Enhancing Rural Electrification: An In-depth Analysis and Optimisation of PV/Hydrogen Fuel Cell/Battery-Powered Microgrids.

S Muronga, D Tinawro, TS Mulaudzi, JK Kirui, I Mnandi, K Madzivhandila, A Ramalata

Department of Physics, University of Venda: University Rd, Thohoyandou,0950
Email: murongashandukani8@gmail.com

Abstract

Access to reliable and affordable electricity is a significant challenge in many rural areas of South Africa, where communities face either no grid connection or frequent power outages due to ageing infrastructure and load-shedding. Extending the centralised grid to these regions is often economically unviable. This study uses HOMER software to simulate and analyse a hybrid microgrid incorporating PV, hydrogen fuel cells, and battery storage to improve energy reliability while minimising costs. Results show that integrating hydrogen fuel cells for long-term storage with batteries for short-term load balancing enhances system resilience. Among the configurations analysed, Case 1 was the most cost-effective, with a Net Present Cost of R5.22 million and a Levelized Cost of Energy of R2.62/kWh. These findings highlight the potential of hybrid PV/H_2/Battery systems as sustainable decentralised energy solutions for rural electrification in South Africa.

1. Introduction

Access to reliable and affordable electricity is a pressing challenge in deep rural South Africa, where numerous communities are either off-grid or experience frequent interruptions due to load-shedding and outdated infrastructure [1]. Although national electrification initiatives have made strides, extending the central grid to these remote areas is often economically impractical and environmentally detrimental [2]. In light of this, decentralised energy systems driven by renewable resources are emerging as compelling alternatives for rural electrification. South Africa has high solar irradiance, with daily solar radiation levels between 4.5 and 6.5 kWh/m², positioning photovoltaic (PV) technology as a highly viable and abundant energy solution [3]. The intermittent nature of solar energy introduces reliability issues, particularly in the absence of sufficient energy storage and backup systems. To mitigate these challenges, hybrid microgrids combining PV with battery storage for short-term load management and hydrogen fuel cells for long-duration energy storage are being recognised as promising solutions [4].

Hydrogen fuel cells offer a remarkable capability to convert surplus solar energy into hydrogen through electrolysis during peak generation times, subsequently reconverting it into electricity during low sunlight, providing a clean, zero-emission energy storage option [5]. Such systems enhance immediate energy response and long-term reliability when integrated with batteries. However, optimising these components' sizing, cost, and performance necessitates a comprehensive techno-economic and environmental modelling approach tailored to the unique local context. Mbali and Dzobo (2021) developed a hybrid PV/Diesel/Battery system for the Upper Blinkwater community, utilising HOMER and Reticmaster software. Their study confirmed the system's technical feasibility, showing an average electricity cost of R1.1093/kWh and an annual diesel consumption of 16,685 L [6]. Unlike previous rural electrification studies, this work uniquely integrates a comparative simulation of PV/H_2/Battery microgrids under rural South African socio-technical constraints.

This study aims to optimise PV/Hydrogen Fuel Cell/Battery hybrid microgrids for rural South African applications focusing on ensuring a reliable energy supply while minimising life-cycle costs. Additionally, this research supports the overarching goals of national decarbonization and energy equity. The insights gained are intended to inform policy, planning, and implementation strategies that enhance energy access, promote local economic development, and build community resilience.

2. Methodology

This study employed the HOMER (Hybrid Optimisation Model for Electric Renewables) software to design and optimise an off-grid hybrid power system for the Masia Community Development Centre in Limpopo, South

Africa, which currently lacks access to the national electricity grid. A thorough on-site energy audit was conducted to establish an accurate load profile that reflects actual consumption patterns. To ensure precise system modelling, meteorological data for the year 2023 were obtained from NASA's Atmospheric Data Centre, while monthly solar irradiation data, essential for evaluating solar potential, were sourced from the National Renewable Energy Laboratory (NREL) using satellite-based, location-specific datasets. The HOMER software was then used to simulate different system configurations, and a range of technical and economic analyses were performed to evaluate system feasibility and identify the most cost-effective and reliable energy solution for the Centre.

