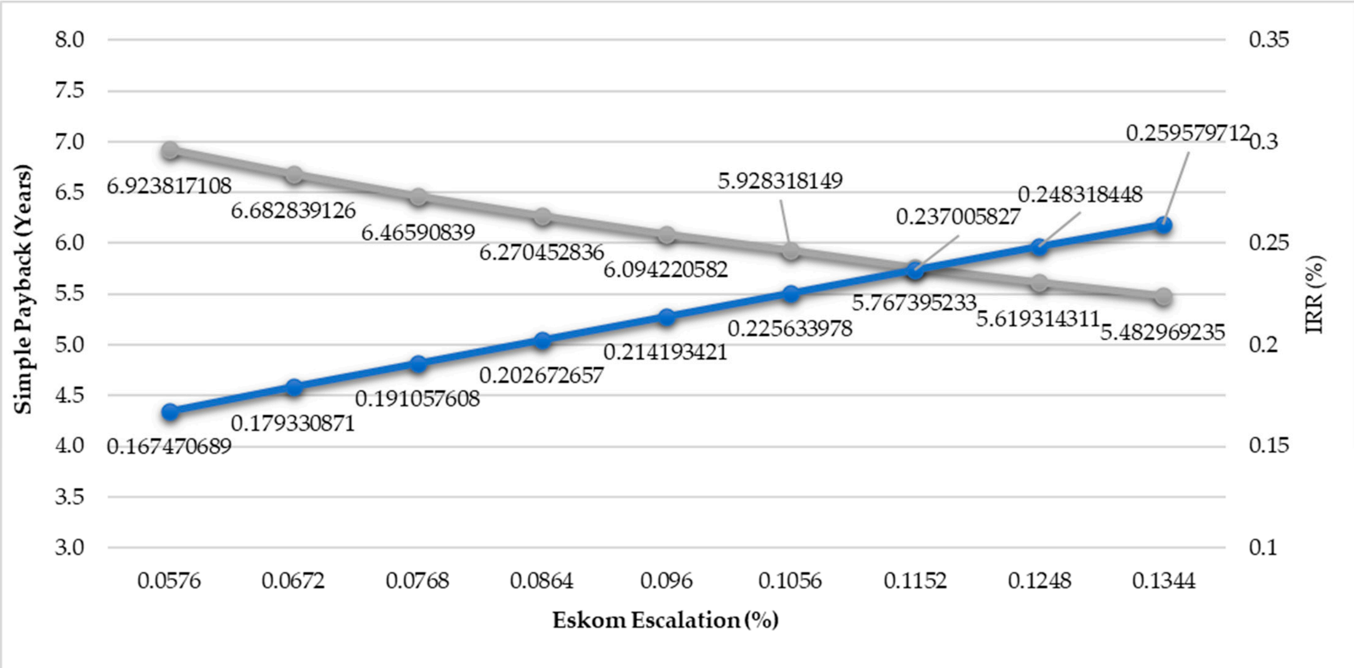


Figure 16. Proposed HRES simple payback and IRR vs. Eskom escalation.

