Integration of Grid-Scale Battery Energy Storage in Solar Microgrids for Rural Communities in Limpopo Province

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Abstract. The persistent challenge of community blackouts resulting from load reduction and shedding necessitates immediate and effective solutions. These power interruptions not only disrupt daily activities but also create imbalances in supply and demand. At the core of this issue lies the inflated cost of electricity and the continual annual tariff hikes. Consequently, some consumers are driven to engage in illegal connections, theft, and meter tampering as a means to mitigate their expenses, which exacerbates the problem of load reduction. This study explores the potential for integrating grid-scale battery energy storage with solar PV systems to enhance energy access for rural communities in Limpopo. Employing the Herman-beta method, we estimated the electricity demand based on the 2022 census data from Statistics South Africa. The technical and economic performance of the communities, specifically Ka-Dzingidzingi, Duthuni, and Mookgopong NU, was evaluated using Homer software, focusing on the integration of these communities with grid-scale solar PV systems. We compared the economic metrics of solar panel capacities at 250W, 375W, and 500W, alongside the selection of a 48V, 14.4kWh lithium-ion battery for the grid-scale implementation. Our findings indicate that the system utilising a 500W solar module yields the most favourable outcomes, with the lowest Net Present Cost and Levelized Cost of Energy across the assessed communities. Specifically, the NPC values were 77.30 million, 137.54 million, and 199 million for Ka-Dzingidzingi, Duthuni, and Mookgopong NU, respectively, while the corresponding LCOE figures were 1.83R/kWh, 1.58R/kWh, and 0.71R/kWh. The metrics for return on investment, internal rate of return, and simple payback period suggest that the success of this initiative hinges on securing investments from both private and public sectors. A collaborative approach in financing will facilitate improved electricity delivery to these communities in Limpopo, thereby significantly enhancing their overall quality of life.

1 Introduction

The issue of power blackouts in Limpopo province, caused by load reduction and shedding, and sometimes due to minor natural weather disruptions, demands urgent solutions. These interruptions disrupt both social life and economic operations in the communities [1]. Communities need access to affordable and reliable electricity provision as it is vital for social development, especially in rural areas. However, challenges continue to persist, including unreliable supply of electricity and unbearably expensive electricity costs. As the cost of purchasing electricity increases annually and the government seem not to care, several consumers resort to illegal connections and meter tampering to save on costs, and that further strains the power grid, resulting in load reduction and shedding [2]. That is why it is essential to lay out a comprehensive strategy to ensure stable, reliable and affordable electricity access in rural areas, and in this case, it is rural communities of Limpopo province. This paper investigates integrating grid-scale battery energy storage systems with solar PV microgrids as a backup solution for rural communities' energy challenges. The aim of the study is to assess the technical and economic feasibility of this integration. For technical and economic simulations, Homer Pro software has been employed as it is at the forefront of microgrid optimisation simulations [3], and for load estimations, the Herman-beta method has been employed as it is the probabilistic approach to designing residential electrical distribution systems [4]. The findings will determine the viability of investing in this solution to enhance energy resilience in Limpopo's rural areas by observing the system's net present cost (NPC), levelized cost of energy (LCOE), return on investment (ROI), internal rate of returns (IRR) and simple payback years (SPB).

To the author's knowledge, there is a need to continue researching solar microgrids integrated with battery storage for rural communities because battery storage solar microgrids have emerged as a vital solution to address energy access challenges in rural areas, particularly in regions where the national grid experiences technical difficulties. These systems possess the capacity to deliver reliable, decentralised, and sustainable electricity. Authors in [5] highlight that rural electrification through centralised grids frequently encounters elevated transmission costs and significant delays, rendering decentralised solutions a more pragmatic alternative. Solar microgrids integrated with battery storage systems effectively address the challenge of solar intermittency, thus providing a reliable power supply essential for fulfilling the energy requirements of lighting, healthcare, education, and small-scale enterprises in off-grid communities [6]. This combination enhances the resilience of local energy systems, enabling sustained operations and contributing to developmental goals in these areas. Authors in [7] highlight that the incorporation of battery energy storage systems enhances power reliability and grid stability. This integration not only mitigates intermittency issues associated with renewable energy sources but also facilitates energy availability during non-generating hours, thereby supporting socio-economic development initiatives. The environmental and economic advantages of solar microgrids with energy storage systems further highlight their critical importance. Conventional rural electrification methods that depend on diesel generators not only exacerbate greenhouse gas emissions but also incur significant operational expenses related to fuel logistics and equipment maintenance [8]. Battery-backed solar systems enhance the reduction of reliance on fossil fuels while providing substantial long-term economic benefits. Research indicates their scalability and flexibility to meet localized energy requirements, facilitating progressive implementation in alignment with the evolving demands of the community [9]. Battery storage solar microgrids significantly bolster community resilience, particularly in regions susceptible to climate-induced disruptions, by providing a stable and renewable energy supply. These systems serve as more than just a technical solution; they function as transformative mechanisms that advance energy justice, promote economic inclusion, and foster environmental sustainability in underserved rural areas. Their integration facilitates decentralized energy access, reduces reliance on fossil fuels, and enhances grid stability, ultimately contributing to a more equitable energy landscape [10].