2.1 Study Area and System Architecture

The Masia Community Development Centre, located in Masia Tshikwarani (23.1836° S, 30.3098° E) within the Collins Chabane Local Municipality in Limpopo Province, South Africa, has been selected as the study area for this study on optimising rural microgrids. Currently, the Centre lacks a functional grid connection and relies on a limited 19.8-kW photovoltaic (PV) solar system, which serves only a portion of the facility's energy needs. This deficiency in energy access underscores the necessity for a resilient, scalable, and entirely off-grid energy solution tailored to rural environments. The study explores a standalone hybrid microgrid that integrates PV panels, hydrogen fuel cell technology, and battery storage to tackle this energy challenge. Employing HOMER software for simulation and optimisation, the system architecture is designed to fulfil the Centre's total daily energy demand, prioritising stability, cost-effectiveness, and sustainability. Modelling inputs include load demand data, solar resource availability, and detailed specifications for system components. Grid integration has been deliberately excluded, reflecting the Centre's current disconnection and the study's focus on achieving energy Independence in rural areas**.** Table 1 below shows the ideal hybrid system, the seasonal and daily load profile, highlighting an impressive average daily energy demand of 425.6 kWh and a peak power demand reaching 64.78 kW. The graph illustrates energy consumption patterns, offering valuable insights into usage trends.

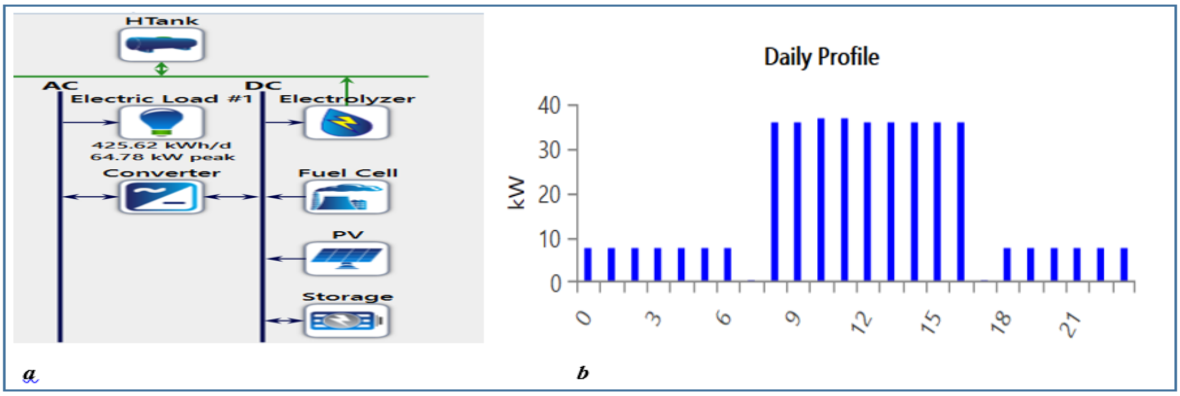

Figure 1: (a)Hybrid energy system architecture.(b) Daily load profile

2.2 Renewable source assessment:

The monthly solar irradiation data of the designated site were acquired from the National Renewable Energy Laboratory (NREL) [7] and the geographical coordinates of Masia Community Development Centre were input into HOMER software. Figure 2 below shows an average daily solar irradiation of 5.85 kWh/m² in 2023. Solar irradiance ranges from 3.93 to 6.5 kWh/m² per day, with peaks in January, November, and December, and the lowest in June. The clearness index varies from 0.501 in February to 0.650 in July.

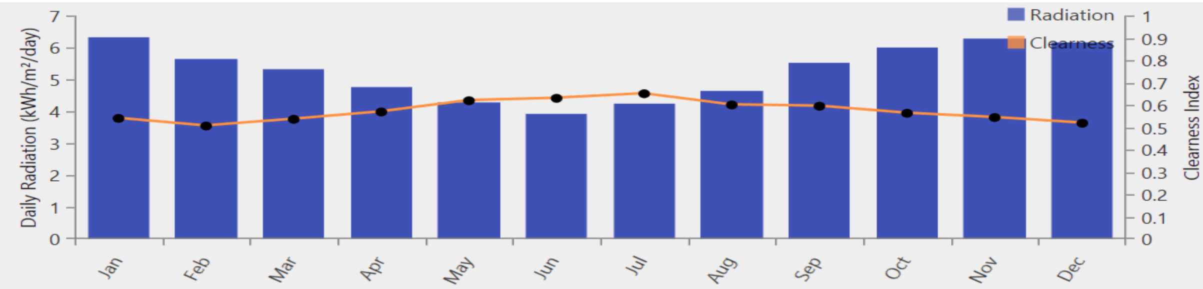

Figure 2 Solar irradiation and clearness of the Masia community development centre

