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Article

Electrification Enhancement Scenarios for Off-Grid Communities in Sub-Saharan Africa- Advancing Energy Access

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Abstract: Sub-Saharan Africa, especially its rural areas, faces significant challenges in achieving universal electrification despite its abundant renewable energy resources. The region has the highest population without access to electricity, largely due to economic, infrastructural, and geographical barriers. Energy poverty is a critical issue that hinders sustainable development and exacerbates inequalities. Namibia's sustainable energy policy aligns with the global Sustainable Development Goals (SDGs), particularly SDG 7, which aims to provide affordable and reliable modern energy access for all. The policy emphasizes mini-grids and decentralized power systems as key strategies for rural electrification. However, despite increased deployment of mini-grids, these solutions often struggle with long-term sustainability. This research explores cost-effective electrification strategies through scenario-based modeling to reduce energy poverty and expand energy access in Namibia's rural communities, focusing on the existing mini-grids in Tsumkwe and Gam. Using a comprehensive methodology that incorporates HOMER Pro for mini-grid capacity expansion and MS Excel for evaluating main-grid extensions, the study aims to identify the most feasible and economical electrification solutions. The analysis compares electricity supply, total net present cost, and the levelized cost of electricity across these systems. The findings will offer insights into addressing energy poverty in Namibia and provide recommendations for sustainable and scalable rural electrification across Sub-Saharan Africa.

Keywords: off-grid communities; grid extension; mini-grid expansion; rural electrification; Sub-Saharan Africa; Namibia

1. Introduction

1.1 Energy Situation in Sub-Saharan Africa

Access to reliable and affordable electricity is to date, a critical challenge in Sub-Saharan Africa (SSA), where almost half the population remains without access to electricity [1]. In 2022, only 51.4% out of a total of 1.21 billion had access to electricity. This limited access to electricity is further intense as regions get remote and rural. An electricity access rate of 80.7% [2] versus 30.7% [3] for urban and rural areas respectively was recorded in 2022, emphasizing the disparities between these communities. While urban areas have, in most SSA countries, not reached universal access rate, the high concentration and density of the national electricity grids sets these rates quite high [4]. Urban consumers are therefore, normally, connected to the national grids due to their proximity to established distribution systems.

This does not hold true for most rural and remote areas. As the distance increases from grid concentrated regions, the costs for grid extension (i.e., including transmission and distribution) increases [5, 6]. This fact discourages grid extension to rural areas which make up about 58% of the total SSA population. 85% of urban areas compared to 35% of rural areas of SSA are grid connected [7], which solidifies the infeasibility of centralized grid extension as a rural electrification solution. It must be noted that approximately half a billion people reside in these rural areas [8]. This group is

then therefore disadvantaged since the economic growth and social development are also hampered. It is for this reason that this paper specifically focuses on rural areas of SSA.

SSA's countries continue to work towards achieving the Sustainable Development Goals (SDG) especially goal 7 which calls to '*ensure access to affordable, reliable, sustainable and modern energy for all*' [9, 10]. Amongst the efforts to bridge the electrification challenge in rural areas, respective policies and frameworks have been formulated in SSA member states and unions [11]. In these efforts, adaptability of renewables has, and continues to be highly emphasized on. Ranging from large scale projects like wind farms, biogas plants, hydropower plants and solar mini-grids to smaller projects like containerized Photovoltaic (PV) systems and solar home systems SHS), a number of renewable or green energy projects have been established.

While all these electrification projects seek to increase access, a core factor to consider is the sustainability of the applied approach. For SSA's rural electrification specifically and due to the abundance of solar resources, reducing costs of solar panels as well as the fast technological advancement, solar based solutions gained rather more traction. Solar mini-grids, containerized systems and SHSs have increasingly been implemented [12, 13]. However, the discussion around grid extension has not ceased due to the success rate of grid performance in urban areas compelling rural residents preferring the same solution.

Solar mini-grids have been used to supply electricity to rural communities [13], herein referred to as off-grid communities. This approach in relation to its sustainability also faces challenges and therefore fails to supply continuous electricity to consumers. Such challenges are mostly associated with community growth which compels increase in electricity demand. Upon surpassing the generation capacity of the mini-grid, the off-grid communities experience black-outs, load shedding and operators enforce demand side management strategies [14]. Such off-grid communities therefore, while electrified still hit a roadblock which requires technical intervention. This paper focuses on these communities and strategies to eradicate energy poverty within these established off-grid communities.