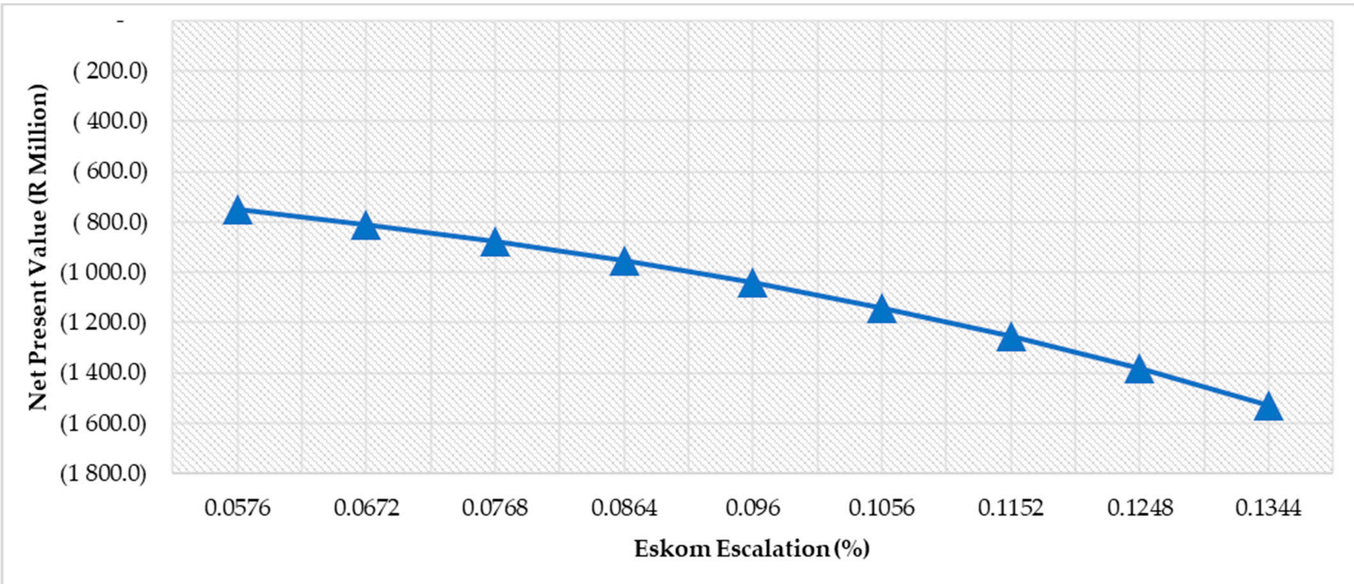


Figure 17. Proposed HRES NPC vs. Eskom escalation.

In summary, the project exhibits promising financial prospects. The high IRR and relatively low LCoE and BCoE values indicate its potential to provide a cost-effective and profitable source of electricity. The comparatively short payback time, both nominal and discounted, implies a rapid return on investment, which is favorable for investors and stakeholders. The positive NPC underscores the project's overall financial viability.

A comprehensive assessment of the modeled renewable energy system reveals that the technical and economic performance is intricately linked to key technical parameters. The efficiency of the HRES, encompassing FPV + WT + BESS, emerges as a critical determinant. The higher technological efficiency directly correlates with increased energy production, positively influencing economic indicators such as the LCoE and BCoE. The system capacity, determined by the installed capacity of solar and wind components, plays a pivotal role in balancing energy generation with demand. Striking an optimal capacity balance is essential to avoid overcapacity and unnecessary costs. Additionally, the reliability of the system components proves paramount, impacting both the technical performance and long-term economic feasibility. Enhancing reliability via regular monitoring and maintenance practices ensures consistent energy generation and minimizes the associated costs, contributing positively to the project's overall financial metrics. In summary, meticulous consideration and optimization of these key technical parameters are vital for achieving an efficient, economically viable, and sustainable renewable energy system.

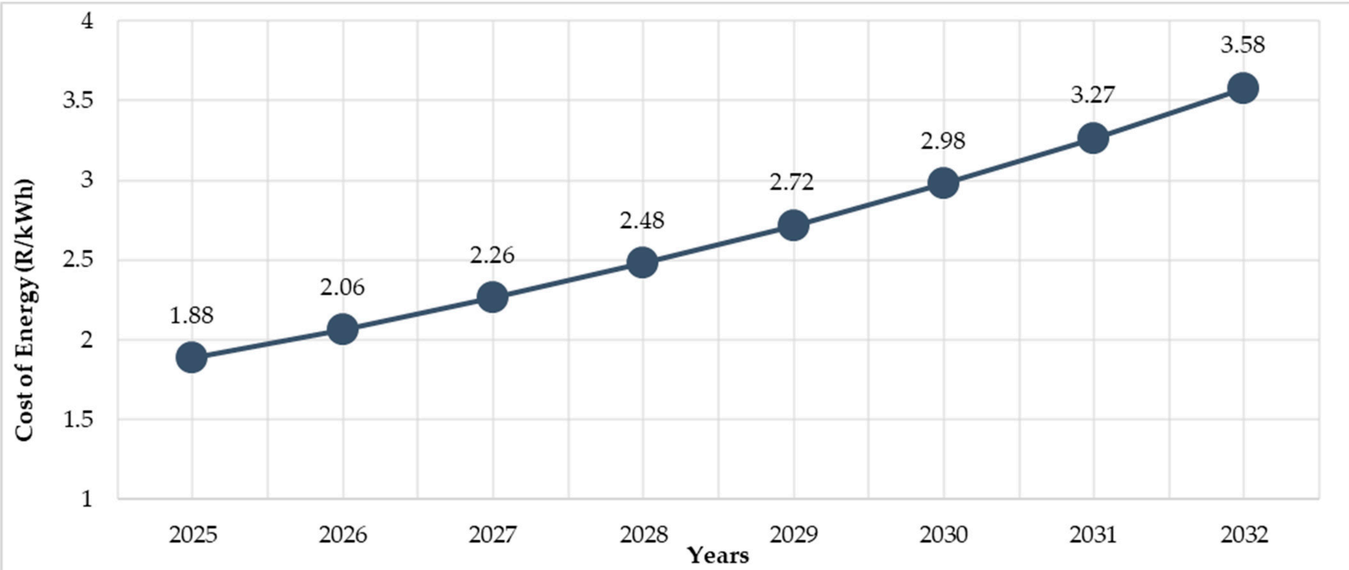


Figure 18. Proposed HRES BCoE for the first eight years.