Figure 3 shows the temperature variation at the Masia Community Development Centre over the year, with a recorded daily average low of 15.58°C in July and a high of 25.54°C in January. This fluctuation reflects the seasonal trends of the Southern Hemisphere, showcasing warmer summers and cooler winters, which is crucial for evaluating microgrid system performance.

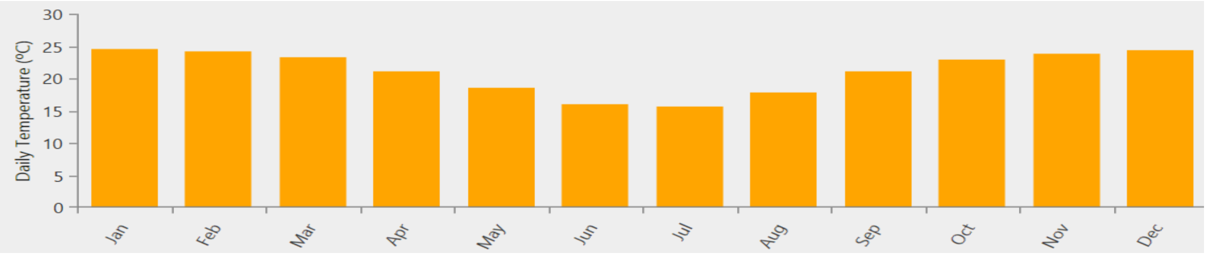

Figure 3: Monthly average temperature

2.3 System components

This study employs photovoltaic (PV) panels, a fuel cell, batteries, and a converter, all modelled in HOMER software, to simulate and analyse an off-grid hybrid energy system. The PV system serves as the primary power source, while the batteries provide energy during periods of low solar input. If the PV panels and batteries cannot meet the energy demand, the fuel cell activates to supply additional power. Any excess energy generated by the PV panels is utilised for electrolysis, which produces hydrogen and recharges the batteries, thereby ensuring a reliable off-grid energy supply. [8].

(a) PV generator model: The power generated by the solar photovoltaic (PV) panels is given by [8, 9]

$$P_{PV} = P_{R-PV}\left[\frac{G}{G_{ref}}\right]\left[1 + K_T\left(T_c - T_{ref}\right)\right],$$

where: P_{PV} is the power generated by the solar photovoltaic(PV) panels, P_{R-PV} is the rated power at the reference condition, G is the solar radiation in $W/_{m^2}$, G_{ref} is the solar radiation at a reference condition and is given by $G_{ref} = 1000\,W/_{m^2}$, T_{ref} is the total cell temperature at reference conditions ($T_{ref} = 25°C$), K_T is the temperature coefficient of the PV panels, T_c The cell temperature.

(b) Battery model: The battery capacity, C(t) at a point in time t, is calculated by HOMER with the equation [10]:

$$C(t) = C(t-1) - \eta_{batt}\left(\frac{P_B(t)}{V_{Bus}}\right)\Delta t$$

where: $C(t-1)$ Battery capacity at the previous increment

: $P_B(t)$ Battery input /output power given by: $P_B(t) = E_g(t) - E_i(t)$

(c) Fuel cell model: The output power of an FC was determined by Eq [11].

$$P_{FC} = (P_{tank-FC})(\eta_{FC})$$

where: P_{FC} is the output power of the fuel cell (in kilowatts, kW), $P_{tank-FC}$ is the input power supplied from the hydrogen tank to the fuel cell, and η_{FC} is the efficiency of the fuel cell.

- Eq estimates the power transferred from the electrolyser to the hydrogen storage tank.

$$P_{elec-tank} = (P_{ren-elec})(\eta_{elec})$$

where: η_{elec} is the electrolyser efficiency assumed to be constant.