Since both grid extension and solar based mini-grids already exist either in rural areas or in their proximity, the need to assess the feasibility of these two solutions in addressing off-grid communities' electrification challenges is key to identifying which solution would assist attain sustainable electrification. SSA records over 21,000 implemented mini-grids, which necessitates the analysis of their performance and sustainability in the long run relative to the addressed communities. On the other hand, grid extension is in most SSA countries, still within the plan of the electrification strategies even for rural areas. While this is the case, literature also suggests a lot of grid extension challenges such as instability.

The next chapter looks at the current off-grid electrification strategies and status-quo in SSA as a basis for the analysis done in this paper.

1.2. Off-grid Electrification Status in Sub-Saharan Africa

As mentioned in the previous section, renewable energies are at the forefront for rural electrification in SSA. Though this varies in terms of capacities depending on the addressed community, available capital and investment fund, as well as the technical design factors, it is safe to say SSA has concentrated its efforts mainly to solar based solutions. Mini-grids are seen to be implemented by both private investors but also governments [15] as is the case in Namibia, for instance. The number of solar mini-grids has increased dramatically in SSA from an estimated 500 that were installed in 2010 to more than 3000 in 2023, accounting for more than a 500% increase in two decades. From 2010, mini-grid connections increased to 11 million, resulting in a rise in SSA's rural electrification rate from 17% to 28% within a decade [16].

In Nigeria and Kenya, for example, solar mini-grids have been prioritized to not only electrify rural areas but also inject electricity into the national grid. In Senegal, solar mini-grids have been identified as the second preferred solution, after grid extension, for rural electrification. Kidenda [17] states that settlements outside a one-kilometre radius from an existing grid should be electrified by solar mini-grids. In addition, he states that solar mini-grids should be the frontier strategy in rural areas with population densities below 1,000 people per km².

Regardless of the consideration for solar mini-grids, grid extension continues to be a strong contender in rural electrification. In Nigeria, grid extension is the top preferred rural electrification

strategy. In Namibia, grid extension is also an ongoing process even though extension plans remain vague [18].

In the broader context of rural electrification in SSA, most of the member countries consider several approaches to reach the SDG7 targets. However, grid extension and solar mini-grids are at the forefront [8, 19, 20]. Similarly, policies have been put in place advocating for the same across many SSA member states.

For this reason, it is crucial to identify the role these two strategies can play in complementing off-grid communities. This paper uses a case of Namibia which already has established off-grid communities for over a decade now.

1.3. Introducing the Case of Namibia

Approximately 46% [21] of Namibia's population resides in rural areas where access to electricity is limited. Namibia's electricity generation relies on a mix of petroleum, hydropower, wind, solar PV, imported electricity, and coal [22]. The country heavily relies on imports, especially from South Africa, Zambia, and Zimbabwe, which further complicates its energy security. As of 2022, hydropower was the highest explored renewable energy source. It is significant to note that this is due to the country's low local generation capacities. Aili et al (2022) [18] mentions that the country's peak demand is met by a local to import ratio of 40:60. Evidently, this highlights the need for increase for in-country self-generation. The authors add on by saying that a deployment of 278 MW of renewable capacities was planned for the next years. The government of Namibia (GoN) expresses its efforts to not only increase its generation capacity but also specifically identifies the role of renewables in reaching the targets as defined in SDG7. The GoN has set out a target to electrify all Namibian households by 2040 by means of either grid extension or off-grid electrification [19]. Additionally, with a renewable energy policy put in place, the GoN intends to optimize and further incorporate renewable energies in the electrical energy mix [23]. The set goal for Namibia was to rise from 27% in 2015 to 70% by 2030 [18]. It also states the role of solar photovoltaics especially in mini-grid and stand-alone application in electrifying rural settlements without connection to the utility grid as well as stand-alone systems such solar home systems for individual uses and applications.

Up until 2022, the solar based power production plants in Namibia was approximately 174.5 MW. Solar power production, amongst other renewables, follows hydro power in terms of the installed capacities in Namibia [18]. This is supported by an abundance of and high solar irradiation values of about 2447 kWh/m² [24, 25] which presents an opportunity to harness solar power for electrification of unelectrified regions. Likewise, this also highlights room for improvement to ensure the installed mini-grids, which have adequately met the need for rural electrification in Namibia, so as to attain sustainable electricity supply as is advocated for by SDG7.

