Technical Feasibility Study of Micro-Grid Integration to Electrify Rural Settlements of Sub-Saharan Africa

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Abstract

Two thirds of Sub-Saharan Africa's (SSA) population reside in rural communities. SSA is the least electrified region in the world with approximately half of its population lacking access to electricity which hinders its citizens' livelihood and economic engagement. Electrification efforts by member nations have and continue to be done according to the respective energy policies. While the national utility companies are at the forefront of this process, geographical, economic, and time factors constrain the achievement of targeted electricity access rates in allocated timelines. Alternative electrification approaches, therefore, need to be implemented. As a case study, this paper focuses on electrification by integrating existing micro-grids into mini-grids to electrify currently unelectrified business and household settlements of Uutsathima village in Namibia. This approach averts the hindering factors for grid extension whilst utilizing the abundant and untapped solar energy. Results of this study indicate that exiting micro-grids have substantially higher electricity production than the primary consumers' demand. This allows for connecting new consumers within the proximity of the grids provided prior analysis of their energy demand is done. Given that minimal infrastructure upgrade is done, for instance, Uutsathima's business centre can be electrified. For result replicability, the methodology of this paper serves as a guide to determining the best scenarios in other off-grid regions of SSA.

Keywords: Electricity, micro-grid, mini-grid, Namibia, off-grid regions, Sub-Saharan Africa, unelectrified settlements

1. Introduction

1.1 Background and context

Given the population share Sub-Saharan Africa (SSA) has in comparison to the global population, cross-cutting issues such as the United Nation's sustainable development goals (SDG) require emphasis to avoid imbalanced development against social welfare (IEA, 2022). Since 2016, in response to the SDG 7, member countries of SSA have continually dedicated efforts, policies, and regulations to increase both reliable electricity access and affordability to its citizens. Whilst focus was put on extending the radius of the national grid, infrastructural, economic constraints, and off-grid RE global initiatives discourage these efforts. At electrification rates of 25% and 71% for rural and urban areas respectively, alternative solutions are necessary to fasten the electrification efforts (Fritzsche et al., 2019). While only 2% of the total utilized primary energy in SSA is accounted by renewable energies (RE), the region exhibits high potential of solar, wind, hydro, biomass among other RE sources (International Renewable Energy Agency (IRENA), 2022).

Introduction and implementation of off-grid as well as hybrid solutions across the region continue to grow, even though varying between countries due to differences in policies and regulatory frameworks which determine the attraction of private and international RE investors. Solar mini-grids for example, range from 5 to 100 per country (Fritzsche et al., 2019). While the term mini-grid is used mainly to describe a standalone grid of a capacity up to 2 MW (Opfer et al., 2022), this study focuses on grids with smaller capacities as low as 2.88 kW, herein termed as micro-grids. Solar micro-grids have mainly been used to electrify single consumer groups in SSA but record a notable increase in overall national electrification as well as the quality of services of business and public institutions which indicates the potential in these alternative electrification approaches.

This study examines the potential of micro-grid integration as an engineering innovative solution in achieving universal electricity access in off-grid regions.

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1.2 Renewable energy strategies in SSA

Due to accelerated electrification rates and efforts of the international RE and off-grid projects, some of the rural off-grid settlements got equipped with solar-based electricity networks. A practical example is the initiative by the government of Namibia in 2016 to electrify its public institutions by use of solar micro-grids. While this proved to answer the electricity dilemma in public institutions, such installations often neglect the private sector. In the rare case that the private sector was addressed, these systems were often sized incorrectly due to inaccurate energy audit on electricity consumption and requirements of the settlements. Factors such as energy consumption, income scenario of the people and population growth have, in the past, been neglected or underestimated. Uutsathima village, located in the Omusati region in Namibia, home to about 444 people, residing in 81 households is used in this context. The village qualifies as a relevant and typical rural SSA settlement with low population density, low-income citizens, unelectrified settlements and yet within the reach of erected micro-grids.

Uutsathima's micro-grids were commissioned as complete systems of photovoltaic modules, batteries, and inverters. The capacities are shown in Tab.2. Because of the abundance of solar energy, the suitability of solar systems was identified by the Namibian Ministry of Mines and Energy as a solution for the remote off-grid settlements such as Uutsathima. An aerial photo (c.f. Fig.1) of Uutsathima's business centre shows how scattered Uutsathima's settlements are. This layout impacts electricity distribution systems.

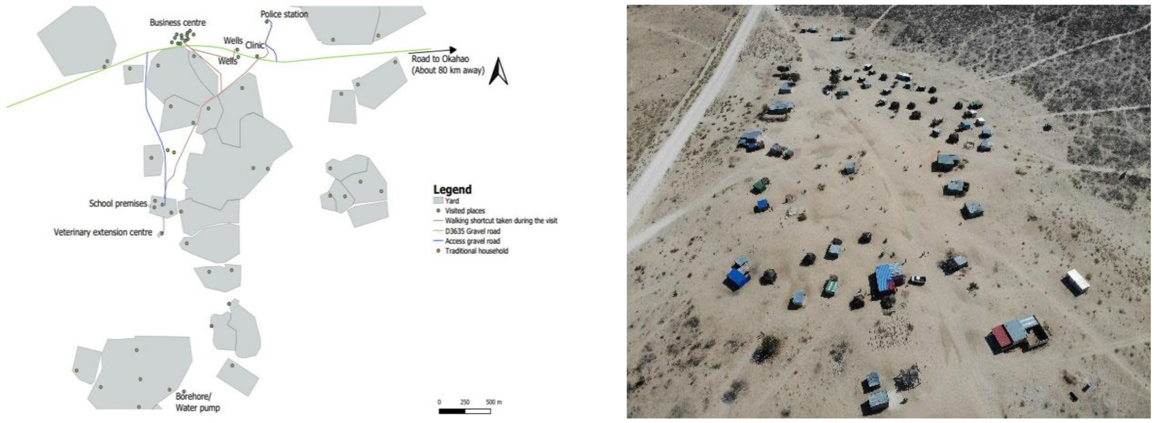

Fig. 1: GIS (Geographic information system) and aerial view of Uutsathima settlement (source: author)

Likewise, the households and business establishments in Uutsathima were neglected. Only the clinic, school, police station, and veterinary extension centre as shown in Fig.2, were recipients of solar off-grid solutions.

