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Mini-grid performance in Sub-Saharan Africa: case studies from Tsumkwe and Gam, Namibia

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Abstract

This paper investigates the performance analysis and operational challenges of mini-grids in Sub-Saharan Africa, focusing on the Tsumkwe and Gam mini-grids, the only officially recognized mini-grids in Namibia. The study addresses a critical gap in understanding mini-grid efficiency, technical difficulties, and future potential. The key research questions focus on assessing mini-grid performance, identifying technical and operational challenges, quantifying the relationship between electricity demand and supply, and providing recommendations for enhancing rural electrification through mini-grids. These insights are crucial for evaluating the effectiveness of mini-grids in the African context and understanding their role in advancing rural electrification. By using a mixed-method approach, the research combines quantitative and qualitative data to offer a comprehensive analysis of these two mini-grid systems of Namibia. The data collected from 2017 to 2022 include metrics on energy supply, consumption, photovoltaic generation, community load, and meteorological conditions. Qualitative insights were gathered through field visits, surveys, and interviews with mini-grid operators, allowing for a thorough examination of community perspectives, operational issues, and technical performance. The findings reveal that the Tsumkwe mini-grid has seen a decline in efficiency due to maintenance problems and battery overheating, while the Gam mini-grid, initially oversized, now struggles with increased demand and new connections. This study provides the first detailed technical insights, identifies consumer archetypes, and evaluates the energy dynamics of mini-grids in Namibia. Recommendations include improved maintenance protocols, advanced battery management, and enhanced data monitoring. By analyzing Tsumkwe and Gam, this paper offers valuable lessons for mini-grid development in Sub-Saharan Africa, stressing the need for continuous evaluation and strategic improvements to achieve sustainable rural electrification.

Keywords Tsumkwe, Gam, Off-grid settlements, Namibia, Sustainable mini-grids, Solar PV systems, Rural electrification, Hybrid mini-grids

Introduction

Access to electricity is considered one of the fundamental elements for human development. In 2016, 1.1 billion people lacked access to electricity. By the end of 2021, the number of people without access to electricity had decreased from 1.1 billion to approximately 768 million. Around 60% of these individuals live in sub-Saharan African (SSA) countries. Despite ongoing efforts to electrify these regions, achieving the Sustainable Development Goal, which aims to ensure access to affordable, reliable, sustainable, and modern energy for

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all, remains a challenge. The current projections suggest that around 700 million people will still lack access to electricity by 2030, with the majority (600 million) residing in SSA (Falchetta et al., 2020; IEA, 2017). The lack of electricity poses significant barriers to the development of modern economies and healthy, productive households. SSA holds the lowest energy access rates in the world. Around 13 countries in SSA have less than 25% electricity access. The population of SSA is predominantly rural, with around two-thirds of residents living in rural communities. However, it is the least electrified region in the world with about half of its population lacking access to reliable electricity, which hinders the livelihoods and productivity of the region. Grid extension alone cannot significantly increase electrification rates in SSA. Electrification is particularly important for low-population-density countries in

SSA, since the long distances between regions present challenges related to infrastructure, time, economic, resource availability, as well as technical awareness (Trotter, 2016).

Namibia faces a low electrification rate of 45% nationwide and 19% for households, compounded by a sparse population density of about 3 people per square kilometer, with 79% living in rural areas. These factors hinder the extension of the electricity grid to remote regions and impede energy target achievement. However, Namibia has substantial solar energy potential, approximately 50% higher than that of Central European countries (Lwakatare et al., 2023), offering a significant opportunity for solar-based electrification. Despite the policy efforts to improve electricity access, remote and underdeveloped areas often remain underserved, as illustrated in Fig. 1, which compares Namibia's national transmission

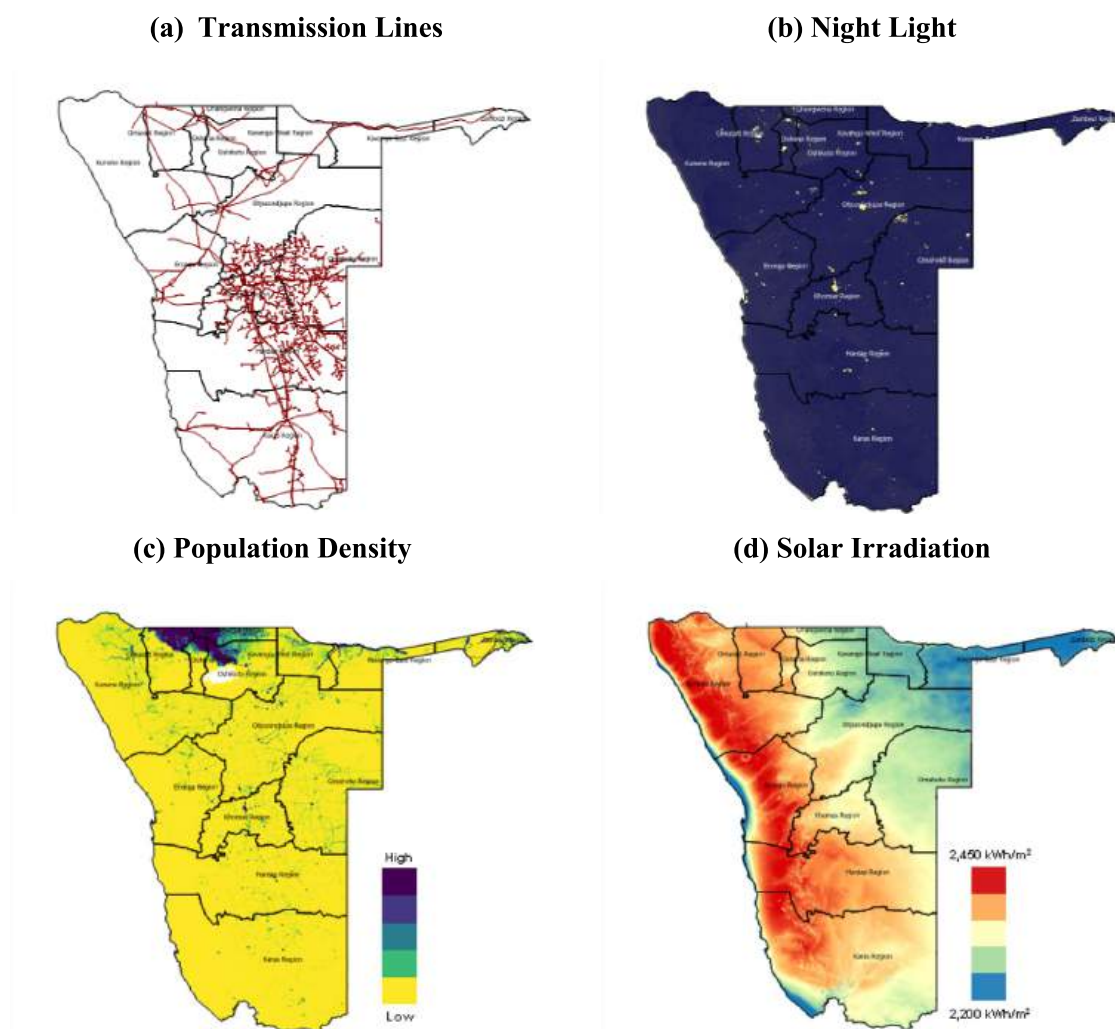


Fig. 1 Overview of grid situation and solar energy potential in Namibia based on Mehta et al. (2023)

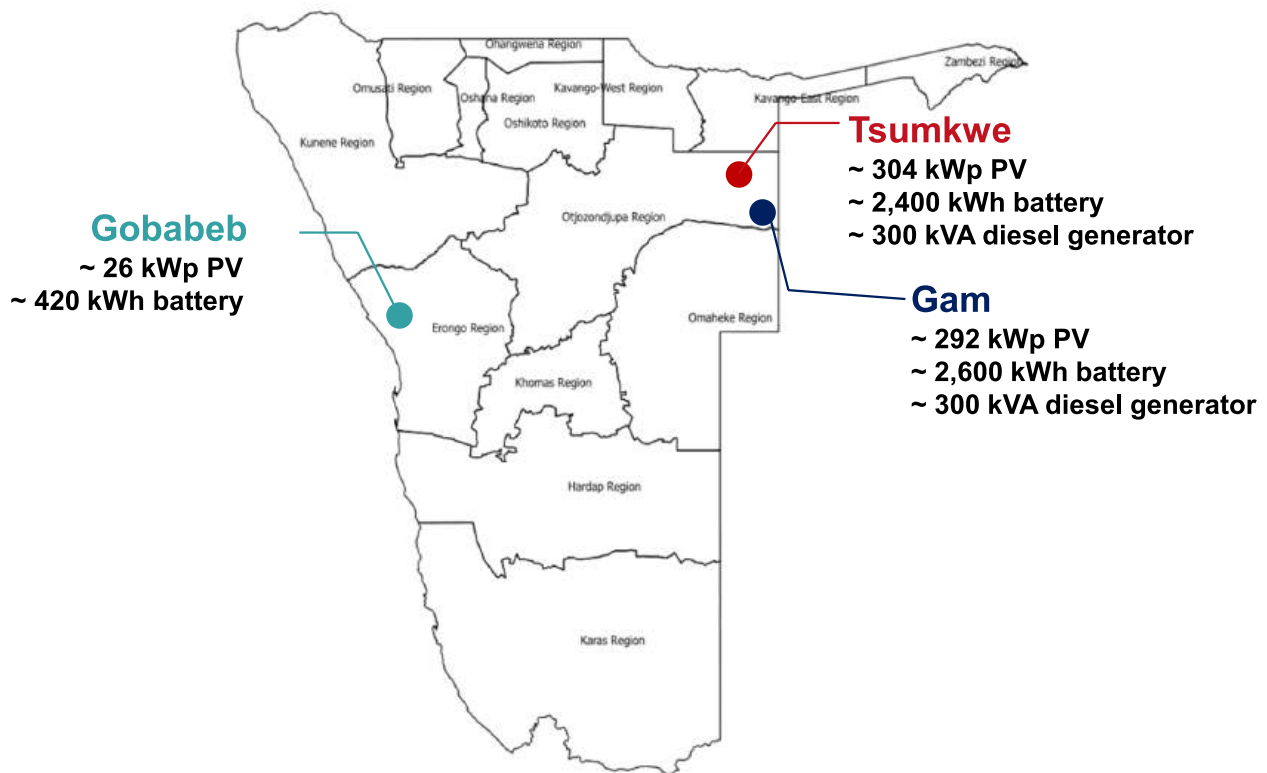


Fig. 2 Location of existing mini-grids in Namibia

line, population density, night light, and global solar irradiation.