- Eq expresses the output energy stored by the hydrogen tank[12].

$$E_{H_2\,.tank} = E_{H_2.tank}(t-1) + \left[P_{elec.tank}(t) - \frac{P_{tank.FC}}{\eta_{Storage}}\right]\Big/_{\Delta t}$$

2.6 Financial metrics: The NPC and LCEO: HOMER calculates NPC by the formula [10, 13, 14]:

$NPC = \frac{C_{ann.tot}}{CRF(i \times proj)}$

Where: $C_{ann.tot}$ is the total annualised cost of the system, CRF is the capital recovery factor, i is the interest rate in %, and $proj$ is the project lifetime.

The capital recovery factor (CRF) is determined by [10, 13, 14] :$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$

Where: i is the real interest rate, and N is the period/number of years.

HOMER uses the following equation to calculate the Levelized cost of energy [10, 13]:

$LCOE = \frac{C_{ann.tot}}{E_{prim} + E_{def}}$

Where: $C_{ann.tot}$ is the total annualised cost, E_{prim} is the total amount of primary load that the system serves per year, E_{def} is the total amount of deferrable load that the system serves per year,

3. Results and Discussion

Table 1 below shows the optimisation results for hybrid energy system configurations featuring photovoltaic (PV) panels, battery storage, fuel cells, hydrogen tanks, converters, and electrolysers, based on their Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), and Operation & Maintenance (O&M) costs. Case 1 emerges as the most economically viable option with the lowest NPC of R5.22 million, LCOE of R2.62, and O&M costs of R167,733, utilising a 148 kW PV system and 40 kW fuel cell. In contrast, Case 2 increased electrolyser size results in higher costs, while Cases 3 and 4 show diminished returns on investment despite larger hydrogen tank capacities. Case 5, although having a slightly lower LCOE, also reflects significant costs. Overall, Case 1 is identified as the most cost-effective solution for rural electrification with a hybrid PV/H_2 fuel cell/battery microgrid.

Table 1 Optimisation results of the PV-Fuel cell-battery hybrid power system

Case	**PV (kW)**	**Batt kW**	**FC (Kw)**	**H_2 Tank (Kg)**	**Conv (KW)**	**EL (kW)**	**NPC (R)**	**LCOE (R)**	**O&M**
1	148	64	40	1000	72.9	30	R5.22M	R2.62	R167 733
2	150	64	40	1000	30	1200	R5.80M	R2.92	R188 671
3	150	64	40	1400	200	70	R8.74M	R4.40	R272 040
4	150	64	50	2000	133	50	R9.05M	R5.55	R309 342
5	125	64	60	3000	167	30	R9.61M	R4.83	R390 771

3.1 Energy production

Based on a monthly analysis, Figure 4 illustrates how solar PV and Fuel cell systems generate varying amounts of electricity throughout the year. Solar PV generates the highest amount of electricity, while the fuel cell serves as a backup, as simulated by Homer. Throughout the year, PV production, represented by orange bars, serves as the primary energy source, consistently generating over 20 MWh each month, with the fuel cell contributing less than 3 MWh each month. The peak production occurs in March and April, likely reflecting increased solar irradiance. Contributions from the grid, represented by green bars, are minimal across all months, highlighting the site's significant reliance on solar energy. The relatively stable PV output indicates an effective solar system, with seasonal fluctuations corresponding to variations in solar exposure. The hybrid system has an annual energy production of 273,314 kWh, with the PV producing 242,516 kWh, which accounts for 88.7% of the total output, and fuel cell production of 30,779 kWh, which accounts for 11.3% of the total output. The renewable fraction stands at an impressive 100% with a capacity shortage of 0.0877%, demonstrating the system's effectiveness in fulfilling the facility's energy requirements.