Fig. 2: Containerized and rooftop PV systems at the veterinary centre and school in Uutsathima (source: author)

This paper derives its motivation from two areas of focus namely research and implementation. Previous research work as well as existing electrification approaches have overlooked the potential of micro-grid integration which is described consequently.

1.3 Previous works

To date, SSA has adapted various electrification schemes as indicated in Fig.3. To eliminate dependence on the grid as well as non-fossil fuels, solutions ranging from imported solar appliances to mini-grid have been employed from small to large off-grid regions (Vanadzina et al., 2019).

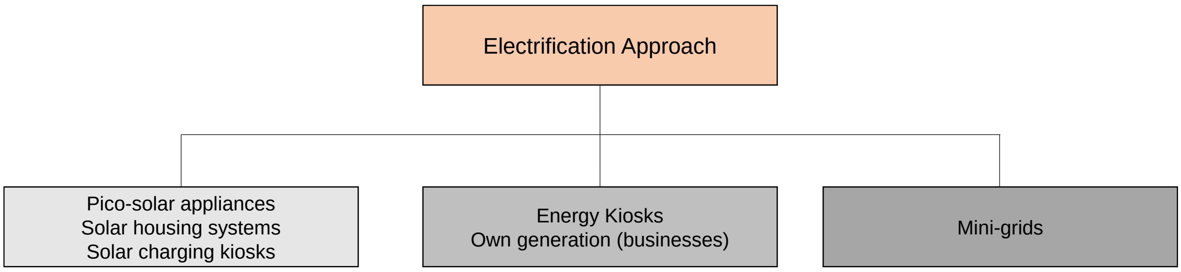

Fig. 3: Existing decentralized electrification solutions in rural SSA (own illustration based on the literature review)

Decentralized solutions have mainly taken two forms, one of which is much supported by international programs and the other relies on imported (mainly from China) and local sales of solar kits and lighting appliances to SSA off-grid regions (Jaglin, 2019). While these may serve as intermittent solutions, none of these thoroughly examine the potential of utilizing the existing infrastructure and grids to expand the radius of electricity access. A thorough search in publication and journal entries was carried out on the topic of micro-grid integration prior to this paper. The literature review results show that research has been devoted towards the role, potential and economic modality of micro-grid operation rather than the idea of integration.

1.4 Gap in the research and research motivation

This existing gap between rural and urban electrification rates as well as public, business and household electrification call for an electrification balance. The integration of the micro-grid is a suitable and simple approach for electrification. However, there is no scientific evidence available for electrification strategies through micro-grid integration for low-population rural settlements in SSA. In response, this paper focuses on the electrification approach by utilizing the already existing microgrids to electrify the previously neglected rural segments. The approach is not prone to barriers and constraints discussed in previous studies in that it uses a demand-side approach to study and analyze the actual electricity demand based on usage patterns as well as appliance ownership. This study also serves as a base for the depiction of future scenarios of micro-grid integration according to the segments making up a unit of settlement. In this case, categorization is given as public institutions, business settlements and households. Results and recommendations also allow for interpolation and translation into other SSA countries or villages depending on the status quo concerning Uutsathima.

2. Research Methodology

To meet the main objective, this paper identifies the implication of residents' actual electrical energy demand to the micro-grids' production. A scenario-based approach is used to generate a blue-print for the electrification approach. Prior to analyzing energy schemes, the selection of a sample rural settlement whose features reflect those of a typical SSA rural settlement was done. Population distribution, electrification situation, geographical behavior especially in effect to solar irradiance and PV potential as well as economic standings prop the selection of Uutsathima village. This paper goes further into segmenting the settlement types within the village based on their activities. Whilst income, number of inhabitants as well as seasonality are often crucial factors to consider in clustering, Lorenzoni et al (2020) report that in rural settings, human activities can be grouped into household needs, community service as well as business or income-generating activities on a small scale with minimal requirement of machinery such as refrigerators. That finding was considered when clustering Uutsathima, especially due to the dominance of pensioners and scholars in the population make-up. As can be seen in Fig.4, this paper follows a specific methodology in attaining the presented results.

Within Uutsathima, a thorough and engineered energy audit was done to understand the demand of the categorized settlements as well as the generation capacities of the existing roof top and containerized micro-grids. Considering that apart from public institutions, the village is mainly unelectrified, the on-site research stays, observations, measurements, and interviews were done to obtain custom data to analyze the actual village energy situation. Such on-site energy audit grants simplicity to generate synthetic load profiles (SLP) that display precise energy consumption values and patterns, due to the absence of electricity meters. Therefore, data collection of precise information on existing appliances per settlement type, their power rating, pattern of use as well as inhabitants' behavior was done. A bottom-up approach was used to generate the community load profile (c.f. Fig.5). The input data were simulated using a MATLAB (The Mathworks Inc., 2021) algorithm which looped every appliance to create independent SLP which were then aggregated to form a single settlement's SLP and then resulted in a single

Uutsathima village load profile as well as scenarios.