The Namibian Ministry of Mines and Energy's rural electrification program aims to expand electricity infrastructure to rural areas, improving socio-economic conditions and fostering economic development. (Ministry of Mines and Energy 2021). To achieve its energy targets, Namibia adopted three common approaches: grid extension, solar home systems, and mini-grids. However, most Namibians live far from the grid in low-density or isolated settlements. Poor infrastructure and difficult terrain, coupled with high costs of \$8,000–\$25,000/km, complicate grid extension (Longe et al., 2013; Luta & Raji, 2018; Mehta et al., 2023). Extending the grid to remote locations in Namibia is often neither technically nor economically feasible, and solar home systems cannot handle high loads. In such cases, off-grid electrification through microgrids/mini-grids, which can operate independently, is a more suitable strategy (Bhattacharyya & Palit, 2016; Chang et al., 2021). The concept of mini-grid can play a crucial role to electrification in Namibia as these networks are more often cost-effective than extending the

transmission lines to rural settlements (Blum et al., 2013; Chang et al., 2021; Szabó et al., 2011).

The details of micro-grids and mini-grids in Namibia are challenging to determine due to many unrecorded systems, particularly those serving private entities, such as lodges, farms, schools, and clinics. These systems often operate outside the regulatory framework. Experts estimate that Namibia has between 100 and 200 micro-grids¹ and around 20 mini-grids,² a small figure as compared to countries like Nigeria and Kenya, where off-grid electrification is more advanced. In addition, there are approximately 25 off-grid communities in Namibia according to Ileka et al. (2017).

Namibia officially has three operational mini-grids (c.f. Figure 2): Gobabeb, Tsumkwe, and Gam. Gobabeb has the smallest installed capacity at 26 kWp of PV, powering the center's buildings, offices, and accommodations. In contrast, the mini-grids in Tsumkwe and Gam provide

¹ Supplies multiple customers using a low voltage distribution system.

² Serves multiple customers using both medium and low voltage distribution systems.

electricity to entire settlements. Alongside solar-home systems and micro-grids in rural Namibia, the hybrid solar off-grid systems in Tsumkwe and Gam are among the largest in sub-Saharan Africa. These systems are centered around a PV plant, with energy storage and diesel generators providing supplementary power, particularly at night (Ileka et al. 2017).

Given Namibia's unique energy landscape—characterized by low electrification rates, dispersed rural populations, and abundant solar resources—mini-grids offer a promising and practical solution to close the energy access gap. Although national policies recognize their importance, technical, financial, and regulatory barriers still limit widespread adoption and performance optimization. Against this backdrop, this study focuses on evaluating the performance and operational challenges of two of Namibia's key mini-grids—Tsumkwe and Gam—to contribute to the growing discourse on off-grid electrification.

Literature review and gap in the research

Rural electrification strategies in Namibia

Although mini-grids offer great potential for rural electrification in Sub-Saharan Africa, many programs have faced setbacks and failures. Challenges have been identified across multiple dimensions, including technical issues on both demand and supply sides, economic factors like viability and tariff structures, social considerations such as business models, and political aspects related to policies and energy planning (Bloomberg NEF 2020; Chattopadhyay et al., 2015). Failure rates have been evaluated as being as high as 50–100% (Gollwitzer et al., 2018; Peters et al., 2019; Yadav & Bhalani, 2022).

Demand-side challenges, such as population growth and new businesses, lead to increased electricity demand, altering load profiles and straining mini-grid systems. These changes can disrupt operations and reduce energy storage efficiency, deviating from the initial planning and sizing of the mini-grid (Lwakatare et al., 2024). The researchers have identified a significant lack of comprehensive data on critical aspects of mini-grid systems, such as operational details, electricity demand, generation patterns, and weather data (Peters et al., 2019; Yadav & Bhalani, 2022). This data gap complicates planning, implementation, and maintenance efforts, hindering decision-making and sustainable operation, particularly in sub-Saharan Africa, where knowledge, technical expertise, and long-term strategies for mini-grids are also scarce (Bhattacharyya & Palit, 2014).

Recently, it was identified that the Ministry of Mines and Energy has a plan to electrify all Namibian households by the year 2040 (New Era 4/14/2022). Rural areas are likely to be electrified through mini-grid technology

as part of the “rural electrification program.” The country aims to enhance electricity access with a focus on renewable energy, targeting 510 MW of grid-connected renewable capacity by 2030 (GIZ, 2022).

Mini-grid-based electrification is key to Namibia's goal of electrifying 60% of its rural population. Understanding mini-grid performance and challenges is essential for guiding effective electrification strategies. However, the research on Namibian mini-grid initiatives is limited, with only three relevant studies available.

Ileka et al. (2017) analyzed hybrid mini-grid systems in Tsumkwe and Gam, highlighting their benefits and challenges for rural electrification, including operational difficulties. The study suggests that the concession model, a public–private partnership, is the most efficient and sustainable approach for managing these systems in rural Namibia.

Azimoh et al. (2017) performed the analyses on the Tsumkwe mini-grid system based on the empirical evidence, interviews and technical simulation through HOMER and MATLAB. The research tried to identify the success factors and challenges of the Tsumkwe mini-grid. The results were provided in terms of socio-economic dimensions and technical dimensions. However, this study presented the technical analysis of mini-grid through the simulation-based software with several limitations.

Hoeck et al. (2021) investigated the challenges of off-grid electrification in rural areas. In this study, the authors discussed the assessment of the situation in Namibia using the examples of Tsumkwe and Gam mini-grids. The paper mainly focuses on highlighting the general challenges for off-grid electrification and categorizing them in social, technical and financial dimensions through various off-grid policies, licensing, tariff setting, and socio-economic and technical implications. However, in-depth technical insight regarding energy generation, energy consumption, and user behavior was not the focus of the study.

Research gap and significance

The existing research on mini-grids in Namibia has largely focused on socio-economic factors and simulation-based technical analyses, overlooking the quantification of the existing mini-grids. To align with the 2040 electrification target, a holistic approach is needed. Although records show that two of three mini-grids in Tsumkwe and Gam are operational at the settlement level, insufficient data on other mini-grids' operations and performance highlights a significant knowledge gap. This gap hampers planning for future installations and understanding how mini-grids will perform in rural Namibia. Comprehensive analysis of existing mini-grids,

considering energy demand and supply dynamics, is crucial for policymakers. However, the current research is scarce, with limited insights into these requirements, underscoring the need for further investigation.

This study provides a novel analysis of mini-grid performance and challenges in Namibia, integrating comprehensive multiyear data set. It combines quantitative metrics on energy supply and consumption with qualitative insights from field visits, surveys, and interviews. The research quantifies the demand–supply relationship, develops consumer archetypes, and offers recommendations to enhance mini-grid performance. By presenting new technical insights and evaluations, this pioneering study significantly contributes to the future of mini-grid planning in Namibia and Sub-Saharan Africa, offering valuable guidance for both researchers and policymakers.

Materials and methods

Recognizing the existing research gap and the need for research, this article aims to present the status-quo of mini-grid performance based on the comprehensive data collection, analysis and representation. The research questions guiding this study are as follows:

- What are the operational performance and challenges of the mini-grids in Namibia?
- What is the scope of mini-grids for rural electrification in Namibia, and what evidence-based recommendations for strategic planning?

To complement the quantitative assessment, qualitative methods were incorporated to provide deeper insights into operational realities, consumer behavior, and challenges. Field visits were conducted to document infrastructure conditions, operational constraints, and technical limitations affecting mini-grid performance. Interviews with mini-grid operators and consumers captured operational experiences and operational challenges. Figure 3 represents the methodology of the presented research.

To comprehensively assess the performance of hybrid mini-grid systems in Namibia, a mixed-method research approach was employed, integrating both quantitative and qualitative methodologies. The study focused on established hybrid mini-grid models in Namibia, specifically the Tsumkwe and Gam solar power plants designed for community-scale electrification, which are the only

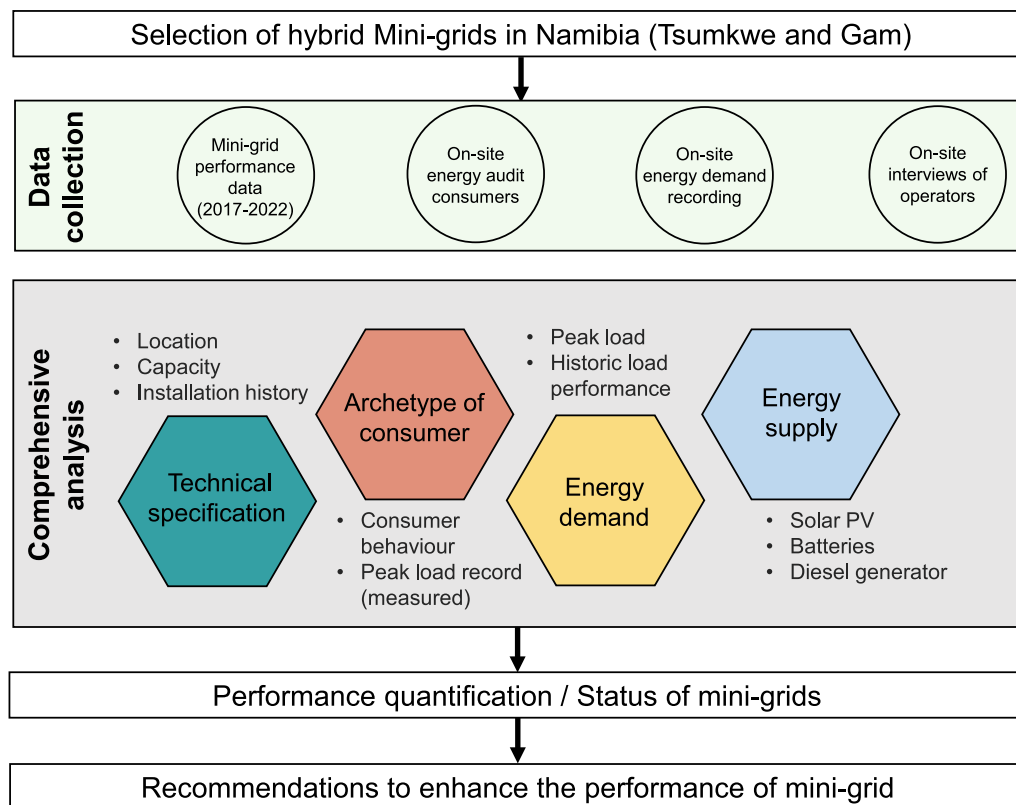


Fig. 3 Methodology of the presented research article

two main community mini-grids in Namibia as mentioned above.

A multifaceted data collection strategy was employed to collect and analyze real-time operational data, onsite monitoring, field surveys, and stakeholder interviews. The data sources and collection techniques are outlined in Table 1.

Quantitative evaluation of mini-grid performance was conducted through a comprehensive analysis designed to generate annual mini-grid performance insights for both Tsumkwe and Gam. This included assessing solar PV electricity generation, energy storage performance, and diesel generator efficiency from the supply side. On the demand side, annual energy consumption patterns, including key consumer profiles, were derived from mini-grid data and smart meter installations. Historical data offered insights into mini-grid performance trends and identified novel aspects of their operation.

Results

Tsumkwe mini-grid

Tsumkwe (19.5985° S, 20.5037° E) is located in Namibia's Otjozondjupa Region, approximately 700 km from Windhoek. As Namibia's largest off-grid settlement, Tsumkwe is home to around 4000 residents from diverse ethnic groups, including San, Kavango, Herero, Ovambo, and Zambezi. Established as a former military post, it transitioned into a civilian community post-independence, with government-funded facilities such as a school, clinic, and police station (Ileka et al. 2017).