In 2022, only 55.23% of the population had access to electricity where urban and rural access was 74.74% and 33.21% respectively [26]. This urban-rural electricity access disparity highlights the challenges Namibia faces in providing electricity to remote areas. Namibia faces significant rural electrification challenges due to its low population density (i.e., 3 people/km²) [19], high costs of grid extension, and high tariffs. However, the GoN Namibia through its Ministry of Mines and Energy (MME) established, among other solar-based solutions, mini-grids in rural areas. Of Namibian off-grid communities equipped with mini-grids are Tsumkwe and Gam. The presence of such solar based off-grid communities only highlight the potential identified by the GoN for solar technology the country's electricity access challenges. However, these systems, which are approximately a decade old, are currently failing to meet the communities' electricity demands due to community growth (i.e., including economic activities, population growth through in-migration and increase of appliance energy intensive appliance ownerships). This, therefore, underscores the urgent need to study reliable and sustainable energy solutions in Namibia's existing off-grid communities to enhance the availability of electricity in the established off-grid communities.

1.4. Aim of the Paper

Despite the increased number of implemented mini-grids and other off-grid decentralized electrification solutions in off-grid communities, electricity availability challenges continue to persist. Statistics continue to show increasing access rates and the number of implemented mini-grids;

however, they fail to capture the actual number of operational mini-grids. The necessity to monitor mini-grid performance goes hand in hand with monitoring the demand growth in the respective off-grid communities.

This paper uses the case of two Namibian off-grid communities and the associated challenges of the installed mini-grids in providing uninterrupted electricity to the end-users. Due to the fact that the main challenge arises from community electricity demand exceeding the mini-grids' generation capacity, this paper also looks at studying the generation and consumption trends before analysing the enhancement scenarios. By using the basis of the electrification plan set out by the GoN to use either grid extension or off-grid electrification, this paper also considers these two scenarios as electrification enhancement strategies.

The overall objective therefore is to study the viability of complementing existing mini-grids by either extending the grid or expanding the mini-grids' capacities to reduce energy poverty in off-grid communities.

1.5. State of the Art and Research Gap

To fully understand the contribution of this paper's work, a literature review on previous works and the status-quo of the discussions around electrification enhancement and rural electrification were done. The most relevant works are highlighted below.

Yibeltal et al. [27] examined capacity expansion planning for off-grid PV mini-grids in rural Africa, focusing on developing optimal long-term strategies to meet evolving electricity demand in remote communities. They evaluated capacity expansion of mini-grid system with a range of maximum annual capacity shortage using multi-year optimization tool in HOMER Pro software aiming to improve the reliability and sustainability of the system. However, they did not compare it with other electrification scenarios such as national grid extension. For the maximum annual capacity shortage values above 0% authors did not consider the use of an alternative option for the unmet load demand.

Moner et al. [28] compared the costs of grid extension and PV/hybrid mini-grid systems for electrifying rural SSA. They developed a formula to calculate and compare the LCOE for both options, factoring in distance from the main grid, connection costs, and community electricity demand. They also calculated the carbon emissions from the diesel generator to cover the same electricity demand as mini-grid does. On the other hand, authors only calculated LCOE for the comparison and no other key performance indicators (KPIs) like break-even grid extension distance.

Abdelhamid et al. [29] analysed the feasibility of implementing remote PV mini-grid systems in five communities in Chad using a techno-economic approach. They examined system configurations, capital and operational costs, and the levelized cost of electricity (LCOE) to assess economic viability. The study also explored financing methods and business models suitable for Chad's energy sector, providing insights into the integration of technical expertise and economic analysis for mini-grid electrification in remote areas. On the other hand, the findings were not generalized to all localities in Chad, and the potential of hybrid photovoltaic was not explored.

Szabo et al. [30] compared electrification costs of distributed solar, diesel generation, and grid extension in rural Africa. They analyze initial investments, operating expenses, and life-cycle costs. In their paper, the authors based their analysis on the assumption that one-third of the energy is consumed during the daytime and two-thirds during the evening and night, rather than using an hourly time series. Additionally, carbon emissions were not considered in the comparison for the diesel generator with the other two options.

The above research works both show a lack of comparative study and focus either on one electrification strategy, electrification enhancement strategy or a limited range of KPIs such as only LCOE. There is therefore need to analyze the viability of the two most common electrification strategies in the context of Namibia i.e. grid extension and mini-grid expansion as enhancing approaches for existing mini-grids. Incorporating a broader range of KPIs to assess this is crucial, which is why this paper uses the levelized cost of electricity, total net present cost, carbon emissions and even the grid extension break even distance as the main KPIs to determine the most effective electrification enhancement strategy.

While previous studies thoroughly evaluate off-grid electrification strategies and suitable renewable energy technologies, there is lack of studies focusing on existing mini-grids. The

evaluation of hybrid PV mini-grid systems have not considered environmental impacts such as the carbon emission from the use of diesel generators. In addition, there is limited consideration of alternative solutions for unmet load demands while key performance indicators beyond the LCOE, such as break-even distances for grid extensions, are also often overlooked. This paper not only looks at an under-studied concept but also applies a holistic methodology that considers and presents results across the technological, economical, and environmental fields.