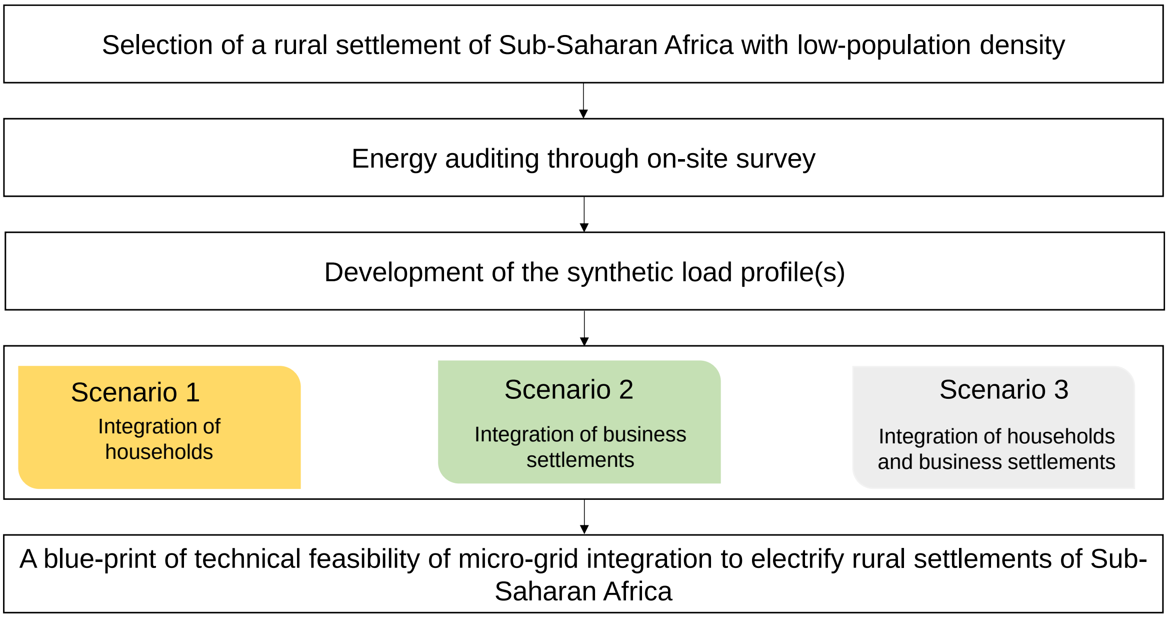

Fig. 4: General research methodology flowchart

An on-ground survey in 2019, identified households as the largest consumer group in Uutsathima and the business centre as a crucial economic zone such that both require electrification to increase safety and productivity. In the presented paper, therefore, three scenarios were considered for mini-grid integration; scenario-1: integration of households, scenario-2: integration of business community and scenario 3: integration of household and business community. The scenarios were also developed by consideration of the local circumstances such as population, income status and routine behavior of the residents.

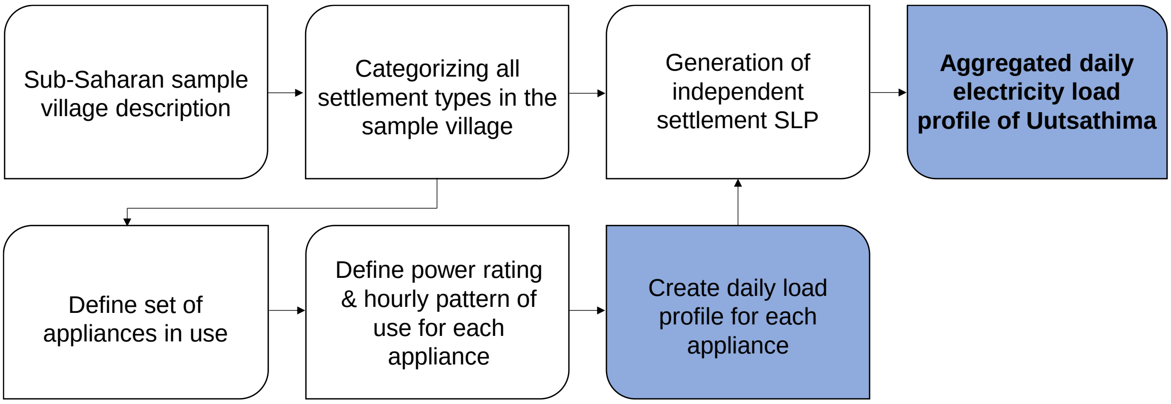

Fig. 5: Methodology for load profile generation

To determine the viability of the presented electrification approach per scenario, respective SLPs were fed into PVsyst (Webgenève, 2022) to size mini-grids whose capacity would meet the actual demand of the integrated consumers. The results from PVsyst (Webgenève, 2022) were then compared in terms of electricity generation as well as storage capacity to envision the feasibility of the existing capacity in meeting the demand and infrastructural requirement for generation, storage, and distribution of electricity.

3. Community Load Profile Development

To understand the electricity demand of the settlement types in Uutsathima as well as the village, this chapter outlines the generated daily average load profiles. The on-site energy audit identified the trend of activities coupled with electricity consumption hence obtaining corresponding peak power, average daily electricity demand and the consumption pattern.

3.1 Description of societal activities and composition

The generation of SLP is crucial for designing, planning, and forecasting electricity production and distribution networks (Chuan and Ukil, 2020). Considering Uutsathima's make-up of 81 households, keenness on the difficulty in forecasting of residential loads due to the variation in load profile resulting from dynamic fluctuations of home appliances is accounted. However, rural settlements often have an advantage of having fewer appliances and activities interlinked with electricity consumption (Flor et al., 2021). Therefore, uniform SLPs are assumed for households. The business centre is segmented into local alcohol vendors, herein termed 'Kapana shops', traditional shops, herein termed 'Kiosk', modern shops that offer cold beverages and phone charging services herein termed 'Shop' and a milling shop. The last cluster considered is the public institutions which encompass the school, clinic, veterinary centre, police station as well as the water pumping station.

3.2 Development of Synthetic Load Profiles (SLP)

The methodology used for development of SLPs (c.f. Fig.5) applies for all customer categories and scenarios. As an outcome, Fig.6 illustrates a daily aggregated SLP of the Uutsathima households upon applying the discussed methodology. It indicates low electrical activities in the households with peak demand at night and no demand at all during the day. A peak power of 6.399 kW at 08:00 PM can be seen. This can be explained by the appliance ownership of in rural regions of developing countries is limited to mainly lights, radios and phones as discussed by (Narayan et al., 2020). The pattern of use indicates the beginning and of the day for household inhabitants suggesting the demand in the mornings and evening when either they wake up or prepare for bed. The afternoon zero electricity demand is explained by the absence of inhabitants during farming or schooling hours. At these hours, cell phones are charged at the shop and radio usage is initiated in the evening for national news and recreation after the end of their outdoor socio-economic activities.