The nearest town with modern energy services is 300 km away, and Tsumkwe is situated 100 km from the national grid, with the grid extension reaching Mangetidune in 2022. This extension, operating at 33 kV with 400 V and a capacity of 200 kVA, is insufficient for Tsumkwe due to the long distance and significant reactive power required. As national grid extension was deemed economically unfeasible, a mini-grid was chosen as an alternative.

In 2011, Tsumkwe's hybrid solar–diesel mini-grid was established as a pilot project, designed for potential replication in Namibia and southern Africa. The mini-grid includes a solar PV system and a 300 kVA diesel generator, providing a reliable power supply during periods of low solar irradiance or high demand. Figure 4 illustrestes the details of the Tsumkwe mini-grid.

Consumer archetypes

Situated in the remote far North-East of Namibia's Otjozondjupa Region, Tsumkwe is the largest off-grid settlement in the country. The Tsumkwe mini-grid serves a diverse customer base, categorized into four groups: residential, commercial (shops), institutional, and utilities (water pumping and communication towers), as shown in Fig. 5. The mini-grid's output is divided into essential and nonessential lines. The essential line, with a capacity of 11 kWp, powers critical services like healthcare facilities and essential infrastructure, ensuring their continuous operation. The nonessential line, with a capacity of 111 kWp, supports less critical but important energy needs within the community.

Households The Tsumkwe community predominantly relies on the Tsumkwe Mini-grid plant for electricity, with most households connected to the grid, though a few residences in the Northeastern sector remain unconnected. The community has around 300 households, with CENORED (Central North Regional Electricity Distributor—the operator of mini-grid) data showing 364 m, including 315 prepaid and 49 conventional meters, reflecting a modernized approach to energy management.

Despite available connections, there is a low trend in new mini-grid connections, suggesting potential saturation in household energy demand. New grid connections cost ~2500 NAD, subsidized by CENORED to ensure affordable energy access. Monthly household electricity expenditures range from 10 to 1000 NAD, categorizing households into low income (10–100 NAD), middle-income (100–300 NAD), and high income (> 300 NAD).

Table 1 Summary of data sources and collection methods used in the study

Data type	Collection method	Frequency/quality of the data	Utilization in analysis
Mini-grid performance data (Tsumkwe & Gam)	Acquired from mini-grid operators	Duration: 2017–2022 Resolution:1 min	Evaluates energy generation, demand, supply, and auxiliary power requirements
Onsite energy demand recording of representative consumers	Installed smart meters at selected consumer premises and semi-structured interview	Duration: 2020–2023 Resolution:15 min	Identifies key consumer categories and load profiles
Semi-structured interviews with mini-grid operators	Field visits and direct operator engagement	Field visit: 2019, 2022 and 2023	Defines system configurations, maintenance practices, and operational challenges

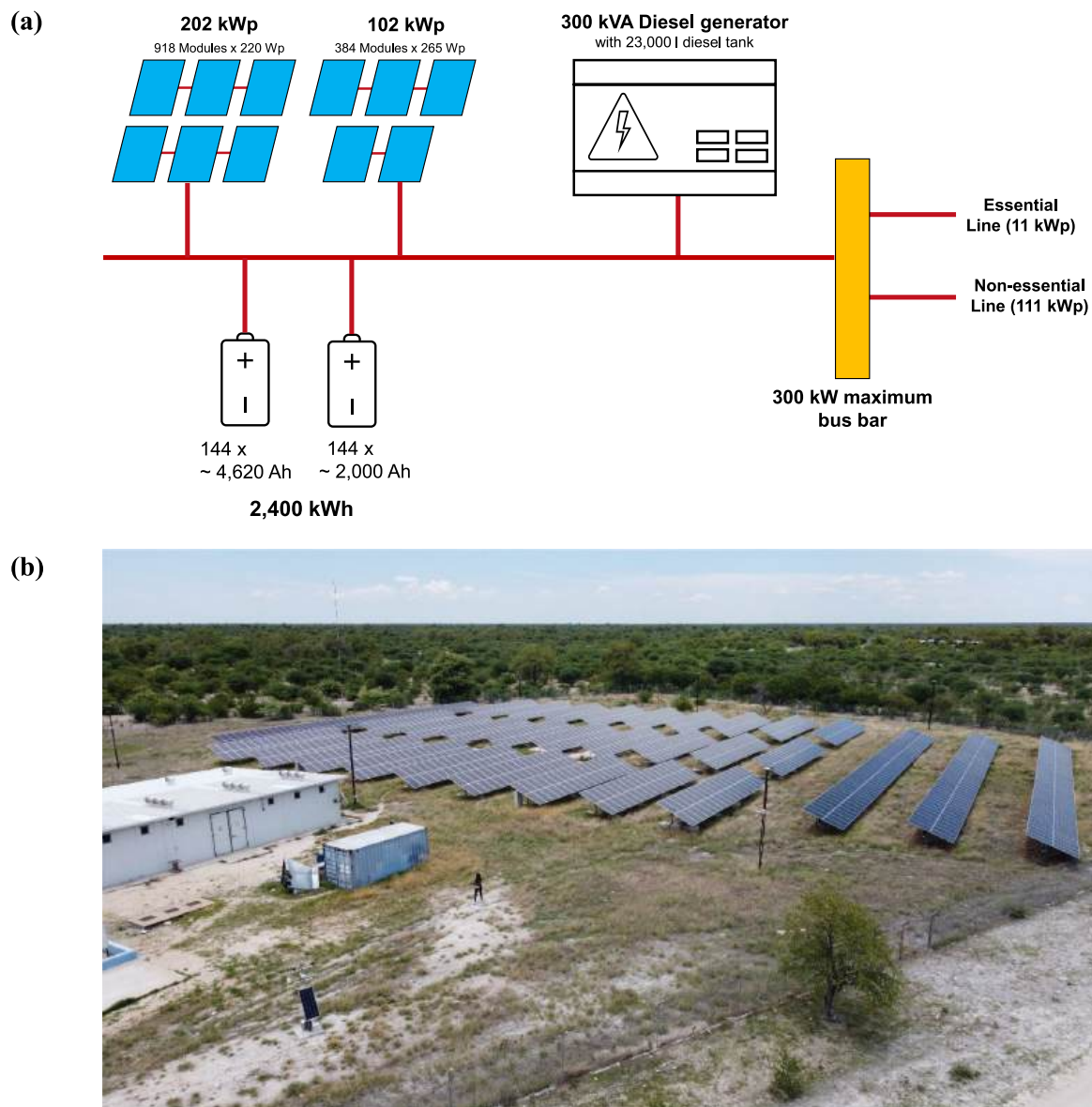


Fig. 4 Overview of Tsumkwe mini-grid: **a** schematic of mini-grid plant **(b)** aerial image of Tsumkwe mini-grid

Low-income households typically have 2–3 basic appliances such as CFL (Compact fluorescent lamp) lights and radios, middle-income households own 5–8 appliances including refrigerators and electric cookers, and high-income households possess more than 10 appliances, including items like washing machines and air conditioners.

Commercial In Tsumkwe, the number of supermarkets and shops is limited, with typically 3–4 establishments offering a range of appliances like tube lights, hotplates, microwaves, PCs, printers, refrigerators, and freezers.

These supermarkets generally have a monthly electricity expenditure of 1000–2000 NAD. In addition, TUCSIN Tsumkwe Lodge, with a capacity of 22 rooms, operates as a fully self-sufficient facility. It uses two boreholes for water supply and equips each room with basic lighting and a table fan. The lodge's kitchen features appliances including a baking oven, microwave, coffee machine, toaster, and freezer.

Institutional Institutional loads refer to electricity consumption associated with institutions for which the electricity bills are paid directly by the Ministry or governing

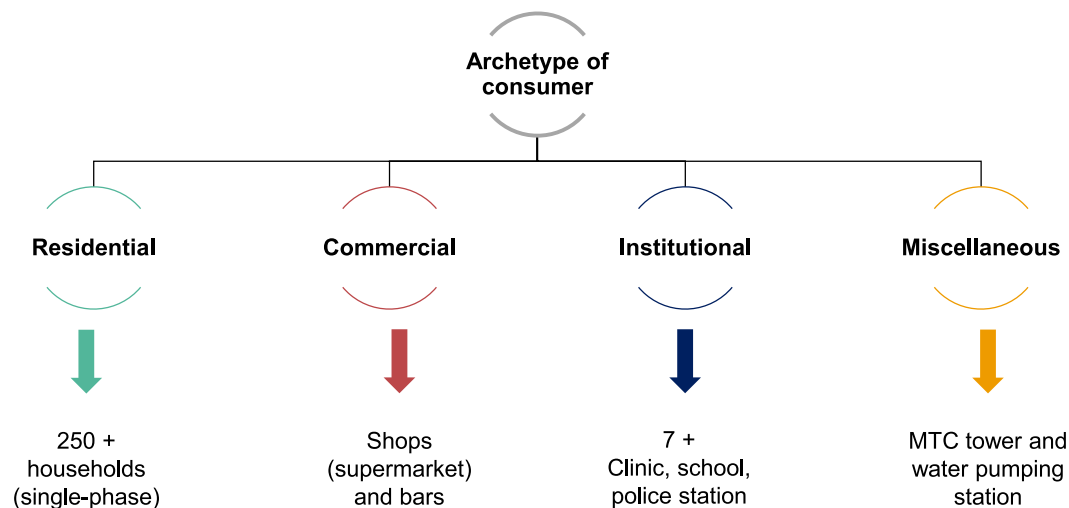


Fig. 5 Consumer archetype of Tsumkwe community based on the energy audit and interview with mini-grids operator

authority overseeing them. These institutions typically include schools, clinics, police stations, courts, and similar government-affiliated entities.

Tsumkwe secondary school features 18–20 classrooms, each with tube lighting, and 40 additional rooms including boarding hostels and teachers' houses. The school has a dedicated PC room with about 20 PCs, a microwave, ceiling fans, laptops, a printer, and phones. The director's office includes an air conditioner, and the school hostel's primary electricity use comes from a 3 kW cold room. Teachers' residences have electrical stoves and two water pumps, with cooking typically occurring between 7:00 PM and 9:00 PM. The school hostel uses gas for cooking. School activities run from 6:30 AM to 1:00 PM, Monday to Friday, with holidays in May until 2021 and from mid-June to mid-July from 2022 onward.

Tsumkwe primary school consists of approximately 10 classrooms, each equipped with 8–10 tube lights. These tube lights have a rated capacity of 58 watts each. In addition, it is notable that teachers from the primary school reside in the secondary school teacher houses.

Tsumkwe clinic is equipped with various refrigeration units to store medicines, as well as air conditioning systems, printers, ceiling fans, tube lights, and PCs. In addition, doctors and clinic staff reside on the premises. The clinic housing resembles middle to high-income residences. Moreover, there is a cooling compressor installed for the mortuary, with a capacity of 4.23 kW.