2 Experiment

2.1 Description of the selected site

The three selected sites for analysis are located in Limpopo Province, South Africa, specifically: Ka-Dzingidzingi, Duthuni, and Mookgopong Non-Urban (NU). The average solar global horizontal irradiance at these locations is recorded at 6.46 kWh/m²/day, while the mean monthly temperature averages 25.62 °C [11]. The map below in Figure 1 shows Limpopo province, with selected locations in blue dots.

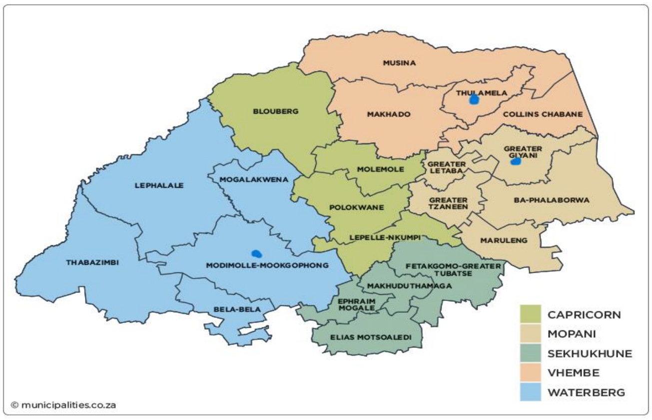

Figure 1: Limpopo province with selected locations denoted by blue dots.

2.2 Population statistics of selected locations

Table 1 below shows the population statistics of the selected location extracted from the Statistics South Africa database. The table shows that Ka-Dzingidzingi is the location with the least population, Duthuni is in the middle, and Mookgopong NU has the highest population of the selected population. This metric is essential for load modelling using the Herman-Beta method from the NRS-034 of 2012.

Locations	Municipality	Population Size	Number of Consumers (N)
Ka-Dzingidzingi	Greater Giyani	4749	1153
Duthuni	Thulamela	8431	2200
Mookgopong NU	Mookgopong	12411	4200

Table 1: Population data of the selected locations

3 The Herman-Beta Method

3.1 Load modelling using probabilistic distribution function (PDF)

The Herman-Beta method employs a probabilistic distribution function to evaluate various loads, consumer connections, and types of network topology. This distribution function is characterised by three key design parameters: alpha (a), beta (b), and the circuit break parameter (c). To derive the estimated maximum demand for residential loads, expressed in kVA or kW, we utilise the following formula (Equation 1), contingent upon knowing the specific values of a, b, and c. Standardised values for these parameters can be referenced in the 2007 publication titled "Electricity Distribution – Guidelines for the Provision of Electricity Distribution Network in Residential Areas", found in NRS-034 [12].

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

where L represent the maximum load in kVA or kW, N denote the total number of consumers, and a and b are parameters related to the load current model. The parameter c functions as the scaling factor, which corresponds to the size of the circuit breaker. When the load is accessible, we can derive estimates for the load parameters for any value of c by applying the standard deviation (σ) and mean (μ) derived from equations 2 and 3, as well as the probability density function (PDF) mean from equation 4 [12].

$$\mathrm{a} = \frac{\mu(c\mu - \mu^2 - \sigma^2)}{c\sigma^2} \tag{2}$$

$$\mathrm{b} = \frac{(c - \mu)(c\mu - \mu^2 - \sigma^2)}{c\sigma^2} \tag{3}$$

$$c = \frac{a}{a+b} \tag{4}$$

3.2 *Consumer classifications and design load current parameters*

Table 2 delineates the classification of consumers based on design load parameters pertinent to rural settlements and villages, as well as the associated design parameters. The classification comprises eight distinct consumer categories, spanning from rural settlements to urban multi-story estates. For the purposes of this investigation, we will focus exclusively on two categories: rural settlements and rural villages.