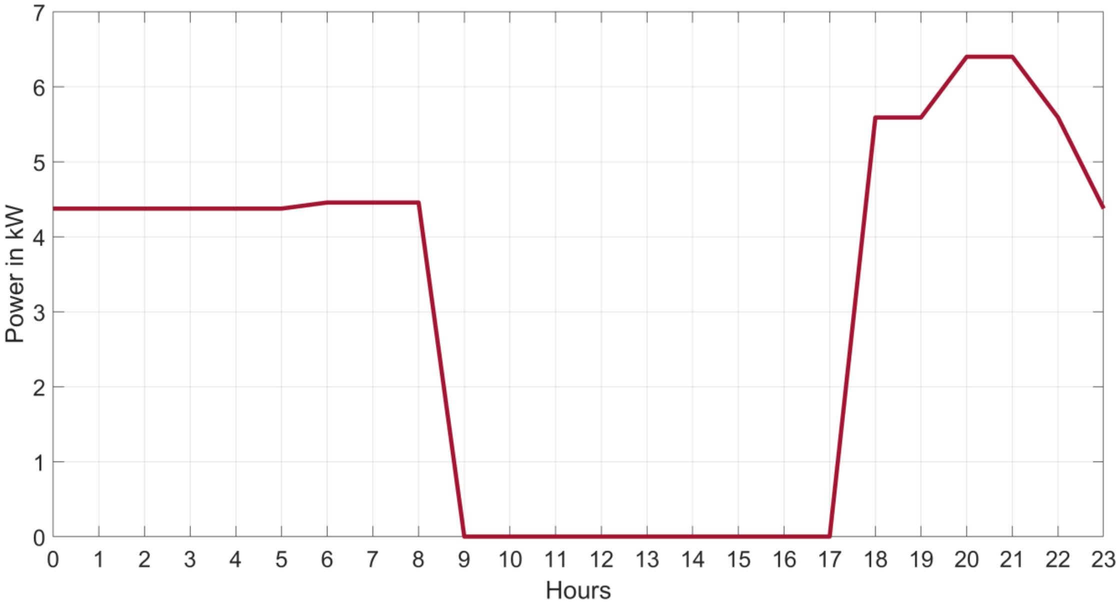

Fig. 6: Daily SLP for Uutsathima households

The business centre, likewise, exhibits an evening peak at 06:00 PM also accounting for the increased business engagement in the evening especially due to the dominance of Kapana shops and the highly rated milling shop in comparison to other electrical appliances. As illustrated in Fig.7, the Kapana shops and kiosks which are limited to lighting application have very low electricity demand in comparison to the shop and milling shop. This can also be seen in Tab.1 which breaks down the peak power and average daily energy consumption per business category. Contrary to the kiosk, the shop exhibits sharp peaks due to the availability of refrigerators and phone chargers. The behavior of power consumption of these activities overshadows the lighting demand. The milling shop whose machine is rated at 3.5 kW can be seen to dominate the electrical demand in the business centre.

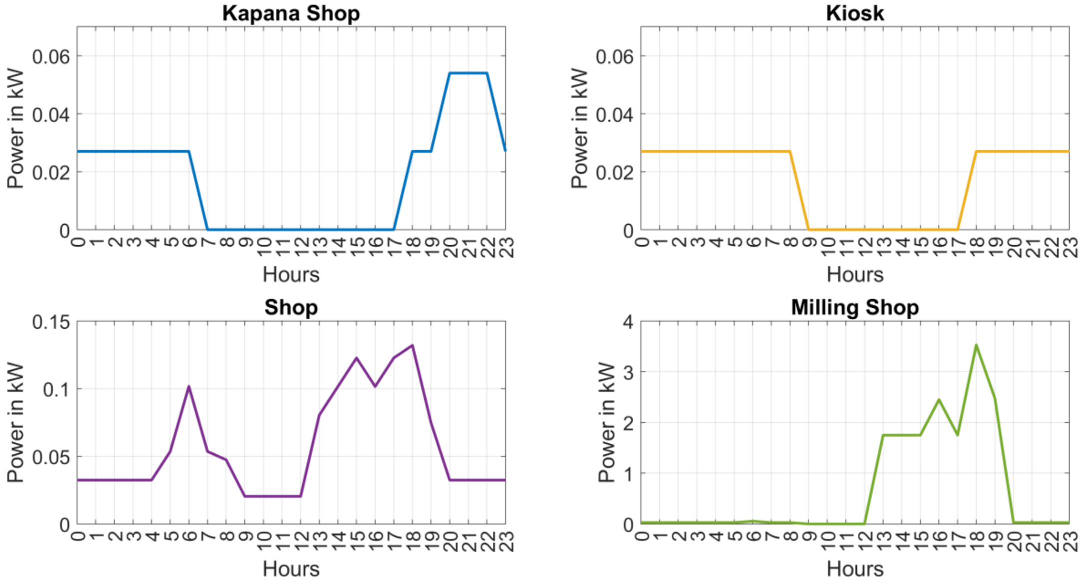

Fig. 7: Daily SLP for business settlements

Due to low income, residents have limited economic capability to mill their flour in large amounts and therefore the need for milling services close to mealtimes. Hence, the milling shop despite its regular opening hours, also exhibits a peak in the evening due to an increase in milling services demand.

Tab. 1 Peak power and daily energy consumption of business segments

Business Unit	Units	Peak Power (kW)	Average Energy (kWh/day)
Kapana shop	50	0.054	0.432
Kiosk	10	0.027	0.405
Shop	4	0.132	1.365
Milling shop	1	3.500	15.832
Business centre	1	5.675	46.942

The public institutions of Uutsathima which are also the primary and the connected consumers to the existing micro-grids exhibit different consumption patterns (c.f. Fig.8). The school in Uutsathima combines the administrative block and the teachers' as well as students' hostel.