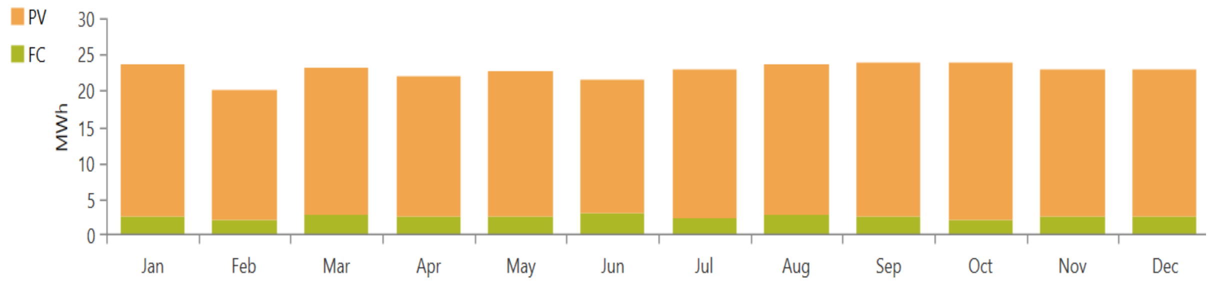

Figure 4: Monthly energy production from PV and FC

Figure 5 demonstrates annual photovoltaic (PV) power generation variability under different conditions, highlighting a significant winter output reduction due to shorter daylight hours. The system consistently meets daily energy demands, producing surplus energy stored in batteries or converted into hydrogen fuel, enhancing its reliability. Despite less favourable weather during the winter months, the PV array's capacity to provide a steady energy supply further contributes to its dependability. A seasonal trend emerges, resembling a bell curve, with energy production peaking from spring to early autumn. During this peak period, output remains consistently high between 8 AM and 4 PM, reaching its maximum around midday.

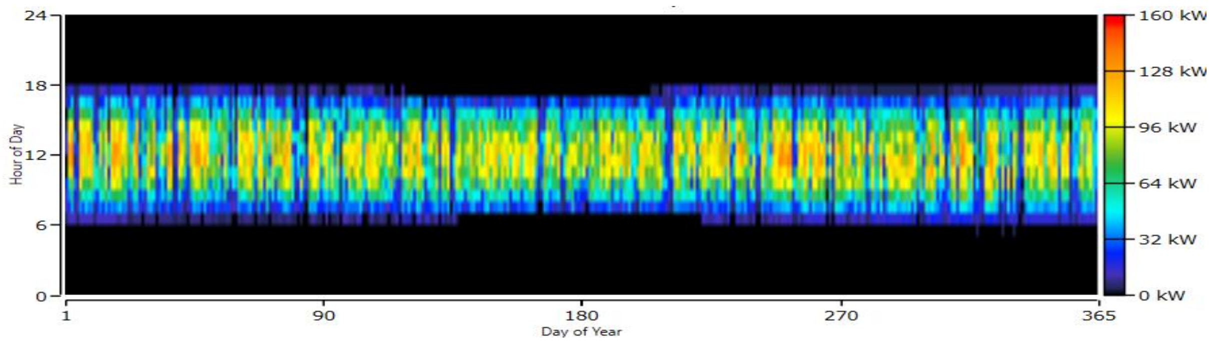

Figure 5: The power output from the PV array

Figure 6 illustrates the activity of the fuel cell throughout an entire year. It shows that the fuel cell is primarily active during daylight hours, especially between 06:00 and 18:00, with peak activity around midday. This pattern indicates that the fuel cell is mainly used as backup support during periods of high demand or when solar energy is insufficient. During nighttime, activity is minimal or non-existent, represented by predominantly black and dark blue regions on the figure. The fuel cell is utilised more frequently in winter due to reduced solar irradiance and shorter daylight hours. It operates non-continuous, demand-driven manner, supplementing the hybrid system only when needed. This suggests that, under normal conditions, there is a primary reliance on solar photovoltaic (PV) energy and battery storage.