2. Materials and Methods

To meet the aim of the paper, this section outlines the methodological approach used.

The research methodology followed in this paper is presented in Figure 1. It outlines the systematic approach followed to assess the feasibility of the analysed electrification enhancement solutions for Tsumkwe and Gam.

The first step analyses the existing mini-grid systems in both communities to understand the current operating scenario. To do so, measurements and recorded data was used to analyse system performance in terms of electricity production but also on the consumer side the consumption patterns were studied. The measurement and recorded data used was available from 2017 to late 2022, however the year 2021 and 2019 were mainly used as the basis for this paper as they present fuller sets of data. Amongst the data collection methods were installed mini-grid monitoring computers which record the solar generation, diesel generation as well as consumption in one minute resolution. Based on this data, analysis of the annual energy generation and consumption profiles of mini-grids was performed. The objective of the first third of the methodology is to establish the electricity capacity shortage as generated by the existing mini-grid infrastructure and thus analyse in the next step, the feasibility of the herein studied electrification enhancement strategies. At this first step, diesel consumption and carbon emissions are also calculated as per the summed up annual values per off-grid community. The calculated values are also supporting inputs for the performed economic analysis of mini-grid components to calculate total net present cost (TNPC) and the levelized cost of electricity (LCOE).

In the second step, the two derived main scenarios in off-grid electrification are evaluated as enhancement strategies for both Tsumkwe and Gam. As in the figure, this step highly relies to meet the capacity shortage established in the first step to therefore achieve an uninterrupted electricity supplier as will be discussed in the later chapters. The selection of these two enhancement scenarios (i.e., grid extension and mini-grid capacity expansion) also stems from the discussion within Tsumkwe and Gam and amongst Namibian energy stakeholders on feasible options to complement the now undersized mini-grids. As a matter of fact, the national grid is only 82 km away from Tsumkwe and 143 km from Gam, and therefore questions rise on whether integrating the mini-grids may enhance electrification and finally solve the energy poverty challenge. Therefore, from a technical point of view, this paper seeks to analyze the feasibility of expanding the mini-grid generation capacities. The evaluation was done within the environment of HOMER Pro and MS Excel.

In the case of the national grid extension, MS Excel is utilized to calculate the techno-economic performance. To thoroughly evaluate feasibility of grid extension, two further categories as shown in Figure 1 are considered; 1. Grid extension considering existing mini-grid battery storage and 2. Grid extension without battery storage. The two sub-categories differ in that one assumes that the existing mini-grid installed battery capacity is fully functional and is useful energy storage while the second assumes otherwise. The justification for this is that the installed batteries at the mini-grids are beyond their lifetime and therefore a realistic analysis is required. In design, this affects the electricity supply and reliance on the main grid. To calculate the electricity supply from the grid in the first sub-category, an analysis in MS Excel was performed considering that if there is PV production, the electricity supply priority is for the immediate demand from the communities, any surplus is then fed into the batteries installed on site. At the bottom of the priority chain is feeding in electricity into the grid, only when the batteries are fully charged and the immediate electricity demand from the communities is less than the generated electricity. In the second category, the national grid takes the role of a back-up generator. It therefore presents a case covering the night-time demand and instances during the day when there is no solar production or the mini-grid is unable to meet the immediate

demand. The surplus generated electricity production from PV modules during the day is fed into the main grid.

The economic analysis was performed to understand the financial feasibility of electrifying the region by extending the national grid from the nearest accessible grid to the mini-grid site. The KPIs to evaluate the financial feasibility are LCOE and TNPC. To calculate these KPIs, the distance from the last grid point to the Tsumkwe and Gam, per km capital cost of grid extension, operation and maintenance cost and electricity demand of the community were taken into consideration. These values were obtained through thorough literature review.

For scenario 2, namely mini-grid capacity expansion, optimization is performed in HOMER Pro software. The methodology involves initially defining a set of parameters as input values to HOMER Pro's optimization tool which generates system configurations with various sizes based on factors like LCOE and TNPC. Input parameters include maximum annual capacity shortage (MACS) and minimum renewable fraction. Maximum annual capacity shortage is the maximum allowable value of the capacity shortage fraction, where the capacity shortage fraction is the ratio of total capacity shortage and total electricity demand [31]. The MACS is the parameter that defines the mini-grid system's reliability and is expressed in percentage (%). The value of MACS depicts how much percentage of the electricity demand is fulfilled by the mini-grid system and how much is being fulfilled by the diesel generators. The minimum renewable fraction represents the minimum share of the generated electricity that is coming from renewable sources and is expressed in % like the MACS. HOMER PRO suggests different system configurations depending on the minimum renewable fraction and different values for MACS.