Tsumkwe police station is equipped with essential amenities including lights, air conditioning, PCs, large printers, and ceiling fans. The electricity expenses are covered by the Ministry of Safety and Security. The station consists of 10 rooms designated for staff, with each room occupied by one person. These rooms are outfitted

with basic amenities typical of middle to high-income residences.

Miscellaneous In Tsumkwe, four water pumps at the main water station include two connected to a single transformer and two linked to a prepaid meter. Each pump, with a power rating of 2.2 kW, operates on a non-essential line and draws water from a depth of 70 m, achieving a flow rate of 6.76 m³/h to fill the tanks. In addition, around 55 streetlights operate for 10 h daily.

Energy audits, electricity bills, and onsite measurements reveal that households in Tsumkwe, despite their number, are not the largest energy consumers. This is due to the limited number of high-income households, around 25, with minimal energy consumption. Households have a peak load of about 3–4 kW. In contrast, institutions like secondary school, lodge, clinic, and police station are the main energy consumers. Figure 6 shows the peak load of various consumers based on data collected throughout 2021 at 15-min intervals.

The following section explains in detail the energy supply and demand of the Tsumkwe community. It also provides valuable information of the mini-grid performance as well as diesel generator, and energy storage.

Energy supply performance

Electricity in Tsumkwe is supplied by a hybrid mini-grid combining solar PV and diesel generators. This section examines how each system contributes to meeting Tsumkwe's energy needs.

Solar PV This section will provide an in-depth analysis of solar PV's performance based on the historical data initiated in mid-2017. The solar irradiation in Tsumkwe typi-

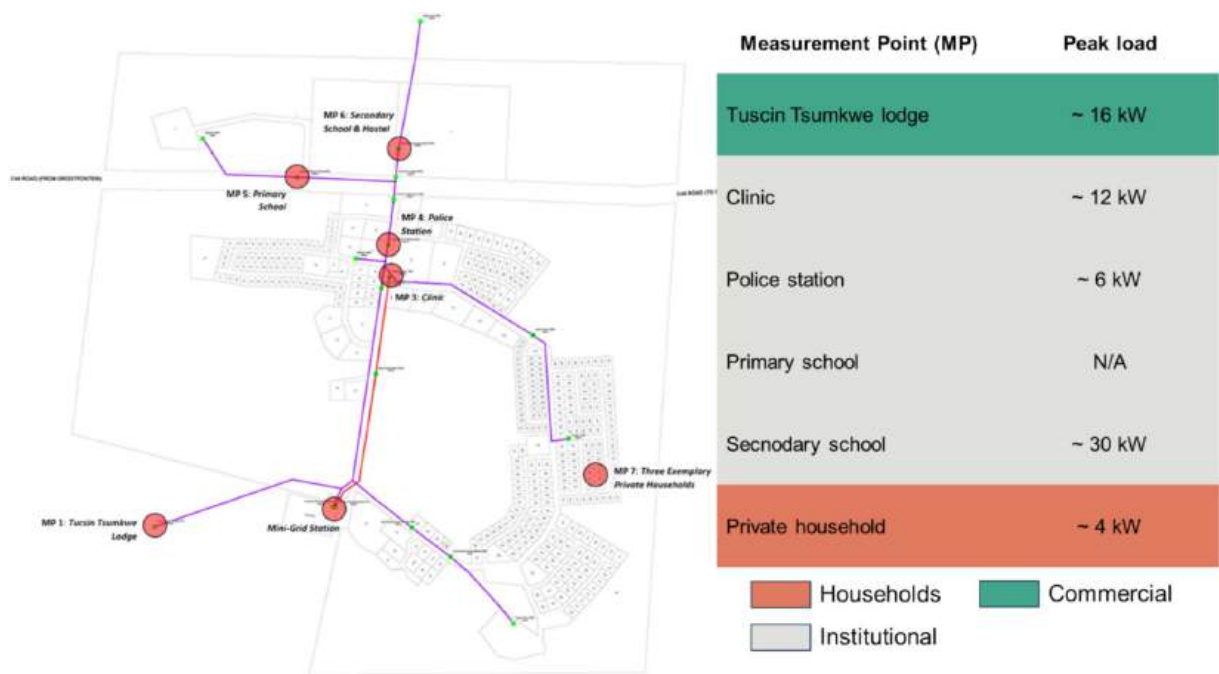


Fig. 6 Measurement point in Tsumkwe community and details of peak load of the consumers based on the onsite data recording

cally ranges from 5 to 6 kWh/m² per day, with an annual average of around 2000 kWh/m² (Mehta et al., 2023). Figure 7 presents an overview of a daily average PV performance spanning from 2017 to 2022. An average generation profile is used to show an overall comparison of the mini-grid's performance without considering weather conditions or changes in consumption patterns. Because there were no upgrades to the mini-grid infrastructure

during the data collection period, the average load profiles reflect performance without the influence of capacity changes. The analysis indicates an annual degradation trend in solar PV production. In 2018, the mini-grid was already in operation for 7 years. The average peak production in 2018 is ~200 kWp, highlighting the decrease in generation.

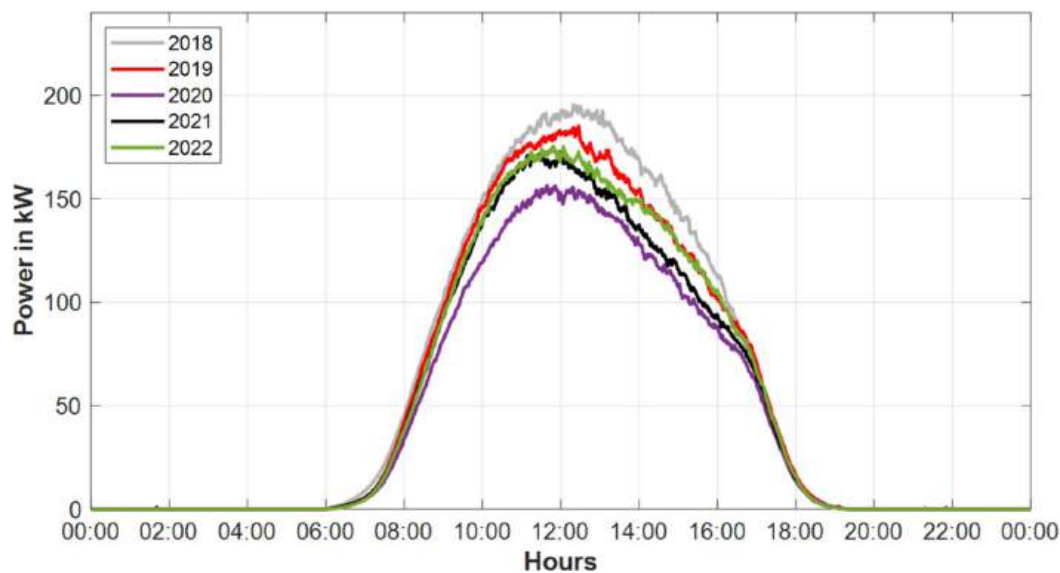


Fig. 7 Annual average solar PV generation of Tsumkwe solar plant (mini-grid) based on the histoirc data measurement

The years following, show a production reduction during the peak sun hours. During the extensive site visit in 2019, no significant system failures were observed and there was no indication of components requiring urgent replacement. However, the PV modules required cleaning. In addition, a replacement of a few defect modules was recommended. As a general recommendation, a proper and regular maintenance plan was required to ensure optimal and efficient production from the system.

In 2020, a significant drop in generation is evident as shown in Fig. 7. The justification for this drop was due to the decrease in demand as a result of the COVID-19 pandemic. This was mainly due to the closing down of the schools (the reader may recall the Tsumkwe Secondary School's peak demand surpassed that of other institutional consumers) and the Tsumkwe lodge (due to reduced tourist activities). Such reduction in demand also prompted the central inverter to generate as per requirement of the community's demand. This is also backed up by the generation recovery year, 2021. For data analysis, the year 2020 was therefore not considered due to an influenced change in the consumption pattern or behavior of the Tsumkwe community. The comparison between 2018, 2019 and 2021 shows a significant decrease in production over the years.

In 2022, solar production showed a 1% annual degradation like 2021. Challenges in data interpretation arose from frequent changes in mini-grid technicians, which disrupted performance tracking. The disparity in production between 2021 and 2018 remains unexplained, though depleted batteries likely impacted PV production data. A further analysis into similar days or weeks could enhance further comparison of generation across these years. Owing to the lack of battery storage data, it was also impossible to assess the correlation between PV generation with battery performance. However, a deduction can be made based on the onsite survey that the batteries' low state of health affected the PV generation since the batteries also acted as loads.

Storage/batteries The 2019 onsite survey showed that the batteries did not significantly impact the mini-grid's overall performance. This was done through overall status checking, testing the voltage stability, charge–discharge cycles, and system efficiency under various load conditions. Some batteries were defective and also some terminal screws were loose. However, another test in 2022, revealed through thermal images that the Tsumkwe mini-grid's battery room (see Fig. 8a) were in inadequate operating conditions. In addition to the battery conditions, the electrolyte filling system was defective. The mini-grid's lead–acid battery datasheet (see Fig. 8b) indicates that battery performance and the number of

operational cycles decline with rising temperatures. For example, at 50% depth of discharge (DoD), the number of cycles drops significantly as temperatures increase from 20 °C to 50 °C.

During a visit, the battery temperature at the Tsumkwe solar power plant was recorded at 48.4 °C. The datasheet shows that at 50 °C, batteries achieve about 1000 cycles even with high DoD. The manufacturer recommends an operating temperature between 10 °C and 30 °C, with a maximum of 55 °C. Thermal images confirm that the battery temperature is near this maximum, which reduces nominal capacity and storage time. This recovery also gave insight that while solar PV generation decreased, the storage capacity likewise decreased. In addition, it was discovered that the batteries are charged using both solar PV and a diesel generator. The generator data was then used to assess the impact on battery depletion.