5.6. Environmental Results

Table 15 demonstrates the reduced carbon emissions with the implementation of the HRES. The analysis between the existing system and HRES reveals a substantial and promising shift toward a more environmentally sustainable energy infrastructure. In terms of carbon emissions, the existing Eskom grid system emits a staggering 38,754,240 kg/year of carbon dioxide (CO_2), whereas the HRES emits a significantly lower amount of 1,715,468 kg/year. This drastic reduction in CO_2 emissions signifies a considerable step toward mitigating climate change, reducing the overall carbon footprint, and curbing the adverse effects of global warming. Additionally, the HRES system emits only 7437 kg/year of sulfur dioxide (SO_2) and 3637 kg/year of nitrogen oxides (NOx) in contrast to the existing system's emissions of 168,017 kg/year of SO_2 and 82,169 kg/year of NOx. This remarkable reduction in SO_2 and NOx emissions signifies a considerable improvement in air quality, a reduction in acid rain formation, and a decreased threat to human health. Investing in HRESs not only demonstrates a commitment to environmental stewardship but also yields a cleaner, more sustainable, and healthier environment for future generations, making it a prudent and ethical choice for energy production and consumption.

Table 15. Emissions generated by the proposed HRES.

Quantity	Value	Units
Carbon dioxide (CO_2)	1,715,468	kg/year
Sulfur dioxide (SO_2)	7437	kg/year
Nitrogen oxides (NOx)	3637	kg/year

The transition to HRESs has multifaceted benefits for the environment. It signifies a significant reduction in greenhouse gas emissions, thereby contributing to global efforts to combat climate change and its associated impacts. Reduced emissions of sulfur dioxide and nitrogen oxides also lead to cleaner air and a decrease in the detrimental effects on ecosystems and human health, further underscoring the environmental advantages of HRES. In essence, investing in HRESs serves as a transformative and commendable step toward a more ecologically responsible and sustainable energy future, embodying the imperative for clean and renewable energy sources in the battle against climate change and environmental degradation.

5.7. Recommendations

Mining companies should strongly consider investing in HRESs as a strategic approach to enhance their revenue, primarily by mitigating power interruptions and bolstering operational reliability, all the while demonstrating a profound commitment to environmental sustainability. By incorporating HRESs, mining operations can significantly reduce their reliance on conventional, often unstable power sources, subsequently diminishing the risks of costly production disruptions due to grid failures. The consistent and reliable power supply offered by an HRES not only ensures smoother mining operations but also engenders potential cost savings. Furthermore, the environmental sustainability inherent to HRESs aligns with modern ethical and regulatory expectations, reducing the environmental footprint and fostering goodwill with stakeholders and consumers alike. Such a comprehensive approach not only enhances operational stability but also augments the mining industry's reputation, positioning it favorably in the global market and ultimately bolstering revenue in improved operational efficiency and environmental conscientiousness.

5.7.1. Grid Code Compliance for BESS and RPP

Category B classification for a BESS, encompassing installations equal to or greater than 1 MW but less than 20 MW, entails adherence to a comprehensive grid code, delineating a multifaceted set of specific requirements [47]. These requirements encompass a broad spectrum of crucial parameters, including tolerance for frequency and voltage deviations, frequency response capabilities, active power constraint functions, reactive power capabilities, power quality standards, protection and fault level protocols, availability, and supervisory control via SCADA systems, communication specifications, rigorous testing and compliance monitoring, provisions for modifications, the provision of data, electrical dynamic simulation models, and requisite reporting to regulatory bodies such as NERSA. These prerequisites must be diligently incorporated into the design, procurement, and construction phases to ensure a meticulously compliant and reliable energy storage solution. A strategic recommendation for BESS grid code compliance is the meticulous integration of these specific requirements into every phase of the project, thereby guaranteeing seamless alignment with the regulatory standards and engendering a robust, efficient, and resilient energy storage system that not only adheres to stringent regulatory guidelines but also enhances grid stability and energy supply reliability. This strategic compliance approach ensures that BESS installations of this magnitude serve as pillars of grid integration, resilience, and sustainable energy solutions.