In the last step the two off-grid electrification enhancement scenarios are compared based on the above mentioned KPIs. The terminology of break-even grid extension distance is also introduced here to calculate the possible distance up to which the main grid can be extended in the TNPC of the compared scenario [32]. Based on the comparison between the technical and economic viability of the energy systems, a sustainable and reliable energy solution for Tsumkwe and Gam is recommended.

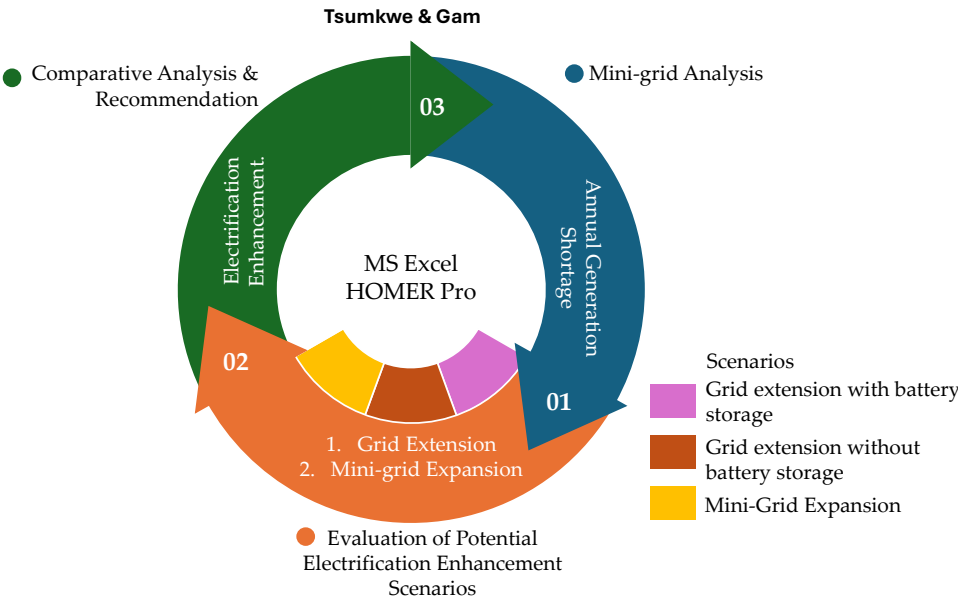


Figure 1. Research methodology.

While the methodology thoroughly focuses on the feasibility of the proposed electrification enhancement strategies, a number of assumptions are considered to reach this papers recommendations.

- The economic values on the mini-grid infrastructure prices, including maintance costs are based on literature review and may not be the exact values at the moment of mini-grid implementation. This may affect the LCOE and other economis analysis, however, the authors have used the most relevant sources

- Due to inavailability of data on the battery performance, the diesel generator running times are assumed to give an insight in battery performance. This assumption would hold true if the diesel generator operation were automated. However, since this is not the case, some discrepancies may arise.
- While data was recorded for over four (4) years, the data used in this paper is mainly that of 2019 and 2021. While these years may not fully reflect the performance of the mini-grid or the off-grid communities best, mean values with other years could not be considered due to either a lot of data gaps or unjustified trends.
- Grid extension costs and associated costs were also based on literature review and in some cases not specific to Namibia.

3. Namibia's Off-grid Communities: Tsumkwe & Gam

To apply the described methodology, this chapter outlines the system components of the Tsumkwe and Gam mini-grids, along with their operation status. The results and discussions are based on the foundation of the methodology and this chapter.

3.1. Tsumkwe Mini-grid

Tsumkwe is the largest off-grid community in Namibia [33]. In 2012, when the Tsumkwe mini-grid (c.f. Figure 2) was implemented, it was economically unfeasible to extend the national grid to the Tsumkwe and hence a hybrid solar PV-diesel mini-grid was established to electrify Tsumkwe. The mini-grid was officially commissioned by the Namibian Ministry of Mines and Energy in February 2012.



Figure 2. Tsumkwe mini-grid.

Since 2015, Central-North Electricity Distribution Company (Pty) Limited (CENORED) has been responsible for the operation and management of the mini-grid (GPS Coordinates -19.5985, 20.5037). The hybrid mini-grid system in Tsumkwe was first established in 2012 with a solar capacity of 202 kWp, which was later expanded by 102 kWp in 2016. The battery system with capacity of 790 kWh was installed in 2012, later expanded by 1140 kWh in 2014, and by another 1070 kWh in 2016. The diesel generator capacity is 350 kVA since 2012. Figure 3 shows the evolution of the power plant.