Diesel generator The initial set-up of the diesel generator was intended for the generator to operate automatically with automated on-and-off times. Figure 9 shows two abrupt generator starts in the years 2018 and 2019 in the evening between 17:00 h and 19:00 h. In the following years, this function was disabled due to the increased demand of electricity from the community and forcing the operators to manually start the generator once the batteries run out. The year 2020 (COVID-19 pandemic) again exhibits a decreased production as there was decreased demand but also due to high fuel costs that limited the running times of the diesel generator. In addition, load shedding was introduced to minimize the operational costs. In 2021 and 2022 the evening generation rises again because of COVID-19 measures getting lifted and fuel prices dropping again. The morning trend of diesel production in 2018 correlates with the pattern of consumption as it exhibits peaks between 06:00 and 08:00 h. Presumably, these are the hours when batteries are ideally drained and before solar peak hours begin to utilize solar production. Owing to the disabling of automatic generator operation, in the years following 2018 very different patterns are seen in the morning hours. The capacity at which the diesel generator ran from 2020 to 2022 is higher in comparison to the previous years, which depicts the decreased storage capacity of the batteries. It must be noted that due to manual generator operation, this analysis needs to also take into account logistical factors. The annual profile shows that there may be days in which the generator was switched off earlier than other days. This could also be that the diesel generators ran out of fuel. Daily profiles become difficult to analyze due to unaccountable patterns due to mini-grid technicians/operators not taking note of the daily operations. The evidence for insufficient infrastructure monitoring and

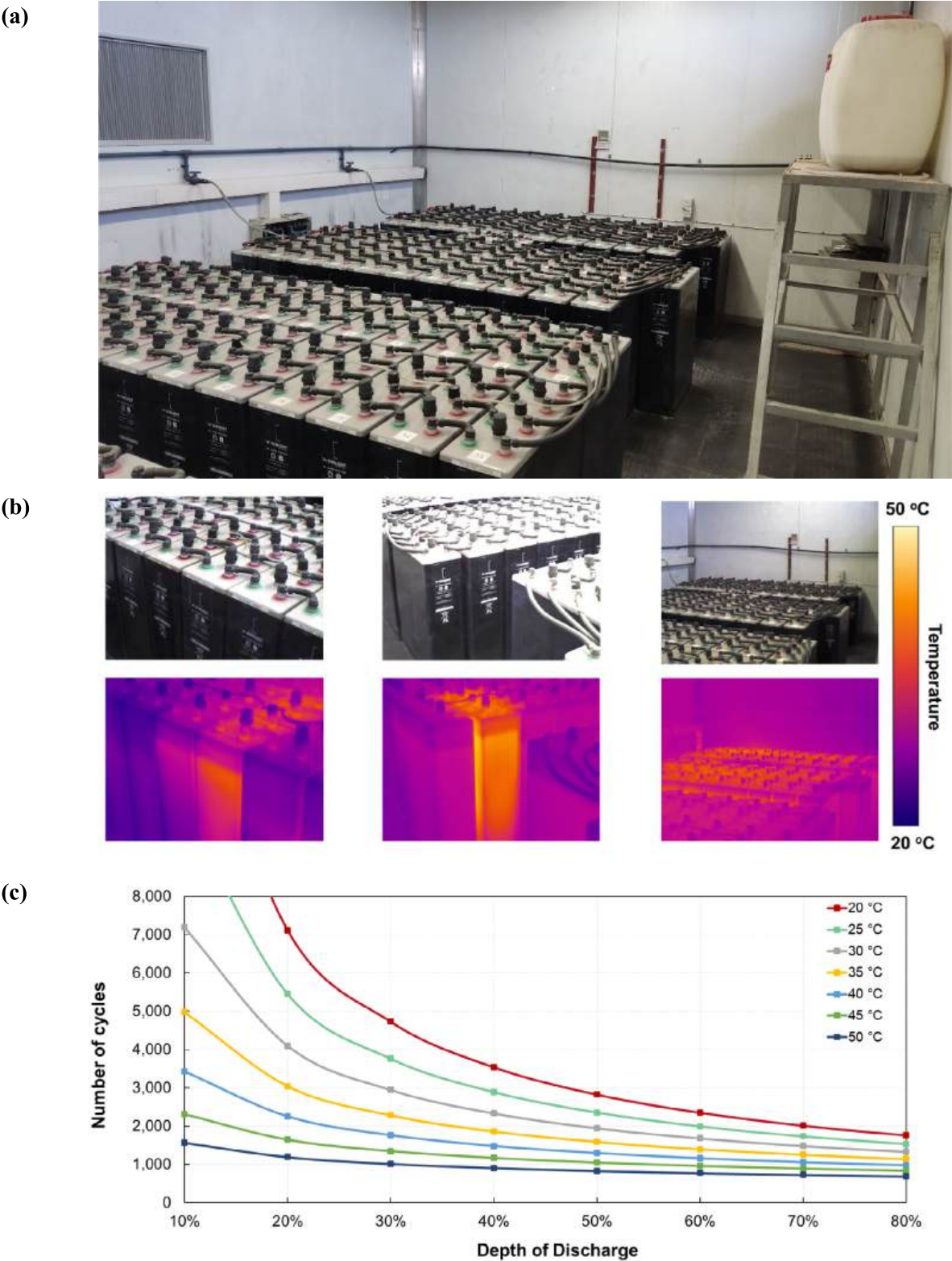


Fig. 8 The energy storage system of Tsumkwe mini-grid: **a** battery room; **b** thermography of the battery bank in Tsumkwe; **c** expected number of cycles vs. DoD of RES OPzS 2V cells (according to datasheet)

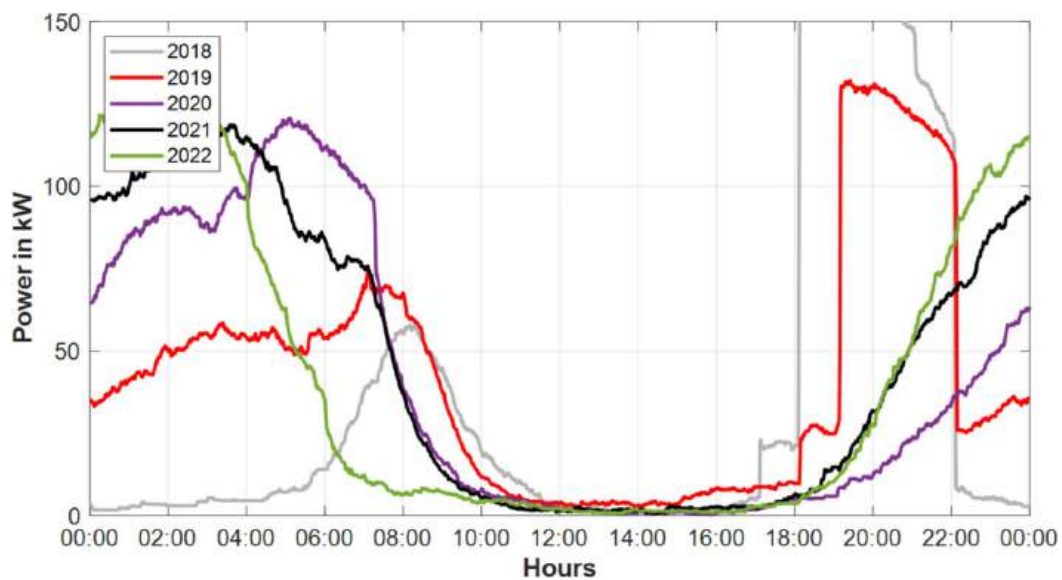


Fig. 9 Diesel-based produced energy at Tsumkwe mini-grid plant based on the historic data

maintenance emphasizes the limitation of the possibility to address daily or weekly profiles.

By analyzing the generator data, Fig. 10 illustrates the impact of battery depletion through the increased reliance on the diesel generator. This analysis takes into consideration three days in 2017, 2018, and 2019 with relatively similar to study the diesel generator generation pattern. In 2017 the batteries that were charged the previous day effectively managed the morning demand until solar generation started at around 08:00 AM. In the evening, once the generator starts operation, it is also evident that the batteries simultaneously start draining, which shows that the batteries concurrently consumed from the diesel generator. The generator covered the night demand and recharged the batteries for some more hours until it was switched off and the batteries took over. By 2018, the generator's operation introduced an additional smaller

peak at 06:30 AM to cover the morning demand before solar generation is sufficient and once the batteries cannot sufficiently meet the morning demand. In 2019, however, there was a notable decrease in battery usage during the night, with the diesel generator running from the previous night until 04:00 AM before switching off, with batteries then used until solar production resumed. This shift reflects an increased dependence on the diesel generator compared to 2017 and 2018. The generator's operation trend suggests excessive diesel use to both charge batteries and meet immediate electricity demand, highlighting a growing reliance on diesel as storage capacity diminished.

Energy demand trends

This section details the consumption trend of the Tsumkwe community and gives an insight to the demand

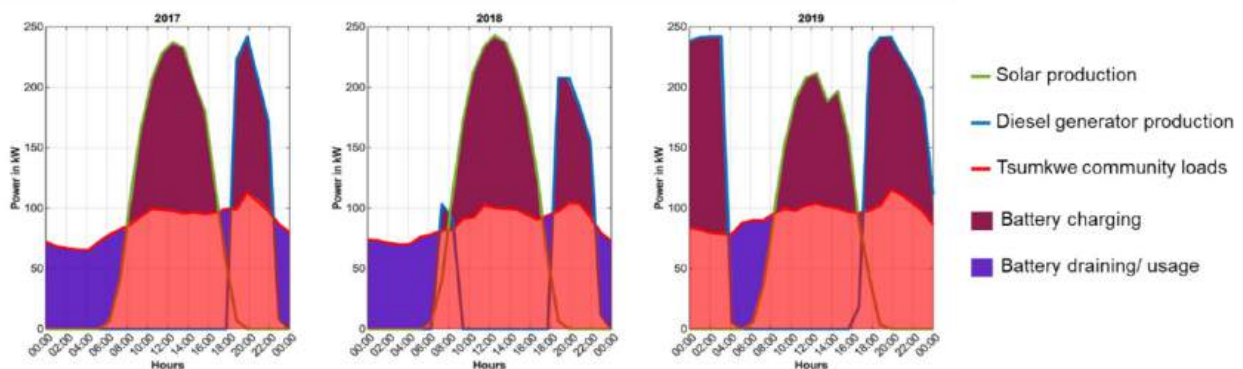


Fig. 10 Battery usage/drainage performance in the context of supply and demand of Tsumkwe mini-grid based on the historic data analysis

evolvment for a settled community. As stated in the mini-grid description, the distribution lines for the mini-grid are the essential and nonessential lines of which the former serves the institutional consumers (i.e., police, clinic, schools) while the latter serves the private consumers such as the private households and the business establishments. The two lines are therefore analyzed separately to thoroughly understand the consumption trends from 2018 to 2022.

Figure 11 shows relatively similar consumption trends and amounts with a high peak during evening times around 20:00 PM in 2018 and 2019. The consumption profiles used in this analysis are average profiles which masks the effect of seasonality, day-of-the-week influence, holidays but also data gaps. This simplifies the overall understanding of annual consumption and also gives a basis for comparison of annual evolvment of community consumption. The graph shows a relatively flat demand during midnight and early mornings with a very slight increased demand around 08:00 AM as well as around 12:00 PM. The consumption again decreases after noon until the night peak. Because this distribution line also serves residential consumers such as teachers, clinic workers and police officers' houses, the consumption trend is highly influenced by residential consumption patterns which are characterized by an increased demand during noon for preparing warm meals and night hours for food preparation, recreation and preparing for next days. This is seen by the corresponding peaks in the graphs. The year 2020, saw a lockdown of institutional and public services. Likewise, the school workers relocated from their work regions to their home regions

and services were reduced at these institutions leading to a reduced electricity demand. For instance, at the school, the boarding students were released which led to elimination of dining services and cooling of foods. This is evident by the reduced consumption on the essential line in 2020. The same effect was experienced at the police and clinic residential establishments.

In 2021, institutional consumption increased due to resuming to normal operation after the recovery from the COVID-19 pandemic. There was also addition of connections due to an increase of personnel including additional teachers and police officers which affected the overall demand. This increase, particularly evident between 06:00 AM and night hours, resulted in higher energy use compared to earlier years. Despite this, the overall consumption trend remained unchanged.