Category B classification for Renewable Power Plants (RPPs) covering installations ranging from 1 MVA up to 20 MVA necessitates meticulous adherence to a comprehensive grid code, which delineates a precise set of specific requirements. These requirements encompass a spectrum of essential facets, including tolerance for frequency and voltage deviations, frequency response capabilities, reactive power capability, reactive power and voltage control functions, power quality standards, protection and fault level protocols, active power constraint functions, control function requisites, RPP availability, supervisory control via SCADA systems, rigorous testing and compliance monitoring, provisions for data sharing and electrical dynamic simulation models, along with obligatory reporting to regulatory bodies, such as NERSA. To ensure a compliant renewable energy power plant solution, it is imperative to diligently integrate these specific requirements into every phase of the project—from design to procurement and construction. The strategic recommendation for RPP grid code compliance lies in the meticulous incorporation of these prerequisites, thereby guaranteeing full alignment with stringent regulatory standards. This approach not only ensures that RPPs function as reliable and stable sources of renewable energy but also foster grid stability, thereby contributing to the sustainability of the energy sector while enhancing the long-term viability and resilience of these essential power facilities.

5.7.2. NERSA Registration

The amended Licensing Exemption and Registration Notice, as published in Government Gazette No. 45266, Vol. 676, and the registration procedure outlined by NERSA specify the eligibility criteria for projects seeking registration and exemption from licensing [48]. Pertaining to the proposed HRES, the activities covered include operating a generation facility with or without energy storage up to a 100 MW capacity, with a Point of Connection on the transmission or distribution power system, provided the electricity is supplied to one or more customers without wheeling. NERSA requires a comprehensive set of information for evaluating registration, including the company registration certificate, shareholding structure, a consent letter from the licensed network service provider (NSP) confirming the network capacity and compliance with NSP requirements, and a wheeling agreement with the NSP (though not applicable to the study's base case or alternatives). To initiate registration, the generation facility operator must submit an application form and pay a registration fee of R200 after NERSA confirms compliance with its requirements. Furthermore, in its commitment to ensuring non-discriminatory access to transmission and distribution power systems, the NSP, Eskom, necessitates compliance with the relevant grid codes. A guideline recommendation for HRES NERSA registration is to diligently compile and submit the requisite documentation, ensuring adherence to the NSP compliance requirements, grid codes, and comprehensive communication with NSPs for efficient and expedited registration, thus facilitating the integration of HRESs into the South African energy landscape.

5.8. System Reliability Analysis

Table 16 presents the reliability analysis results for the proposed HRES using the LPSP methodology. The table provides a comprehensive assessment of key components within the HRES, including the SFPV, WT, and BESS. For each component, the table includes the Failure Rate per year (λ), Repair Time (μ), and Availability (A), crucial parameters in determining the reliability of the system. These values are obtained from the HRES component specifications. The LPSP values, representing the probability of experiencing a loss of power supply, are calculated based on these parameters and the HRES resource capacity factor. The SFPV/WT annual resource availability is discussed in the system setup for the proposed location. The Overall HRE system row consolidates the metrics for the entire system, offering a holistic view of the HRES's reliability.

Table 16. Proposed HRES reliability analysis using the LPSP method.

Component	Failure Rate Per Year (λ)	Repair Time (Hours) (μ)	Availability (A)	LPSP
SFPV	0.001	24	0.976	0.024
WT	0.0008	48	0.9616	0.0384
VRF-BESS	0.0015	72	0.892	0.108
Overall HRE system	0.0033	144	0.8492	0.1508

For the SFPV array, the low failure rate per year of 0.001, combined with a relatively short repair time of 24 h, yields a high availability of 0.976 and a low LPSP of 0.024, indicating high reliability. Similarly, the WT with a slightly lower failure rate showcases commendable reliability with an LPSP of 0.0384. The BESS exhibits an LPSP of 0.108, influenced by a lower availability of 0.892. The overall HRE system, considering the combined metrics of all components, reflects an LPSP of 0.1508, suggesting a relatively reliable hybrid system. The LPSP values signify the probability of experiencing a loss of power supply, and lower values indicate higher reliability. Thus, the results imply that the proposed SFPV, WT, and VRF-BESS components contribute significantly to the overall system reliability.