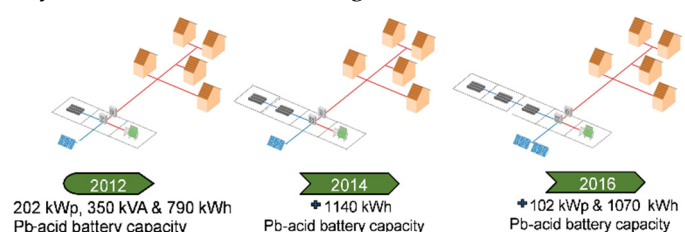


Figure 3. Tsumkwe mini-grid evolution.

The operating condition of the battery system at Tsumkwe was observed to hinder the battery performance. The batteries had degraded over the years because of the high room-temperatures affecting the life cycle of the system, since the batteries now operate at high operating temperatures affecting the achievable number of charging-discharging cycles. As a result, the batteries at the Tsumkwe mini-grid posed as loads rather than storage units.

The Tsumkwe mini-grid serves an off-grid community with approximately 200 households, nine institutions (schools, clinic, police station), and supermarkets (amongst other retail businesses). The institutional loads were observed to be the main electricity consumers.

To understand the generation and consumption mismatch, analysis was done. Figure 4 presents the daily energy consumption and solar production profile of Tsumkwe in 2021. The total annual electricity demand of Tsumkwe was calculated to be 655 MWh, with an average daily demand of 1,796 kWh/day. The annual electricity production from PV was 452 MWh, resulting in an annual capacity shortage of 34%. While an annual presentation of solar production and electricity consumption fails to present justification for this mismatch, this 34% shortage could better be explained by daily generation and production trends. As of the afternoon hours, the solar production capacities seemed, on most days, capable to off-set the instant electricity demand. However, through interviewing the residents and business owners, it was established that demand side management strategies such as load shedding had been initiated. The evening/ nighttime hours however, mainly showed that the battery capacities could not meet the instant demand and therefore the irregular introduction of the diesel generator was observed. It could therefore be deduced that this capacity shortage could be due to either insufficient PV production for both instant demand or battery charging or due to degradation in batteries storage capabilities. Likewise, the electricity production from diesel generator was summed up and found to be 364 MWh in 2019, and 422 MWh in 2021, highlighting the increased reliance on the diesel generator and/or increased electricity demand, reduction of battery storage capacity and reduced PV output.

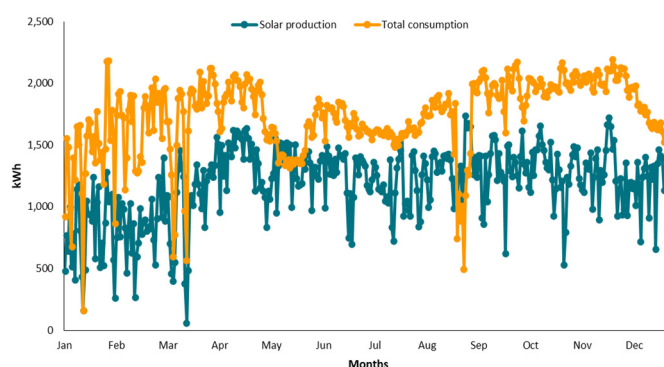


Figure 4. Daily energy profile of Tsumkwe in 2021.

Since there lacks a monitoring of diesel consumption on site and due to the manual operation of the diesel generator, an estimation for diesel consumption was done. In general, the specific fuel consumption rate of diesel generators ranges from 0.23 to 0.3 litres per kWh [34]. The assumed value throughout this paper is 0.3 litres per kWh, which was then multiplied by the generator electricity production in 2021 to estimate the annual diesel fuel consumption [34]. At the calculated 126,600 liters/ year, and considering each liter emits 2.68 kg of CO₂ [35], the total CO₂ by the consumption of diesel fuel in Tsumkwe was 265,261 kg in 2021.