In 2022, additional private households were added to the existing distribution line, leading to an increase in afternoon peak consumption. The evening and night peaks remained relatively proportional to the previous years.

The analysis of the nonessential line (see Fig. 12) shows that data from 2020, affected by the pandemic, does not reflect typical consumption patterns and is therefore excluded from analysis. Figure 12 illustrates that 2020 had unusually low power consumption, failing to represent standard trends. In contrast, 2018, 2019, and 2021 exhibited similar consumption values, indicating stable consumption patterns in settled communities. This consistency is attributed to the uniformity of appliances across most households, with few exceptions among high-income households. For example, the 2022

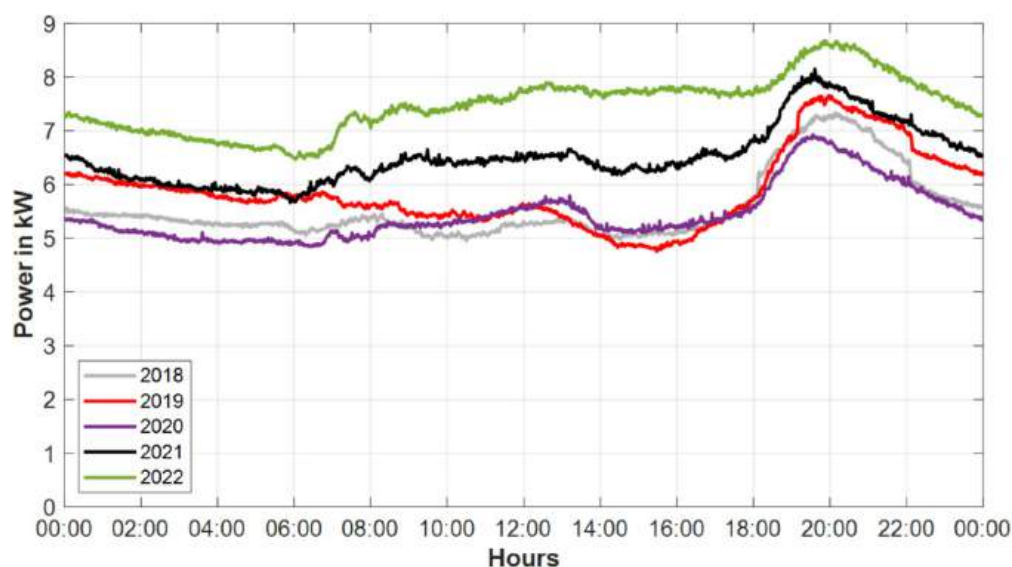


Fig. 11 Average annual consumption on the essential line in Tsumkwe

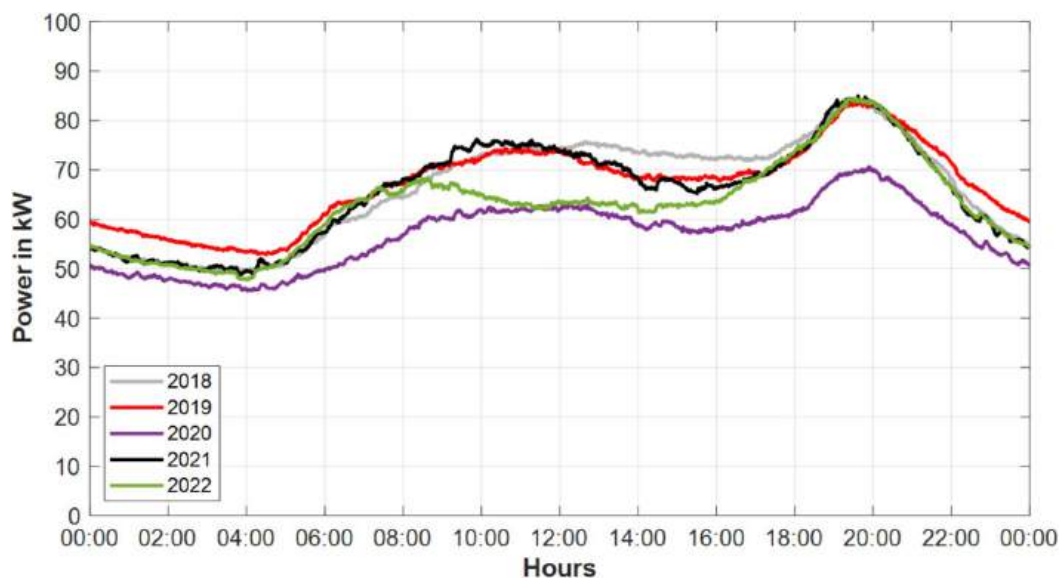


Fig. 12 Average annual consumption on the nonessential line in Tsumkwe

energy audit revealed that only a few homes had washing machines, while middle-income households had similar appliances, contributing to consistent consumption values. Notably, in 2022, the installation of a 25.8 kWp solar PV system at Tsumkwe Secondary School reduced the afternoon peak, highlighting the impact of additional renewable energy capacity.

Figures 11 and 12 illustrate that residential power consumption significantly impacts overall consumption when residential users dominate a distribution line. The peaks in these figures correspond to residential consumption patterns. In contrast, institutional consumers, represented by essential loads, display flatter consumption trends due to their constant energy use during working hours.

Gam mini-grid

Gam (20.2383° S, 20.8165° E) is a remote settlement located 112 km southeast of Tsumkwe in the Otjozondjupa region of Northeastern Namibia, near the western border of Botswana. It is the second largest off-grid settlement in the Tsumkwe constituency, situated 416 km from Grootfontein. Originally inhabited by a small number of San people due to its permanent water sources, Gam was resettled between 1993 and 1996 with about 3000 Herero people. The population now ranges from 2500 to 3000 individuals. The local economy centers around cattle farming and employment in various government ministries, including agriculture, police, education, and healthcare.

Before the mini-grid installation, Gam's power supply was unreliable, depending on poorly maintained diesel

generators that frequently caused outages, impacting essential services such as the local clinic and school. To address this, the Namibian Government, through the Ministry of Mines and Energy, commissioned a survey that led to the establishment of an off-grid solar hybrid power plant in Gam. The plant, designed and constructed by HOPSOL (solar energy company in Windhoek, Namibia) and commissioned in November 2014, features a 292-kW solar PV generator with thin-film modules, a 180 kW inverter/charger, a 2600 kWh lead-acid battery bank, and 300 kVA diesel generators. This system aims to provide Gam with reliable 24-h electricity, improving the quality of life and access to essential services. Figure 13 details the Gam mini-grid setup. Once completed, the Ministry handed over the mini-grid to the Tsumkwe-based Department of Works for operation and maintenance. In 2017, similar to Tsumkwe, the mini-grid operation and maintenance in Gam were taken over by CENORED.

Consumer archetypes

Like Tsumkwe, Gam has similar consumer types, but the data on consumers is limited due to technical issues with measurement devices and COVID-19 travel restrictions. These factors, combined with fewer resources and language barriers, have made data collection challenging, leaving Gam's consumer archetypes less developed than those in Tsumkwe. The Gam school, serving 224 primary and 50 secondary students, is a major nonessential electrical consumer. It is analyzed using one transformer that also services teacher housing. The school, equipped with ceiling lights but no computer equipment, operates

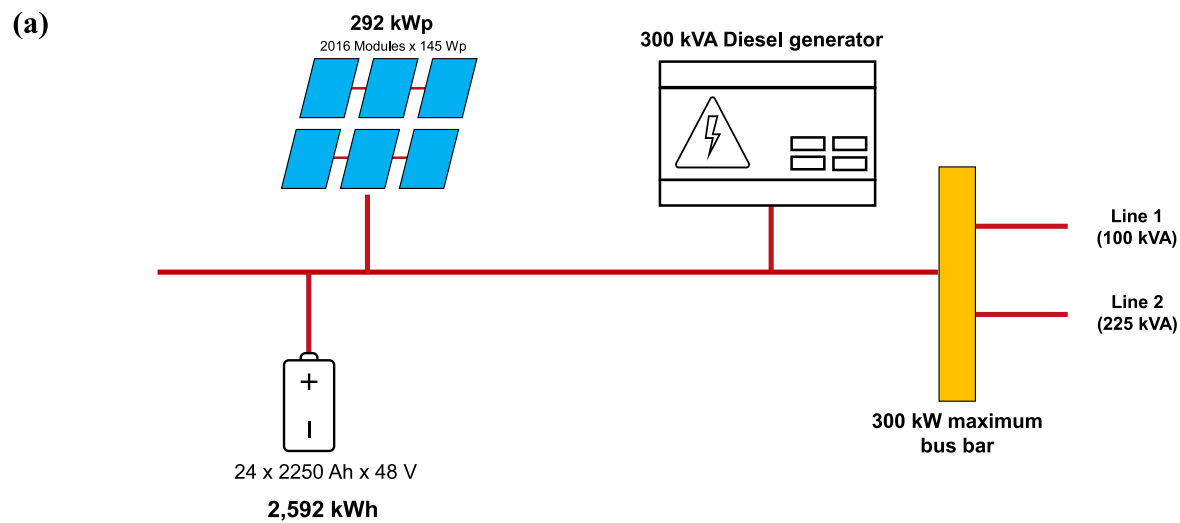


Fig. 13 Overview of Gam mini-grid: **a** schematic of mini-grid plant, **b** aerial image of Gam mini-grid by author

Monday to Friday, with minimal use on weekends and holidays. Cooking is done with firewood. This analysis aims to assess energy efficiency and explore sustainable practices. The police station, categorized as an essential load, is another key electrical consumer. It is served by a single transformer. Despite its smaller size compared to Tsumkwe's police station, it operates continuously, making its energy usage crucial for public safety. However, due to permission issues, detailed data was not available, and the measurement device at the police station malfunctioned, preventing data collection. Figure 14 shows peak load information where available.

Energy supply performance

This section details the Gam mini-grid's operation. Data gaps and a lack of prioritization hindered comprehensive monitoring. The analysis for Gam therefore is based on the data available for 2019 and 2021 and manages to

provide insights into the mini-grid's performance. The following subsections will explore the energy supply in Gam for these years.

Solar PV The solar PV power plant in Gam consistently produced more electricity than the demand from its consumers from installation until 2019. In 2019, peak production occurred around 10:00 AM, with output gradually decreasing until evening hours. During this time, the system's inverter limited production to match the low demand. By 2021, peak production had shifted to around 12:00 PM, and the inverter no longer restricted output, indicating an increase in demand. This shift was due to the connection of approximately 410 additional households to the mini-grid in 2020 (CENORED, 2021), which significantly raised electricity consumption and altered the production and demand dynamics. Figure 15 illustrates these changes in daily production patterns.