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

Table 2: Consumer class and design parameters [12]

4 Microgrid Design for all Locations

4.1 *Microgrid design schematics*

A microgrid is a small-scale energy system comprising distributed energy resources and loads [13]. The system can be configured for either grid-connected or off-grid operation, providing a viable alternative for delivering reliable and cost-effective energy solutions to consumers. This sub-section outlines the models of the various components that form the microgrid system developed for this study. The architecture of the microgrid includes a 500W solar photovoltaic system, a 14.4 kWh battery bank operating at 48 V, 500 kW electrolysers, and integration with the utility grid. The design, illustrated in Homer Pro software, is detailed in Figure 2, which includes schematic diagrams that depict both the peak load in kW and the average daily energy consumption in kWh/day for each selected site.

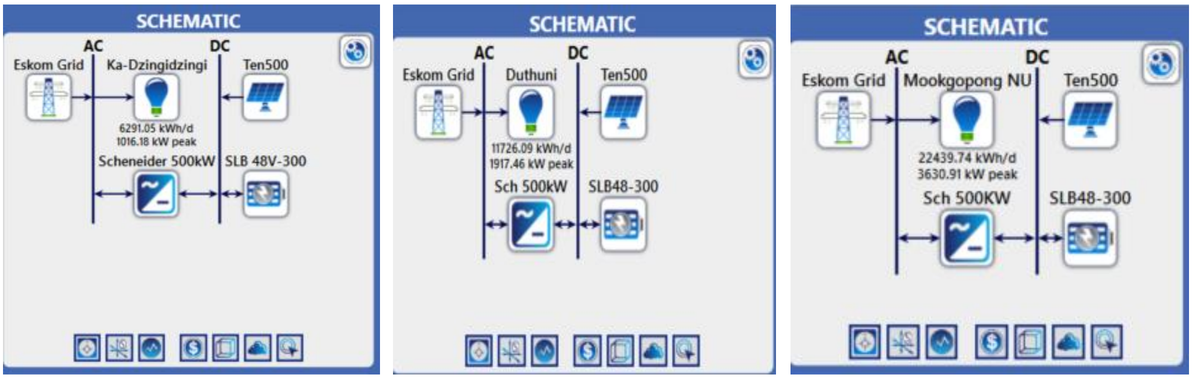

Figure 2. Schematic diagrams for selected locations in Homer software

4.2 *Estimated electric load for selected locations and component sizing*

As shown in Figure 2 above, the estimated load for Ka-Dzingidzingi is 1016.18kW$_{peak}$, followed by the one for Duthuni, which is about 1917.46kW$_{peak}$, and lastly is Mookgopong, sitting at 3630.91kW$_{peak}$

Locations	Estimated Peak Load (kW)	Number of Solar Panels	Number of inverters
Ka-Dzingidzingi	1016.18	1848	2*500 kW
Duthuni	1917.46	3486	3*500 kW
Mookgopong NU	3630.91	6602	4*500 kW

Table 3: Estimated peak load with component sizing

5 Results

5.1 *Technical Findings*

The technical analysis of this investigation focuses on several key factors related to microgrid performance, including energy production, consumption, excess energy, and the renewable energy fraction across various locations. The presence of excess energy indicates that the energy generated is sufficient to meet the demands of the system; notably, in all examined locations, energy consumption remains below energy production, allowing for surplus energy to be utilised for battery charging. A significant contributor to the high levels of energy production in the Limpopo province is the region's elevated solar irradiance, coupled with the robust backup capabilities provided by the integrated battery systems. Furthermore, the investigation reveals a high renewable energy fraction, which can be attributed to a combination of favourable environmental conditions, the availability of effective energy storage solutions, and a substantial installed capacity of renewable energy technologies. This synergy of factors supports the overall efficiency and sustainability of the proposed microgrids in the study.