Economic Evaluation of System

The economic analysis of mini-grids, typically includes the initial cost (C_i) operation and maintenance costs ($C_{O\&M}$), and replacement costs for each component (C_R). C_i includes the component cost and their installation cost, i.e., the cost of solar panels and the associated installation cost. It also includes ongoing expenses associated with routine upkeep, monitoring, and servicing to ensure optimal performance and longevity of the components. C_R accounts for the expenditure incurred when replacing components at the end of their lifetime or due to malfunction. The lifetime (N) of the

energy systems considered in this paper is 25 years, and the discount rate (i) is 8% [27]. Considering all these cost factors throughout the lifetime of the mini-grid, an economic evaluation is performed to analyze the system's feasibility. Table 1 shows the cost details for Tsumkwe mini-grid system. The C_I of PV panels is 1,990 €/kWp, $C_{O\&M}$ is 12.6 €/kWp/year[27]. The lifetime cost of the battery storage system consists of C_I , $C_{O\&M}$ and C_R which is 325 €/kWh, 20.1 €/kWh/year, and 292 €/kWh respectively[27]. The converter of the mini-grid system accounts for a smaller share of the total cost than the first two components. The C_I of the converter is 283 €/kWp, $C_{O\&M}$ is 3.87 €/kWp/year and C_R is 255 €/kWp [27]. The C_I of a diesel generator is 460 €/kW [31]. The cost of diesel fuel is 1.01 €/litre [36] and annual consumption is around 126,600 litres.

Table 1. Techno-economic details of the Tsumkwe mini-grid.

System	PV (kWp)	Battery (kWh)	TNPC € million	LCOE €/kWh
Tsumkwe mini-grid system	302	3,000	4.68	0.55

The TNPC is calculated by the following formula, where N is the lifetime of the system, i is the discount rate CF_t is the cash flow in year between 1 to 25.

$$TNPC = C_I + \sum_{t=1}^N \frac{CF_t}{(1+i)^t} \quad [37]$$

Equation 1

The following equation calculates the LCOE

$$LCOE_{existing\ mini-grids} = \frac{\text{Present value of total cost over the lifetime}}{\text{Present value of electricity generated over the lifetime}}$$

Equation 2

3.2 Gam Mini-Grid

The Gam settlement is the second largest off-grid settlement after Tsumkwe, and is located in Otjozondjupa region [33]. The Gam power plant (c.f., Figure 5) was commissioned in November 2014 and was designed and installed by HopSol. Similar to the Tsumkwe mini-grid, since 2017, CENORED has been responsible for the operation and management of the Gam solar power plant (GPS Coordinates -20.2389, 20.8109).

The hybrid PV-diesel mini-grid system includes thin film PV modules with a generation capacity of 292 kWp, a 300 kVA diesel generator, and a lead acid battery storage capacity of 2,600 kWh. Initially, the Gam off-grid community's electricity demand did not require supply from the diesel generator, however during the evolvement of the community, this has changed. The consumer group of mini-grids is spread over households, businesses, and institutions, e.g., schools, clinics.



Figure 5. Gam mini-grid.

The energy consumption and generation profile of Gam showed that the mini-grid was previously producing surplus electricity until 2021 when 400 new household connections were connected. This compelled an introduction of a diesel generator in 2020, which previously was not required. Figure 6 illustrates the daily energy consumption and production profile of the Gam mini-grid in 2021. For few days during the months of January to February and August to October, because of the lack of recorded data, the energy demand values are unknown.

In 2021, the recorded total demand of Gam village was 276 MWh, solar generation was 308 MWh, and diesel production contributed around 15 MWh. The average daily energy consumption was around 757 kWh. The total electricity production from the diesel fuel in 2021 was 15,000 kWh, with the total diesel consumption of 4,500 litres and CO₂ around 12,060 kg.

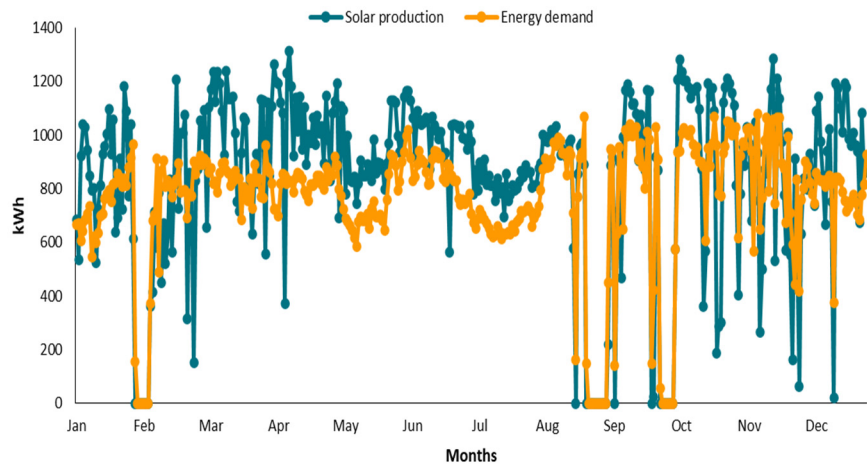


Figure 6. Daily energy profile of Gam in 2021.