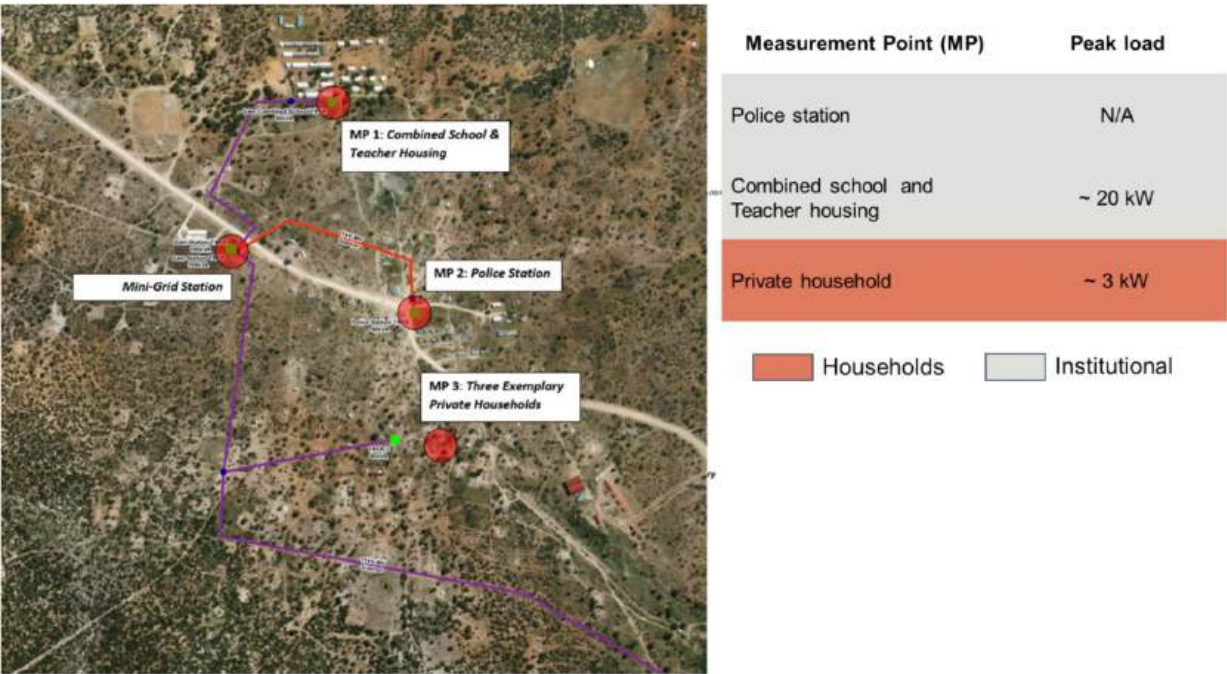


Fig. 14 Measurement point in Gam community and details of peak load of the consumers

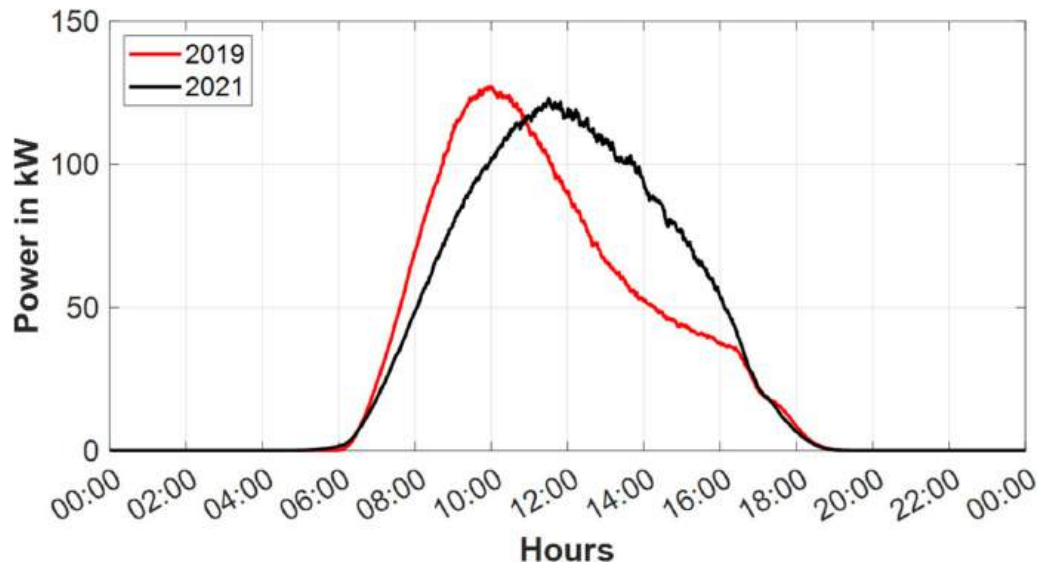


Fig. 15 Solar PV generation daily production patterns of Gam solar plant (mini-grid) based on the historic data measurement

During the 2019 onsite visit, hotspots were identified on some solar PV modules. Through thermography, it was also revealed that these hotspots had minimal impact on the module temperatures (see Fig. 16). Additionally, the PV modules were poorly cleaned, and the inverter room experienced rising temperatures due to a malfunctioning cooling system.

Storage/batteries As in Tsumkwe, battery data was unavailable. The 2022 onsite visit revealed inadequate ventilation in battery rooms and identified batteries needing replacement. By thermal imaging it was observed that some batteries were operating at up to 48 °C, while string temperatures ranged from 25 °C to 35 °C (see Fig. 17). This issue, like in Tsumkwe but at an

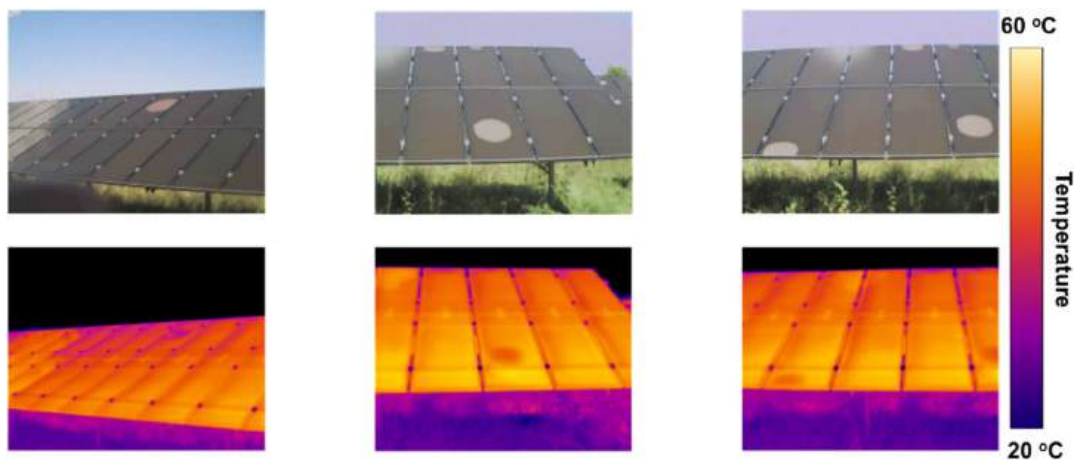


Fig. 16 Thermography of solar modules at Gam solar mini-grid plant

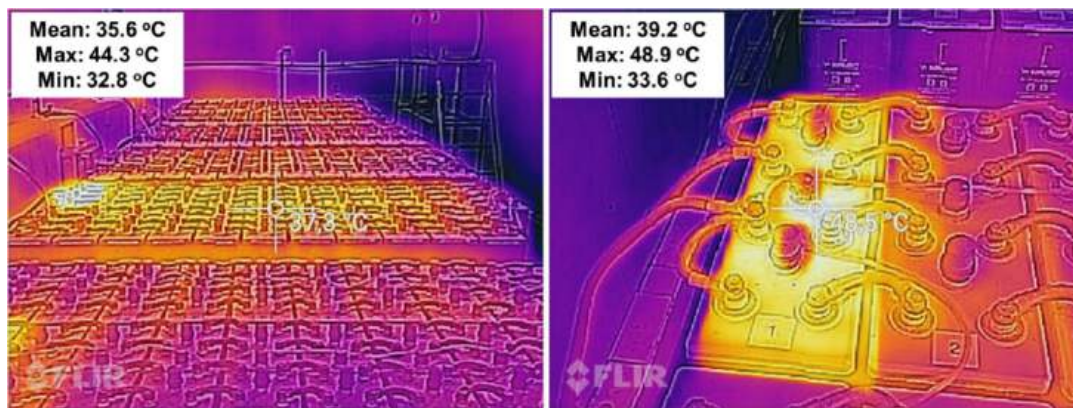


Fig. 17 Thermography of the energy storage system of Gam mini-grid plant

earlier stage, highlights the need for improved battery management, as discussed in later sections.

Diesel generator Because the solar PV generation in the years leading to 2021, as well as the battery storage capacity, met the community demand, Gam's diesel generator was not used. However, upon the increase in demand in 2020, the following years the diesel generator was introduced. Although data is not consistently available to interpret diesel generator use and dependence, Fig. 18 shows an increased frequency of generator use in 2021 when compared with 2019 when there was no use of the diesel generator at all. Data gaps in 2021 challenge data analysis. It is also important to note that the diesel generators are manually operated and might therefore not always show the necessity of. Likewise, the generator being in operation was noted to not always imply unavailability of demand or sustainability of the batter-

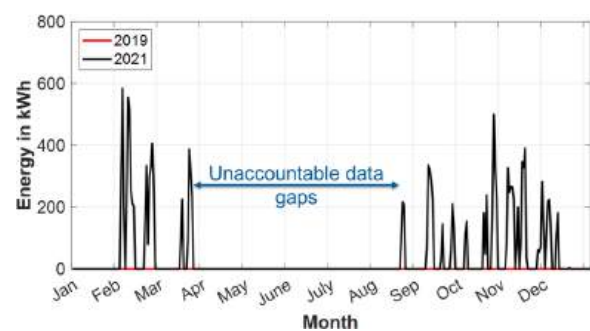


Fig. 18 Diesel-based produced energy at Gam mini-grid plant based on the historic data

ies and/or solar PV to cover the demand but rather lack of diesel fuel or the operator behavior/limitations.

Energy demand trends

By 2019, Gam's PV power plant generated surplus electricity, as only 200 households had been connected to the mini-grid since its installation in 2014, excluding institutions like the school, police station, and clinic. However, with the completion of Phase 2 in November 2020, an additional 410 households were connected due to in-migration and community expansion. This surge in demand transformed the mini-grid from a surplus system to a deficit, requiring the integration of a diesel generator to meet the community's growing energy needs.

The two distribution lines of the mini-grid are for the corresponding institutional consumers and private consumers. In Gam these are named the 100 kVA line and the 225 kVA line, respectively. The 100 kVA line in Gam, as in Fig. 19, shows a reduced and base load of approximately 7 kW between midnight and 05:00 AM, with a gradual increase demand from 06:00 AM

which reaches a relatively plateau-like trend throughout the day and in the evening around 18:00 PM the highest peak is exhibited. While some teacher houses are available at the Gam school which may affect the consumption trend, the Gam institutional loads exhibit dominance and less influence by residential loads. When comparing the two years shows that the trend of consumption remains relatively the same, but the consumption increases by a maximum of 22% at 16:00 PM. The addition of the workforce (i.e., human resources) at the Gam public establishments and the growth of the village –which compels an increase in electricity demand– also contribute to this increase.