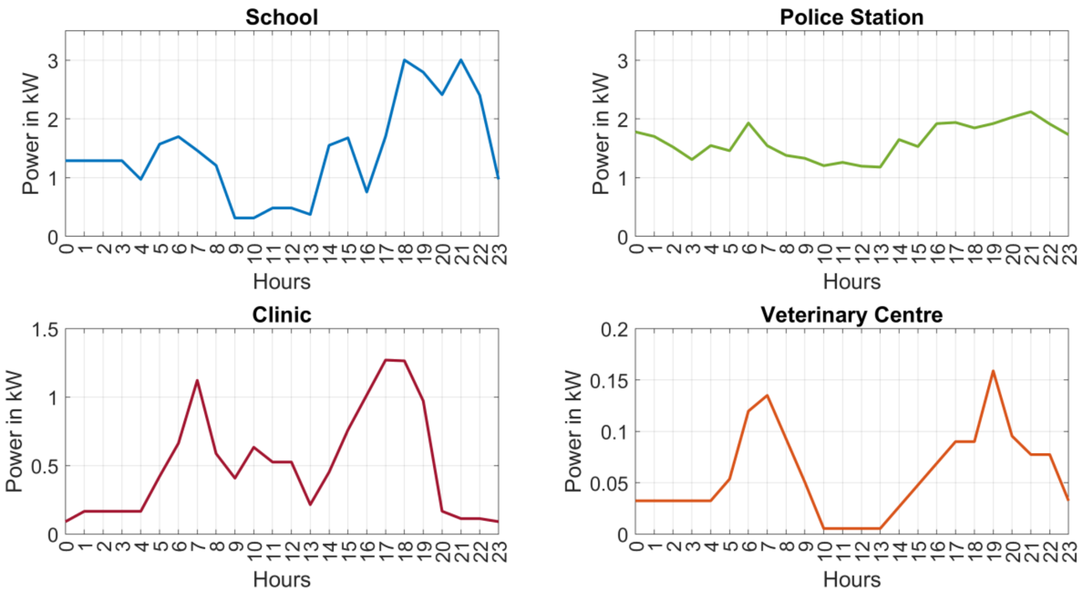

Fig. 8: Daily electrical load profile of Uutsathima's public institutions

The SLP follows the pattern such as that of a residential household due to higher demand in residences than in the school classrooms and offices. However, during the afternoon, power is consumed on printing and photocopying service which results into mid-day peaks. Due to the availability of always-on devices such wi-fi routers and monitors the school always has an electrical consumption. The clinic and veterinary centre were learnt to be equipped with refrigerators due to the demand in medicinal cold storage facilities. An addition of the workers' residence also explains the evening peaks. This research faced a challenge in accessing the police station and therefore the SLP was generated as a 20% factored-down annual SLP of the police station in Tsumkwe, which is a similar off-grid settlement in Namibia.

3.3 Aggregated load profile of Uutsathima village

Based on the generated clustered SLPs, an aggregated profile for the village was then generated to understand the typical consumption of a SSA off-grid rural village. The MATLAB (The Mathworks Inc., 2021) algorithm looped over every appliance and then every settlement to formulate the resulting Uutsathima SLP. The village exhibits a daily peak power and average energy consumption are 15.629 kW and 217.804 kWh/day, respectively.

Fig.9 shows a morning peak mainly due to household consumption and the Uutsathima village water pump turned on at 7:00 AM. Reduced activities at households, schools, and veterinary residences demonstrate a drop in consumption, leaving minor consumption and the water pump until the pump is switched off. In the evenings, the village exhibits higher demand due to increased residential activities, milling activities and liquor sales at the business centre.

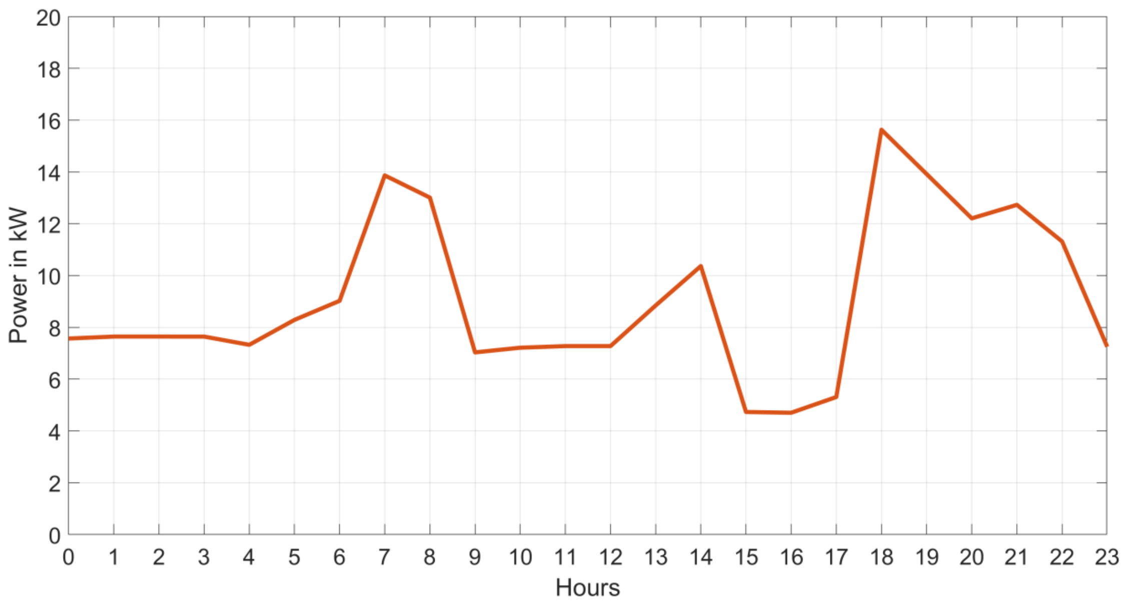

Fig. 9: Aggregated daily SLP of Uutsathima village

4. Energy Supply Scenario

Integration of micro-grids relies solely on the pre-existing capacity. In this chapter, the existing capacities which were obtained through the on-site survey are presented. Likewise, the generation of three scenarios by illustration of SLP is explained.

4.1 Existing micro-grid capacities

The energy supply is based on the existing micro-grids whose capacities (c.f. Tab.2) are, in this paper, analyzed on whether it is suitable to cover for the energy demand of the unelectrified categories. In the analysis of this paper, all capacities are considered regardless of their status of operation.

Tab. 2 Overview of the existing Uutsathima micro-grids

Micro- Grid	Component Capacities			Status
	PV Module (kWp)	Batteries (kWh)	Inverter (kW)	
Clinic	6.00	43.20	8	Operational
Veterinary centre	2.88	72.96	5	Not operational
School residences	2.88	109.44	3	Operational
School administration	2.88	109.44	5	Operational
Police station	8.00	87.36	5	Operational
Police water treatment	3.51	28.80	4	Operational

The answer to the research question, categorizing the demand side into different possible approaches, is done to identify the best applicable approach to utilize the total capacity of the existing micro-grids. The scenarios were distinguished and integrated into three scenarios.

Scenario 1: Integration of households

Scenario 2: Integration of business community

Scenario 3: Integration of household and business community (the whole village except the water pump)

4.2 Scenarios

Due to the pattern of consumption of the village as well as the high evening demand, the availability of enough storage capacity is crucial which relies on the generation time. However, due to the water pump's dominance in energy consumption at peak production hours, the pump was in neglected from all scenario generations. Fig.10 shows the consumption pattern of the water pump which in fact accounts for 19% of the daily villages' electrical energy consumption share. This paper recommends the use of a solar-powered borehole pump for water pumping purposes in such rural settlements.