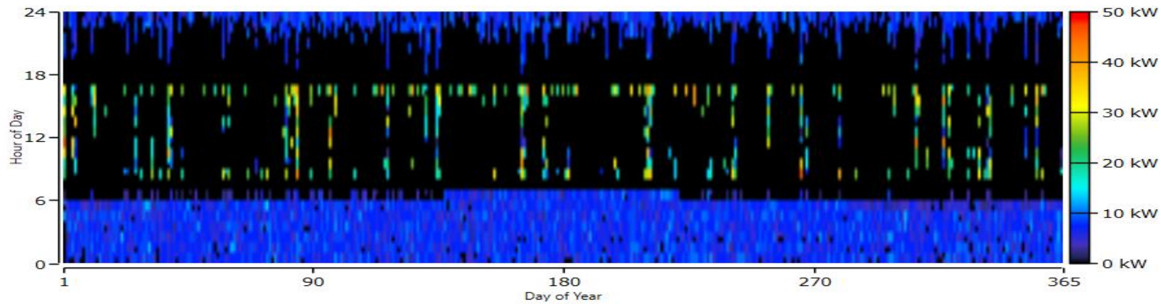

Figure 6: The power output from the Fuel cell

4. Conclusion

The simulation of a hybrid microgrid that combines photovoltaic (PV) systems, hydrogen fuel cells, and batteries presents a viable and cost-effective solution for rural electrification in South Africa. The analysis demonstrates that integrating hydrogen fuel cells for long-term storage alongside batteries for short-term use significantly enhances system resilience in off-grid applications for remote areas. Case 1 gives the most economical configuration, featuring the lowest Net Present Cost (NPC) of R5.22 million and a competitive Levelized Cost of Energy (LCOE) of R2.62/kWh, coupled with minimal operation and maintenance (O&M) expenses. An optimally sized hybrid system effectively reduces costs while ensuring a reliable energy supply. This reinforces the potential of hybrid PV/Fuel cell systems as sustainable and decentralised solutions for off-grid rural electrification in South Africa.

5. References

[1] DE, "IRP. Integrated Resource Plan," Department of Energy, 2019.

[2] V. Motjoadi, P. Bokoro and M. Onibonoje, "A review of microgrid-based approach to rural electrification in South Africa: Architecture and policy framework," *Energies,* vol. 13, no. 9, p. 22, 2020.

[3] CSIR, "Solar Energy Resource Map of South Africa.," Council for Scientific and Industrial Research., Pretoria, 2021.

[4] S. Zulu, S. Mahlalela and O. Mutanga, "Techno-economic analysis of hybrid microgrids in sub-Saharan Africar," *Renewable Energy,* pp. 456-463, 2022.

[5] IRENA, Green Hydrogen-A Guide to Policy Making, Abu Dhabi: International Renewable Energy Agency IRENA, 2020.

[6] L. Mbali and O. Dzobo, "Design of an Off-grid Hybrid PV/Diesel Energy System with Battery Storage for Electrification of a Remote Region: A Case Study of Upper Blink Water Community, South Africa," in *2021 IEEE AFRICON*, Arusha, Tanzania, 2021.

[7] H. Al-Najjar, H. El-Khozondar, C. Pfeifer and R. Al Afif, "Hybrid grid-tie electrification analysis of bio-shared renewable energy systems for domestic application.," *Sustain. Cities Soc.,* vol. 77, 2022.

[8] B. Adebanji, O. Atoki, T. Fasina, O. Adetan and A. Abe, "Comparative study of off-grid and grid-connected hybrid power system: issues, future prospects, and policy framework," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 22(2), pp. 752-759, 2021.

[9] K. Okedu, R. Uhunmwangho and N. Bassey, "A Comparative Study of on and off Grid Tied Integrated Diesel Solar PV Generation System," *INTERNATIONAL JOURNAL OF ENGINEERING TECHNOLOGIES,* vol. 1, 2015.

[10] T. Lambert, P. Gilman and P. Lilienthal, "Micropower system modeling with HOMER," *Integration of alternative sources of energy,* vol. 1(1), pp. 379-385, 2006.

[11] A. Alturki, "Optimal design for a hybrid microgrid-hydrogen storage facility in Saudi Arabia," *Energy, Sustainability and Society,* vol. 12(1), pp. 1-17, 2022.

[12] F. Thanaa, M. Eskander and M. T. (. El-Hagry, "Energy flow and management of a hybrid wind/PV/fuel cell generation system," *Energy conversion and management,* Vols. 47(9-10), pp. 1264-1280, 2006.

[13] R. Dash, L. Behera, B. Mohanty and P. K. Hota, "Cost and sensitivity analysis of a microgrid using HOMER-Pro software in both grid-connected and standalone mode," *ICRIEECE,* pp. . 3444-3449, 2018.

[14] S. Asamoah, S. Gyamfi, F. Uba and G. Mensah, "Comparative assessment of a stand-alone and a grid-connected hybrid system for a community water supply system: A case study of Nankese community in the eastern region of Ghana," *Scientific African,* vol. 19, 2022.