DEVELOPMENT OF A COST-OPTIMAL POWER SUPPLY FOR RURAL NAMIBIA: AN OEMOF-BASED CASE STUDY OF TSUMKWE

Summary

This study addresses the critical electrification gap in Sub-Saharan Africa by optimising a standalone mini-grid for *Tsumkwe*, Namibia. Using the *Open Energy Modelling Framework*, a hierarchical optimisation identifies the most cost-effective and sustainable energy mix. The research evaluates solar PV, wind, biomass, and grid connection variants. Results show that expanding the PV capacity to 700 kW_P is the global optimum, yielding a 55 % reduction in annual system costs and an 88 % decrease in CO_2 emissions. The findings confirm that decentralised renewable systems provide superior energy security and economic viability compared to grid extensions in sparsely populated regions.

Keywords: Mini-Grids, Rural Electrification, OEMOF, Techno-Economic analysis, Sub-Saharan Africa

Field of application for the findings: Rural energy planning and decentralised infrastructure development

Addressed audience: Energy policy makers, energy utilities, and renewable energy researchers

1. Introduction

The global challenge of universal energy access is most acute in Sub-Saharan Africa (SSA), where a significant portion of the population remains without modern electricity services (The World Bank, 2024). While the global electrification rate has reached above 90 % (IEA et al., 2025, p. 15), the deficit in SSA continues to widen, accounting for 85 % of the global population without access (IEA et al., 2025, p. 115). In sparsely populated countries like Namibia, where the population density is only four people per square kilometre (The World Bank, 2023), traditional grid extension is often expensive and technically challenging.

Solar mini-grids have emerged as a primary and robust technology for rural electrification, providing a scalable and decentralised alternative to centralised power systems or grid extension. The economic viability of these solutions has been significantly enhanced by a dramatic decrease in the price of photovoltaic (PV) technology. Consequently, solar PV has become a cost-effective source of electricity, creating opportunities for African countries to expand energy access through decentralised renewable energy infrastructures rather than fossil-fuel-based development pathways.

Beyond basic lighting, solar mini-grid systems facilitate essential social services, including healthcare through vaccine refrigeration, education via digital resources, and economic growth through productive energy use. Namibia, possessing some of the highest solar radiation levels globally, is uniquely positioned to capitalise on these technologies. However, existing mini-grid systems in Namibia suffer from degradation due to maintenance deficits and shifting demand (Institute of new Energy Systems (InES), 2024, p. 9), necessitating advanced computational tools for systematic optimisation and planning.

2. Tsumkwe: The Case Study Area

The settlement of *Tsumkwe*, located in the northeastern region of Namibia, serves as a case study for this investigation. *Tsumkwe* is home to approximately 4,000 residents from diverse ethnic backgrounds. The settlement's remote location – approx. 600 km from the capital, Windhoek – makes connection to the national electricity grid economically challenging. Current infrastructure includes primary and secondary schools, a clinic, and a police station, all of which rely on a stable power supply (Mehta et al., 2025).

In 2011, a hybrid mini-grid system was installed in *Tsumkwe*, consisting of a 303 kW_P solar array, a 2,400 kW h lead-acid battery bank, and two 150 kV A diesel generators (Mehta et al., 2025). At the time of commissioning, it was one of the largest hybrid off-grid systems in Africa (Hoeck et al., 2022).

Over time, however, the system has faced significant operational failures. A major issue was the overheating of the battery storage room, where temperatures reached up to 50 °C, leading to accelerated chemical degradation and capacity loss (Institute of new Energy Systems (InES), 2024, p. 17). Coupled with rising energy demand, these failures forced the settlement to rely increasingly on expensive and polluting diesel generation. The current study seeks to provide a data-driven optimisation roadmap to restore and expand this system sustainably.

Although *Tsumkwe* is currently off-grid, the national electricity grid has recently been extended to Mangetti Dune, located approximately 80 km away (Lwakatare et al., 2024). This development raises a critical research question: Is it economically and technically more viable to extend the grid infrastructure to *Tsumkwe* or to rehabilitate and optimise the existing decentralised mini-grid? This study directly addresses this trade-off by simulating a grid-extension scenario against the off-grid optimisation.

3. Optimisation of the Tsumkwe Mini-Grid System

The methodology utilises the *Open Energy Modelling Framework* (OEMOF), specifically the oemof.solph library, to perform a hierarchical optimisation of the *Tsumkwe* mini-grid system (c.f. figure 1). OEMOF is an open-source Python framework that represents energy systems as directed graphs of nodes and edges, allowing for modular and transparent modelling (OEMOF Community, 2026). The primary objective is the minimisation of the total annual system costs (annuity) over a 20-year lifetime, accounting for capital expenditures (CAPEX), operating expenses (OPEX), and demand-related costs such as fuel.