Locations	Energy produced (kWh/yr)	Energy consumed (kWh/yr)	Excess energy (kWh/year)	Renewable fraction (%)
Ka-Dzingidzingi	2 382 102	2 344 021	7 385	27.7
Duthuni	4 957 321	4 831 899	23 162	44.8
Mookgopong NU	20 775 999	19 922 495	116 869	78.4

Table 4: Technical results for proposed microgrid optimisation

5.2 Economic findings

The economic findings of this investigation, as shown in the table, look at the capital expenditure, LCOE, NPC, ROI, IRR and SPB. Capital expenditure refers to the total financial resources allocated primarily for investment in the acquisition, maintenance, or enhancement of assets, including but not limited to buildings, machinery, and infrastructure [14]. Larger projects typically necessitate greater capital expenditure. An analysis presented in Table 5 reveals that the proposed microgrid system for Ka-Dzingidzingi has the lowest anticipated capital costs among the selected locations, ranking next to Duthuni, while Mookgopong follows with the highest costs. This discrepancy is attributed to the size of the microgrid systems, with Ka-Dzingidzingi microgrid operating at approximately 1016.18 kW, compared to Duthuni 1917.46 kW and Mookgopong NU's substantial 3630.91 kW capacity. In economic analysis of energy projects, two critical metrics are the NPC and the LCOE. NPC represents the total cost of a project over its lifetime, while LCOE reflects the average cost per unit of electricity, expressed in rand per kilowatt-hour (R/kWh) in South Africa [15]. When the NPC and LCOE of a project are significantly higher than those of comparable completed projects, it may indicate that pursuing the project is unwise, as the lengthy payback period could result in a financial loss. In this investigation, the Ka-Dzingidzingi location has the lowest NPC at 77.30 million rand, attributed to minimal capital investment. Duthuni follows with an NPC of 137.54 million, while Mookgopong NU has a substantially higher NPC of approximately 252.67 million. Conversely, the analysis reveals that Mookgopong, despite having the highest NPC, achieves the lowest LCOE of 0.71 R/kWh. This can be attributed to its larger microgrid size, which results in high energy production, coupled with a long operational lifetime of about 25 years, no fuel costs, and a high degree of renewable energy integration. Duthuni presents a moderate LCOE of 1.58 R/kWh, and Ka-Dzingidzingi, which has the smallest proposed microgrid, experiences a relatively high LCOE of around 1.83 R/kWh due to its limited energy production capacity. In analysing historical data, it becomes evident that recovering investment in energy systems can often take a decade or more. This protracted payback period is primarily attributed to the high initial investment costs compared to the relatively lower LCOE associated with these systems. Consequently, the success and viability of such investments are likely to be enhanced through collaborative efforts between private enterprises and public entities, fostering a synergy that maximises both financial and operational efficiencies.

Locations	Capital	LCOE	NPC	ROI	IRR	SPB
Ka-Dzingidzingi	5.88M	1.83	77.30M	4.1	6.3	11.85
Duthuni	17.5M	1.58	137.54M	5.5	8.2	10.11
Mookgopong NU	117M	0.71	252.67M	3.1	5.0	13.30

Table 5: Economic results for proposed microgrid optimisation

6 Conclusion

This paper explores the integration of grid-scale battery energy storage systems with solar PV microgrids as a sustainable backup solution to address the energy challenges of power failures, load reduction, and load shedding in rural communities of Limpopo province. The study meticulously evaluates the technical and economic feasibility of this integrated system. Utilising the Herman-beta method for load modelling, alongside Homer Pro software for system configuration and economic simulations, the analysis focused on three rural communities with varied characteristics specifically differing population densities, ambient temperatures, and global horizontal irradiance levels. A critical component in the simulation setup was consumer classification, which significantly informed the calculation of peak electric loads via the Herman-beta method. The findings indicate a direct correlation between population density and peak load demands; for instance, Ka-Dzingidzingi, with a lower population density, exhibited lower peak loads, while Mookgopong NU, characterised by a higher population density, demonstrated elevated peak load demands. The modelling results show that the proposed system can generate sufficient electricity, yielding surplus energy across all studied locations. This surplus not only contributes to battery charging but is also available to support these communities during power outages and peak usage periods in the morning and evening. From an economic perspective, the adoption of this integrated system appears vital for the enhancement of energy supply in these rural areas. However, the financial viability presents a mixed picture; while the system offers half benefits, half losses, the recovery of investment for stakeholders could take over a decade due to the substantial capital costs associated with battery storage installation. A key economic metric, the LCOE, is notably low at approximately 2.50 R/kWh, indicating potential acceptance by local communities. For successful deployment, collaborative investment between the public energy sector and private investors is essential. A structured partnership could facilitate the realisation of this project, ensuring a viable energy solution for the targeted rural populations.

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