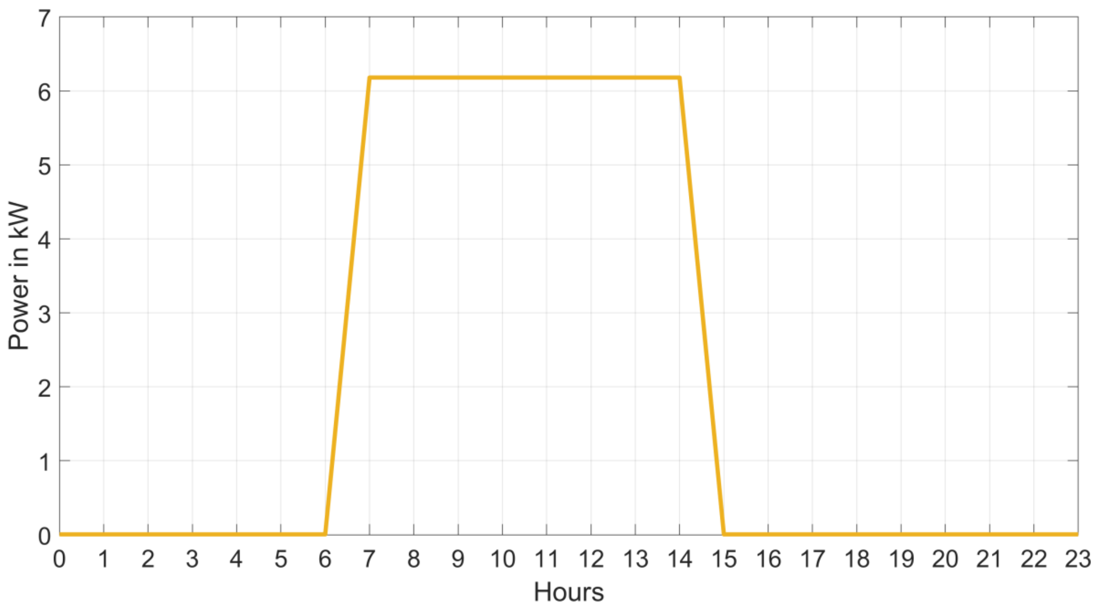

Fig. 10: Daily electricity load profile of the water pump

Since public institutions remain the primary consumers of the existing generated electrical power, all three scenarios integrate their demand. Fig.11 shows a comparison between the electricity demand of the generated scenarios. Scenario 1 exhibits a peak power of 12.62 kW, an average power of 5.58 kW and total average energy consumption of 134 kWh/day. It can be noted that regardless of the inclusion of all public institutions in the load profile, the influence of households dictates the shape of the curve (c.f. Fig 11). While households exhibit no energy demand during the day, refrigerators and Wi-Fi routers from public institutions raise the energy demand during the day.

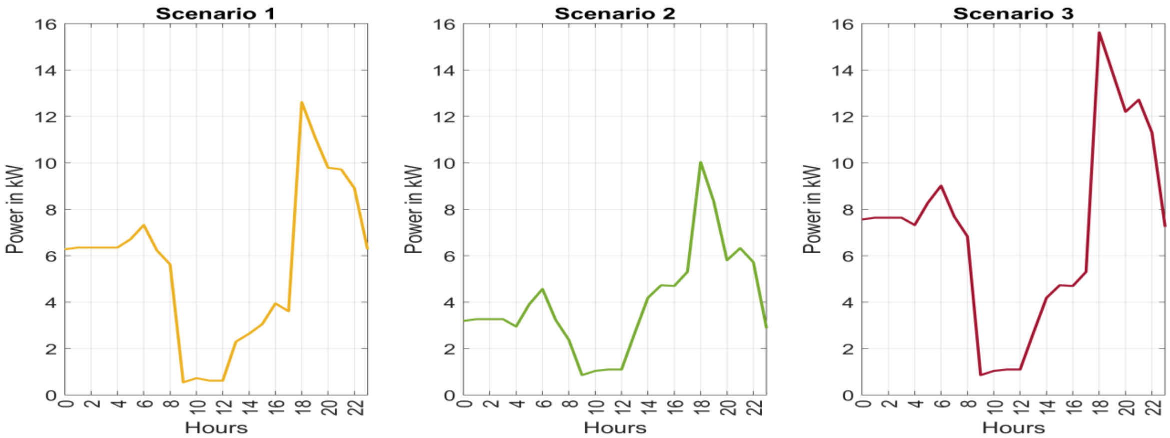

Fig. 11: Daily electricity load profile for generated scenarios

Scenario 2 exhibits the lowest energy demand due to small loads at the business centre. Peak power of 10.03 kW at 6:00 PM is mainly due to the business centre's milling machine, which is the highest-rated appliance in Uutsathima. Due to low demand at the business centre and the irregular consumption pattern, the load profiles take shape mainly of the public institutions except for the evening peak, which explains the high demand due to most business entities operating in evening hours.

Scenario 3 exhibits peak power of 15.62 kW at 7:00 PM, influenced by an increase in activity in households, business centre and all other residential settlements at the school, clinic, and veterinary centre's residents. It also has an average power consumption of 7.01 kW and daily energy consumption of 168 kWh/day. This scenario excludes the water pump and is therefore no summation or aggregation of scenario 1 and 2.

Tab.3 summarizes the peak power and daily energy demand per scenario.

Tab. 3 Peak power and daily energy consumption of scenarios

Scenario description	Peak power (kW)	Daily energy (kWh)
Integration of households	12.62	134
Integration of business community	10.03	95
Integration of household and business community	15.62	168

5. Results & Discussion

Using the simulation and energy audit methods discussed, this chapter presents the results from running PVsyst simulations to size a mini-grid for every scenario using elaborate illustrations and graphs. The PVsyst simulation also input meteo data on Uutsathima's temperature, diffuse and direct solar irradiation over the last decade to achieve custom reliable results.