Focusing on the 225 kVA line, again the trend of consumption is similar in 2021 as in 2019. The introduction of 400 households in 2020 can be seen in the increase of the demand by up to 76% at the evening peak around 19:00 PM (c.f. Figure 20).

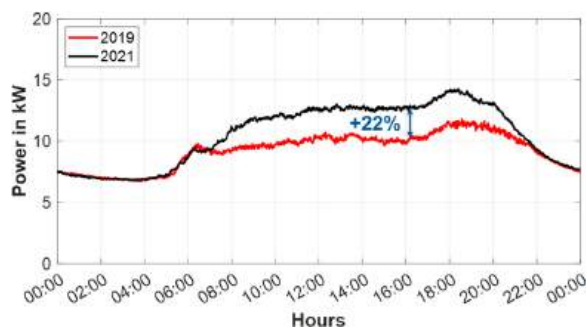


Fig. 19 Average annual consumption on the 100 kVA line of Gam community

Table 2 Comparative overview of existing mini-grid performance in Namibia

Indicator	Tsumkwe	Gam
Installation year	2011	2014
Technology	Hybrid (solar PV, diesel)	Hybrid (solar PV, diesel)
Installed capacity	303 kWp	292 kWp
Storage capacity	2,400 kWh	2,600 kWh
Storage technology	Lead-acid battery	Lead-acid battery
Operator	CENORED	CENORED
Current status (2024)	Undersized	Undersized

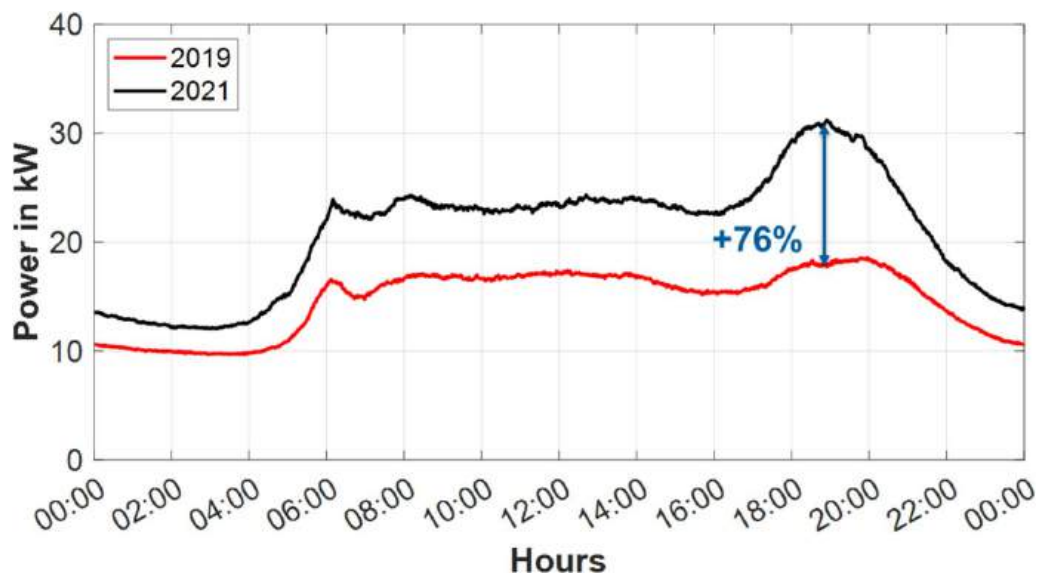


Fig. 20 Load at 225 kVA line of Gam community

Comparative performance overview

Table 2 provides a comprehensive comparative overview of existing mini-grids in Namibia.

Discussion

Summary

The mini-grids in Tsumkwe and Gam showcase different performance characteristics and challenges in managing solar PV systems. Tsumkwe's 303 kWp system initially performed well, peaking at 200 kWp in 2018, but has since faced degradation, exacerbated by the COVID-19 pandemic's impact on energy demand and insufficient battery data. By 2022, the system showed a 1% annual degradation rate, consistent with expected rates but limited by data constraints. In contrast, Gam's initially oversized system produced surplus power until 2020, when the addition of 410 new households shifted peak production from 10:00 AM in 2019 to 12:00 PM in 2021. Despite the initial surplus, rising demand led to performance struggles, with some hotspots detected in the solar modules, though they didn't significantly impact overall performance. Battery data was lacking, but issues like insufficient ventilation and overheating were observed.

Tsumkwe's reliance on diesel generators increased over time due to system degradation and low solar production, while Gam introduced diesel generators reactively after the demand surge in 2020, reflecting an adjustment to rising needs rather than a proactive strategy. This comparative analysis highlights the need for adaptive management in hybrid energy systems. Tsumkwe's experience underscores the importance of regular maintenance and data monitoring to address system degradation, while Gam's case illustrates the challenges of scaling infrastructure to meet growing demand and the role of diesel generators as backup. Both cases emphasize the need for ongoing assessment and adaptation to ensure the sustainability and efficiency of mini-grid systems in remote communities.

Challenges and recommendations

Although the existence of two operational mini-grids in Tsumkwe and Gam demonstrates the technical feasibility of decentralized energy systems in Namibia, several challenges hinder their optimal performance and long-term sustainability.

A major technical issue affecting both mini-grids is battery degradation caused by high ambient temperatures and limited battery lifespans. In Tsumkwe, degraded batteries have increased reliance on diesel generators, which currently meet approximately 50% of the energy demand. Replacing these batteries with more robust or temperature-resistant alternatives is essential to improve system efficiency and reduce diesel dependency. In Gam,

the unanticipated connection of 410 new households has resulted in a severely undersized system, leading to supply instability and reduced reliability. This underscores the need for forward-looking planning that aligns new connections with the mini-grid's design capacity. Future expansions should be preceded by technical assessments and upgrades to avoid system overloading.

Inadequate data monitoring and performance assessment, particularly in Gam, further constrain effective system management. Missing or incomplete datasets and the absence of real-time monitoring limit the ability to evaluate operational efficiency. Regular audits, improved data management practices, and upgraded measurement and reporting equipment are recommended to enable accurate and timely performance evaluations. Community engagement also remains an underutilized but critical aspect of mini-grid sustainability. Targeted awareness campaigns and training workshops can promote energy-saving behaviors, optimize demand patterns, and reduce unnecessary wastage. Overall, addressing these technical, operational, and social challenges through strategic investments in system upgrades, better planning processes, and community involvement will enhance the performance, reliability, and sustainability of mini-grids in Namibia. Moreover, exploring innovative generation and distribution strategies tailored to local conditions can support long-term rural electrification goals.

To support the interpretation of operational challenges and inform practical solutions, Table 3 summarizes the key technical, operational, and community-related barriers faced by the Tsumkwe and Gam mini-grids in Namibia. It also outlines targeted recommendations to enhance system performance, reliability, and long-term sustainability. This structured overview serves as a strategic guide for policymakers, mini-grid operators, and development practitioners involved in rural electrification efforts.

Limitations of the presented study

This study does not include a numerical analysis of historical data, nor does it perform statistical or sensitivity analyses. Instead, it presents a simplified overview of the annual performance of PV generation, energy demand, and energy supply to classify and interpret the performance of two officially recorded mini-grids. Although this is the first known attempt to apply such an approach in the literature, it is important to acknowledge its limitations.

Despite access to high-resolution datasets, the analysis was deliberately kept simple to enhance clarity and accessibility for a broad audience, including international readers, local communities, mini-grid operators, and utility stakeholders. This approach prioritizes practical insights

Table 3 Summary of key challenges and recommendations for improving mini-grid performance in Namibia

Category	Challenge	Recommendation
Battery performance	High temperatures reduce battery lifespan; degraded batteries in Tsumkwe increase diesel reliance	Replace degraded batteries with temperature-resilient or advanced battery technologies
System sizing	Gam mini-grid is undersized due to the sudden connection of 410 households	Conduct technical assessments before expansion; align new connections with grid capacity
Data monitoring	Missing or incomplete data, especially in Gam; limited real-time performance tracking	Upgrade measurement equipment; establish regular audits and refined data reporting protocols
Community engagement	Lack of energy-saving awareness among users	Organize workshops and campaigns to promote energy-efficient practices
Energy dependence	Tsumkwe depends on diesel for ~50% of energy needs	Reduce diesel reliance by improving battery storage and optimizing renewable energy integration
Future growth	Increased demand strains current infrastructure	Explore innovative generation and distribution strategies to meet rising electricity needs

over technical depth. However, the absence of statistical rigor may limit the depth of interpretability, especially for readers seeking detailed quantitative validation.

In addition, the study is constrained by data gaps and occasional meter malfunctions, which affected the continuity and completeness of the dataset. These limitations restricted the scope of analysis and may have introduced minor biases in the reported performance trends. Furthermore, the year 2020 was intentionally excluded due to the impact of COVID-19 lockdowns, which caused atypical energy consumption patterns. Including data from this year would have skewed the findings and reduced their generalizability to normal operational conditions.

Future research could address these limitations by incorporating advanced statistical methods, sensitivity analyses, and a more complete longitudinal dataset to provide a more detailed and statistically robust evaluation of mini-grid performance.

Conclusion

This study provides an in-depth analysis of the operational challenges and performance issues experienced by the Tsumkwe and Gam mini-grid systems in Namibia. Initially, both systems performed well, with Tsumkwe's solar PV array delivering high production capacity and Gam's setup meeting early energy demands. However, over time, Tsumkwe has suffered from significant performance decline due to dust accumulation, insufficient maintenance, battery overheating, and increased reliance on diesel generators. Similarly, Gam, which was originally designed for lower energy needs, now faces capacity challenges following the integration of new households, compounded by battery overheating and insufficient data monitoring. These findings underscore the urgent need for comprehensive system upgrades. Implementing rigorous

maintenance routines, deploying advanced thermal management for batteries, and enhancing real-time data monitoring are critical to prevent further degradation. Expanding system capacity and optimizing diesel generator usage will also be essential for improving reliability and reducing operational costs. Investing in technician training and fostering community engagement on energy conservation can further bolster the long-term sustainability of these mini-grids. Looking ahead, future research should focus on developing adaptive mini-grid models that integrate predictive maintenance, smart energy management, and modular system expansions. Pilot projects incorporating hybrid renewable systems, demand-side management, and AI-based forecasting tools could offer valuable insights into scalable and resilient energy solutions. These efforts will be vital for guiding policy, attracting investment, and ultimately advancing universal, sustainable energy access in Namibia and other similar contexts.

Author contributions

Conceptualization, K.M., B.L., and M.E.; methodology, K.M. and B.L.; software, K.M. and B.L.; validation, B.L., K.M., W.Z., and M.E.; formal analysis, K.M., B.L., and M.E.; resources, K.M., B.L., and W.Z.; data curation, K.M. and B.L.; writing—original draft preparation, K.M. and B.L.; writing—review and editing, B.L. and M.E.; visualization, K.M. and B.L.; supervision, W.Z., and M.E.; project administration, K.M. and W.Z.; funding acquisition, W.Z. All authors have read and agreed to the published version of the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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