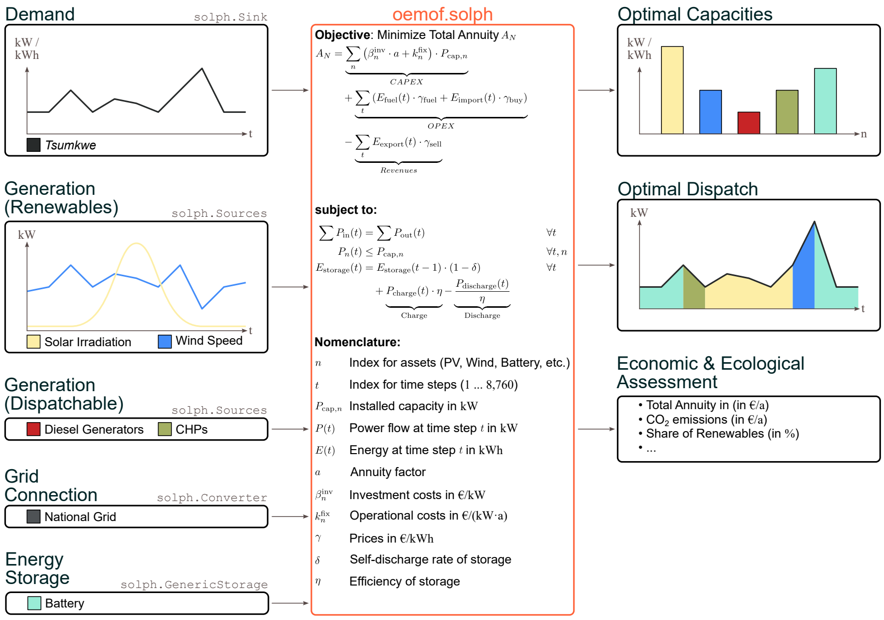

Fig. 1: Schematic overview of the OEMOF workflow. Left: Input; Middle: Optimisation kernel; Right: Results.

The optimisation space explores various technological configurations, such as wind power, biomass-based combined heat and power (CHP) units, and a potential connection to the national grid, alongside the expansion of photovoltaic and battery storage capacities. The model integrates high-resolution input data, including hourly meteorological time series (solar irradiance and wind speed) and real consumption profiles measured in *Tsumkwe*.

Technical constraints, such as the efficiency of diesel generators and discharge rates of storage systems, are enforced to ensure physical accuracy. By simulating 8,760 hours of operation, the model evaluates energy flows and potential system bottlenecks, such as battery state-of-charge limits.

4. Results and Discussion

The optimisation analysis reveals that photovoltaic-based expansion is the most efficient configuration for *Tsumkwe*. The model determines that an additional 400 kW_P of solar capacity should be installed, increasing the total installed capacity to approximately 700 kW_P. This expansion is sufficient to eliminate the need for diesel generation entirely, provided the existing 2,400 kW h battery capacity is restored to full functionality.

Alternative technologies were selected within the cost-optimal solution: wind energy was found to be uncompetitive due to low average wind speeds (6.1 m/s), while biomass-fired plants and national grid extension were excluded due to high fixed costs and infrastructure requirements (Lwakatare et al., 2024).

Economic results show a 55 % reduction in annual system costs compared to the diesel-dominated baseline, saving approximately 65,000 € per year. Over the 20-year lifetime, total savings exceed 1.3 million €, with the new solar investment paying back within nine years. These findings confirm that decentralised solar is a "bankable" solution for rural Namibia. Ecologically, the optimised system reduces lifecycle CO_2 emissions by 88 %. This synergy between cost reduction and decarbonisation suggests that economic and environmental goals are mutually reinforcing in the SSA context.

5. Conclusion

This study provides a robust blueprint for the optimisation of rural mini-grid systems in SSA. By applying the OEMOF framework to the case of *Tsumkwe*, it has been demonstrated that a transition to a 100 % renewable power supply is both financially advantageous and ecologically responsible. The recommended expansion to 700 kW_P of PV capacity offers a clear pathway to energy autarky, reducing system costs by over 55 % while significantly contributing to national climate targets.

The practical implications for Namibian authorities are immediate: prioritising the solar expansion and restoring battery infrastructure is the most viable path to securing *Tsumkwe*'s energy future. For researchers, the modularity of the open-source modelling approach allows for its application across various geographic and economic contexts within the SSA region. Ultimately, this data-driven planning methodology facilitates the leapfrogging of fossil-fuel infrastructure, empowering remote communities through decentralised, clean, and stable energy systems.

References

Inken Hoeck, Elmar Steurer, Özge Dolunay, and Helvi Ileka. Challenges for off-grid electrification in rural areas. assessment of the situation in namibia using the examples of gam and tsumkwe. *Energy, Ecology and Environment*, 7(5):508–522, 2022.

IEA, IRENA, UNSD, The World Bank, and WHO. Tracking SDG 7: The energy progress report. Technical report, 2025. Available at: https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2025 (Accessed: 12 February 2026).

Institute of new Energy Systems (InES). CLIENT II – pathway to renewable off-grid community energy for development. Technical report, Technische Hochschule Ingolstadt (THI), 2024.

Bertha Lwakatare, Priyanka Vyavahare, Kedar Mehta, and Wilfried Zörner. Electrification planning for off-grid communities in sub-saharan africa: Advancing energy access. *Energies*, 17(23), 2024.

Kedar Mehta, Bertha Lwakatare, Wilfried Zörner, and Mathias Ehrenwirth. Mini-grid performance in sub-saharan africa: case studies from tsumkwe and gam, namibia. *Sustainable Energy Research*, 12(1), 2025.

OEMOF Community. oemof.solph v0.6.2. https://oemof-solph.readthedocs.io/en/stable/, 2026. (Accessed: 12 February 2026).

The World Bank. Population density. https://data.worldbank.org/indicator/EN.POP.DNST, 2023. (Accessed: 12 February 2026).

The World Bank. Access to electricity. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS, 2024. (Accessed: 12 February 2026).