5.1 Design of mini-grids for developed scenarios

For scenario 1 and assuming a uniform profile throughout the year, system components for storage and PV arrays were selected. Due to the absence of critical loads and low energy demand, one day of autonomy is considered for the battery bank. System design in PVsyst yields a mini-grid of 25.30 kWp and an annual energy production of 46.43 MWh/year. Scenarios 2 and 3 were simulated using the same approach. The mini-grid capacities obtained were 18.40 kWp with annual production of 33.69 MWh/year and 32.20 kWp with annual production of 58.02 MWh/year for scenarios 2 and 3 respectively. Scenario 3, unlike the previous two, has a collective summation of Uutsathima's power consumption. An increase in demand suggests that a larger capacity mini-grid would be required to meet the village's electricity demand. A summary of the three sized mini-grids is given in Tab.4. For feasibility of micro-grid integration, both the PV and battery storage capacities should sustain the energy demand of the expected consumers. In this case the comparison can be made against the sized mini-grids per scenario. Fig.12 shows the monthly mini-grid energy production for every scenario.

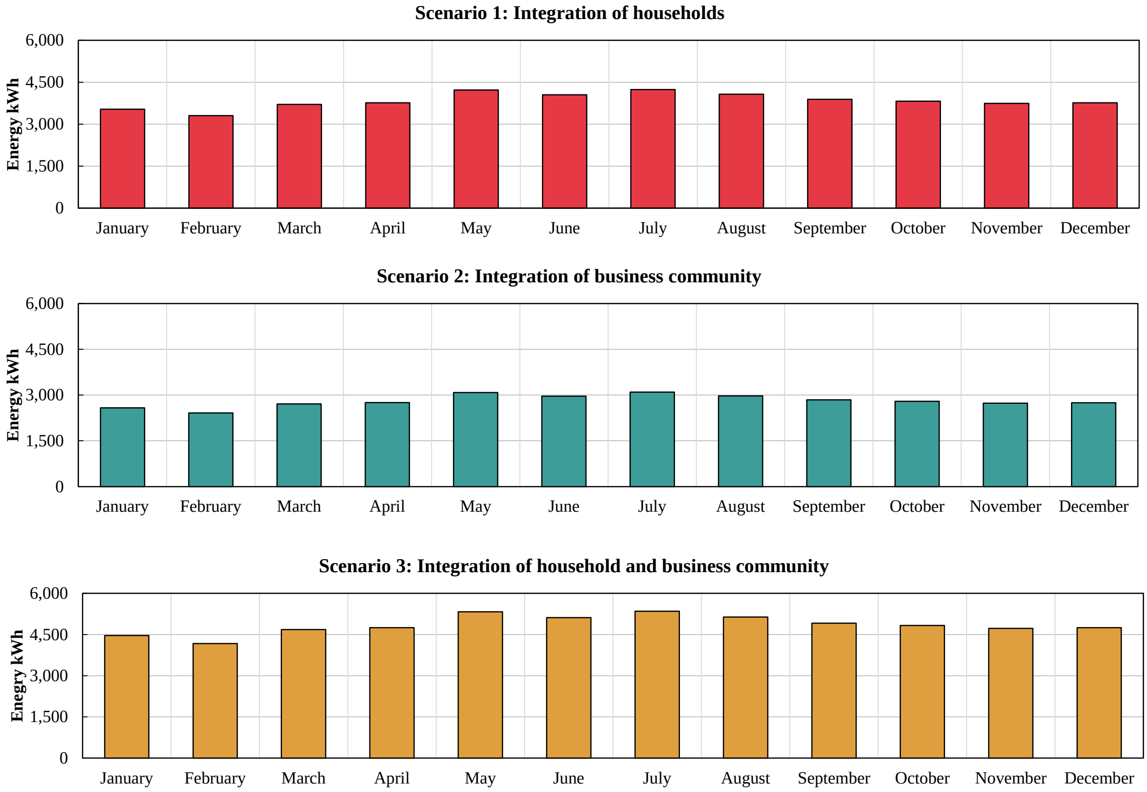

Fig. 12: Monthly PV mini-grid electricity generation for scenarios 1, 2 & 3

5.2 Result discussion

To establish the feasibility of micro-grid integration, this paper used a bottom-up approach to generate load profiles representing the actual demand of Uutsathima village. Categorizing its settlements helped link demand and supply sides by considering three different scenarios. Whilst the goal is to meet the village's demand by utilizing the existing capacity, the engineering approach used was to size a mini-grid for each scenario to determine the required capacity.

Tab. 4 Mini-grid results for the three case scenarios

Parameter	Value			Number of components		
Scenario	1	2	3	1	2	3
System capacity (kWp)	25.30	18.40	32.00	1	1	1
PV modules (Wp)	230.00			110	80	140
Batteries (V / kWh)	96 / 559.10	96/ 279.60	96/279.60	96	48	48
Performance ratio (%)	74.01	74.42	72.64	-		

The location and distance between existing micro-grids affect the infrastructure for transmission and distribution of electricity when integration is to be implemented. This means that an addition of transmission and distribution components would be required in the case of micro-grid integration so it can sustain the community's layout. However, based on these capacities, possible solutions and recommendations are reached.

5.3 How can the existing capacity cover Uutsathima's electricity demand?

This paper brings forward three possible solutions for micro-grid utilization to cover the electricity demand in Uutsathima. Tab.5 identifies which solutions may be implemented in the case of Uutsathima. However, infrastructural configuration is important to note. The orientation and sparse distribution of settlements in Uutsathima limits any possibility of physical integration between the village.

Tab. 5 Examination of micro-grid integration per case scenario

Grid	Nominal Capacity (kWp)	Battery Capacity (kWh)	Integration (technically feasible)
Existing micro-grids	26.15	451.20	Yes
Scenario 1	25.30	559.10	No
Scenario 2	18.40	279.60	Yes
Scenario 3	32.20	679.60	No

The comparison between the nominal capacities of the existing micro-grids and scenarios 1 & 2 shows a difference of 0.85 kWp and 7.75 kWp, respectively. This indicates that existing micro-grids generate excess unused energy that could potentially be made available to the household and business settlements. This study also established that if a mini-grid were to be sized for public institutions alone, a capacity of approximately 10 kWp could cover 100% of their electrical demand leaving an excess of 16.15 kWp of nominal capacity. Therefore, the first discovery in these results is that there is, in fact, a potential of using the existing capacity to extend electrification within Uutsathima. However, due to the dispersed orientation of the settlements some limitations arise. Thus, while arithmetically, there is a potential in utilizing the excess capacity, technically, this requires transmission and adjustment of system components. The business centre, for example, is close to the clinic and police station and further from the veterinary centre and school, while household settlements are sparsely distributed. The viability of micro-grid integration then depends on the relative location between them and the unelectrified settlements. If this approach is chosen, the replacement of system components such as the independent inverters with a single mini-grid inverter and placement of battery banks relative to the PV arrays and inverter should be done. Additionally, transmission cables should be run through the distances. To implement this approach, recommendations are to consider the costs for system adjustment, consumers' location relative to the existing grid, and susceptible system losses.