The demonstrated reliability of the proposed HRES during conditions of load shedding and load curtailment holds notable significance for sustaining continuous revenue generation within mining operations. This resilience ensures an uninterrupted power supply, thereby mitigating potential disruptions in energy availability. The inherent capacity of the system to navigate such challenges contributes not only to the operational continuity of mining activities but also to the sustained generation of revenue. The results showcase a robust and reliable HRES that holds considerable promise for meeting the energy demands of the study area consistently throughout the year. The SFPV array demonstrates impressive capabilities, achieving an 85.5% performance ratio and an annual energy production of 15,835 MWh. This underscores the efficiency of converting solar energy into electricity, contributing significantly to the overall reliability of the system. The WT complements this by showcasing an annual energy production of 172,580,718 kWh, operating for 2977 h per year, and achieving a wind penetration rate of 25%. The VRF-BESS adds a dynamic dimension with its energy shifting and renewable energy smoothing scheme, backed by an advanced CMA-ES dispatch algorithm exhibiting a rapid 3 s response time.

Furthermore, the ascertained reliability of the HRES, as indicated by the LPSP value of 0.1508, not only lays the groundwork for heightened economic viability but also presents a multitude of advantages specifically tailored to the exigencies of mining operations. In instances of load shedding and load curtailment, scenarios prevalent in the operational landscape of mining enterprises, the imperative need for a consistent and uninterrupted power supply becomes increasingly pronounced. The pivotal role assumed by the proposed HRES in ensuring continuous power availability during these circumstances significantly contributes to the operational resilience of mining activities. This, in turn, safeguards against production downtime and revenue losses, thereby enhancing the overall operational efficiency of the mining infrastructure. The observed reliability of the HRES, acting as a stalwart in the face of power supply challenges, serves as a catalyst for fortifying the IRR and accelerating the payback period of the initial investment. Beyond these financial considerations, the system's dependability establishes it as a cornerstone for sustainable and commercially viable energy solutions tailored to the distinctive requirements of mining enterprises, thereby fostering long-term energy security and economic prosperity.

6. Conclusions

This paper has presented a comprehensive analysis of the HRES microgrid, encompassing the optimization of its components, economic performance, and environmental impact focusing on mining companies in South Africa. The HRES comprises an optimal 5 MW SFPV array, a 1 MW WT, a 1 MW/4 MWh VRF-BESS, and an intelligent CMA-ES battery energy dispatch algorithm. The empirical findings of this investigation indicate that the HRES presents a compelling case in terms of cost-effectiveness, sustainability, and environmental friendliness when juxtaposed with the conventional coal-fired power stations operated by Eskom. The proposed HRES showcases impressive efficiency, achieving an overall performance rating of 86% and demonstrates commendable reliability, ensuring consistent and efficient power generation. In summary, the key outcome of this study is as follows:

i. The proposed SFPV demonstrated capabilities of efficiently converting solar energy into electricity with a performance ratio of 85.5% and an annual energy production of 15,835 MWh.
ii. The WT showed an annual energy production of 172,580,718 kWh while operating for a total of 2977 h per year, achieving a wind penetration rate of 25%.
iii. The VRF-BESS state of charge portrays a dynamic energy shifting and renewable energy smoothing scheme, with a projected life throughput of 15,439 kilowatt-hours

(kWh), underscoring the cumulative energy managed by the system throughout its operational lifespan. Notably, the CMA-ES dispatch algorithm exhibited an impressive 3 s rapid response time.

iv. The envisaged HRES entails a CapEx totaling R172 million, boasting a commendable IRR standing at 23.5%. This configuration presents an investment payback period of 4.9 years, facilitating the recuperation of invested capital, while also offering the promise of potential profitability over the ensuing two decades.

v. The project demonstrates a comparatively modest LCoE at 4.27 R/kWh and a competitive BCoE at 1.91 R/kWh, along with a positive NPC, indicative of its capacity to supply electricity at an economically advantageous rate devoid of external subsidies or incentives.

vi. The proposed HRES is estimated to annually reduce CO_2 emissions by 1,715,468 kg/year (95.6%), SO_2 emissions by 7437 kg/year (95.5%), and NOx emissions by 3637 kg/year (95.7%), signifying a substantial environmental benefit.

vii. The overall HRE system demonstrates a reliable performance with an LPSP of 0.1508, signifying a low likelihood of power supply disruptions.

For future directions, it is imperative to further investigate the long-term economic and environmental benefits of an HRES, considering variations in energy demand and potential adaptations in response to evolving energy policies and market dynamics. Additionally, in the context of the South African energy landscape, the research should focus on addressing challenges related to grid integration, ensuring a seamless transition from conventional power sources to renewable microgrids. Future research should focus on the trending Open Neural Network Exchange (ONNX) energy management algorithm for optimized storage and distribution and innovative financing models to drive the widespread adoption of HRESs, and explore the scalability of solutions like biogas, hydro power, biomass, and hydrogen BESS technologies for diverse industrial sectors, fostering a holistic and sustainable transition to renewable energy.

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