Alternatively, electrification of the business centre is a possible could be electrified by micro-grid integration. The capacity at the clinic and police is 17.51 kWp, and the collective demand for case scenario 2 is slightly higher. This indicates that the demand for the business centre can be supplied from the clinic and police station, given that the battery capacity is sized accordingly. While the load profile of the police station is relatively flat throughout the day, that of the business centre and the clinic has peaks in the evening, suggesting high demand during evening times. The feasibility of this solution depends highly on the battery capacity and, in the case of Uutsathima, the remaining lifetime of the batteries. Consideration in this scenario is given due to the business centre's location being very near the two public institutions. Replacement of the inverters is again required due to the integration of the three independent grids at the clinic and police containerized grid and water treatment systems.

Arguably, the objective of this paper is to find a means to electrify the complete village of Uutsathima. Therefore, due to the technical complexity of micro-grid integration resulting from the population and settlement distribution as well as additional costs, a third solution is presented in this paper. It also identifies the difficulty of energy audit during load profiles and answers the question of why most mini-grids in rural unelectrified regions are either oversized or undersized. Availability of excess energy generated greater than the used energy or load energy demand indicates a lack of prior analysis of the consumers' actual energy demand in Uutsathima.

While scenario 3 sizes a mini-grid to cover Uutsathima's total energy demand inclusive of public institutions, the development of a new mini-grid for all the unelectrified settlements is another technically simplified solution. To avoid various decentralized generation and control systems, a single mini-grid with centralized inverter and storage units for the distribution of electricity into the village's settlements is recommended. This also leaves provision for load evolution at the public institutions by using the available excess energy.

6. Conclusion

The distinction between rural and urban regions of SSA extends to the difficulty and ease of energy and specifically electricity accessibility. While urban areas are prone to easier electrification by grid extension, rural regions of SSA are hindered by low population densities, poor infrastructure, and low economic engagement, which altogether reduce the viability of grid extension. To avoid these economic and time constraints, alternative electrification schemes must be implemented to fasten electrification in rural regions. Many projects and research focus on implementing new off-grid solutions, however, there lies a potential in assessing the feasibility of micro-grid integration, eliminating time factors and high investment costs. This paper used a rural low, population density, and low-income community in Namibia to analyze the energy status quo and draw scientific results and recommendations. The bottom-up approach using a MATLAB algorithm was used to generate independent settlement and aggregated load profiles. Three scenarios were considered by doing further PVsyst simulations to identify the most feasible solution. Findings of the analysis showed that while approximately 50% of the existing Uutsathima micro-grids generation capacity was not used, integration of existing micro-grids is highly dependent on the distribution and location of new consumers relative to the existing micro-grids. Replacement of many system components, expansion of the storage capacity, and establishing transmission lines pose additional costs that deem integration invalid when settlement density is too low. The results identified integrating Uutsathima's police station and clinic micro-grids and business centre load inclusion, as well as an erection of an independent mini-grid to electrify households as the most feasible solution. While this paper only examined the technical feasibility, further analysis needs to compare the economic benefit of integration by system component replacement and inquire about new inverters for micro-grid integration versus the erection of a new mini-grid.

7. Acknowledgments

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8. References

Chuan, L., Ukil, A., 2020. Modeling and Validation of Electrical Load Profiling in Residential Buildings in Singapore, 1. DOI: 10.1109/TPWRS.2014.2367509

Flor, M., Herraiz, S., Contreras, I., 2021. Definition of Residential Power Load Profiles Clusters Using Machine Learning and Spatial Analysis. Energies 14 (20), 6565. DOI: 10.3390/en14206565

Fritzsche, K., Shuttleworth, L., Brand, B., Blechinger, P., 2019. Exploring the Nexus of Mini-Grids and Digital Technologies. Potentials, challenges and options for sustainable energy access in Sub-Saharan Africa.

IEA, 2022. Africa Energy Outlook 2019 – Analysis - IEA. https://www.iea.org/reports/africa-energy-outlook-2019. Accessed 30 August 2022.

International Renewable Energy Agency (IRENA), 2022. Country Profiles: Namibia. https://www.irena.org/Statistics/View-Data-by-Topic/Renewable-Energy-Balances/Country-Profiles. Accessed 30 August 2022.

Jaglin, S., 2019. Off-grid Electricity in sub-Saharan Africa: from rural experiments to urban hybridisations.

Lorenzoni, L., Cherubini, P., Fioriti, D., Poli, D., Micangeli, A., Giglioli, R., 2020. Energy for Sustainable Development. Classification and Modeling of Load Profiles of Isolated Mini-grids in Developing Countries. Energy for Sustainable Development 59, 208–225. DOI: 10.1016/j.esd.2020.10.001

Narayan, N., Qin, Z., Popovic-Gerber, J., Diehl, J.-C., Bauer, P., Zeman, M., 2020. Stochastic load profile construction for the multi-tier framework for household electricity access using off-grid DC appliances. Energy Efficiency 13 (2), 197–215. DOI: 10.1007/s12053-018-9725-6

Opfer, K., Beaucamp, L., Njamnshi, A.B., 2022. A Factsheet for Civil Society. Renewable Energy for a Decentralised, People-Centred Energy Transition in Africa.

The Mathworks Inc., 2021. Self-Paced Online Courses - MATLAB & Simulink. MATLAB R2021b & Simulink. https://matlabacademy.mathworks.com/. Accessed 2 September 2022.

Vanadzina, E., Pinomaa, A., Honkapuro, S., Mendes, G., 2019. An innovative business model for rural sub-Saharan Africa electrification. Energy Procedia 159, 364–369. DOI: 10.1016/j.egypro.2019.01.001

Webgenève, 2022. PVSyst (Version 7.2) Photovoltaic Software. https://www.pvsyst.com/. Accessed 2 September 2022.