Economic Evaluation of the System

Table 2 presents details for the Gam mini-grid system. The TNPC of the Gam mini-grid system is € 3.03 million and the LCOE is 0.91 €/kWh.

Table 2. Techno-economic details of the Gam mini-grid.

System	PV (kWp)	Battery (kWh)	TNPC € million	LCOE €/kWh
Gam mini-grid system	292	2,600	3.03	0.91

4. Techno-Economic Analysis of Electrification Enhancement Scenarios

Upon establishing the system components and the related challenges for both mini-grids, the analysis of the proposed mini-grid enhancement scenarios is undertaken. Both the technical and economic analysis are carried out for each scenario established in the methodology. This chapter explores the techno-economic analysis of these scenarios for both Tsumkwe and Gam and their potential to enhance the power plants in meeting the community's electricity demands.

4.1. Tsumkwe Electrification Enhancement

4.1.1. Grid Extension

As previously explained, two sub-scenarios are considered for the national grid extension to Tsumkwe: one with battery storage systems and one without. The nearest national grid point from Tsumkwe is at Mangetti Dune [19], which is 82 km to the west of Tsumkwe. In SSA, the per km cost of grid extension is 30,000 - 40,000 €/km, depending on the type of terrain [28]. The per km cost considered in this paper is 30,000 €/km and the C_{O&M} for extending the grid is 180 €/km/year. The following formula is followed in this thesis to calculate the LCOE in the case of grid extension.

$$LCOE_{\text{grid extension}} = \frac{\text{Total net present cost of extending the grid to measured distance}}{\text{Total energy supply from the national grid}}$$

Equation 3

Grid extension with battery storage system

In this case, it is assumed that even after extending the main grid to Tsumkwe, the battery storage system is still working as in the designed operating condition/capacity. Hence, the excess electricity from PV would be used to charge the battery storage system. The analysis on Tsumkwe's electricity demand and the generation, an establishment of the mismatched supply is deduced. To meet this demand, the required electricity supply from the national grid would be 225,392 kWh/year. Using Equation 3, the calculated LCOE is 1.09 €/kWh with the TNPC of € 2.62 million. The mini-grid itself would supply 65% of the demand and the remaining 35% would be acquired from the grid.

Grid extension without battery storage system

Since the battery system at The Tsumkwe mini-grid is already in poor operating condition, this scenario considers a grid extension as a primary back-up generator. This assumption rules out the role of the installed battery capacity in Tsumkwe. The electricity generated by the national grid would meet both daytime demand during instances of higher demand than that generated by the mini-grid, as well as the nighttime demand. Table 3 presents the techno-economic details for grid extension to Tsumkwe calculated using Equation 3 and Equation 1. The amount of electricity supplied by the national grid in this case is thus higher as it takes on the nighttime demand. The required annual electrical energy supply is thus 391,946 kWh/year. The TNPC remains the same, as in the scenarios with battery storage i.e., €2.62 million. The LCOE is 0.63 €/kWh, around 42% less than the previous scenario due to higher electricity supply from the grid with the same infrastructure as in the previous scenario.

The grid contributes about 59% of the electricity supply and the mini-grid only contributes about 41% without battery backup.

Table 3. Techno-economic details for grid extension to Tsumkwe.

Scenario	Electricity demand kWh/year	TNPC € million	LCOE €/kWh
With batteries	225,392	2.62	1.09
Without batteries	391,946	2.62	0.63

4.1.2 Mini-Grid Capacity Expansion

The existing mini-grid system in Tsumkwe results in a capacity shortage of 225,392 kWh/year. Using Equation 4 the capacity shortage fraction of the mini-grid was calculated and found to be 34%.

Capacity shortage fraction = $\frac{\text{Total capacity shortage (kWh/year)}}{\text{Total electrical demand (kWh/year)}}$ [38]

Equation 4

This paper considers three cases to mitigate this shortage; 1. 25% capacity shortage, 2. 15% capacity shortage and 3. 0% capacity shortage, where:

- 1. 25% capacity shortage implies that the mini-grid can meet 75% of the annual electrical energy demand
- 2. 15% capacity shortage implies that the mini-grid can meet 85% of the annual electrical energy demand
- 3. 0% capacity shortage implies that the mini-grid can meet the full electrical energy demand

Depending on these cases, the mini-grid's expanded capacity is optimized in HOMER Pro. According to the above-mentioned ranges, the mini-grid would be able to serve the minimum demands ranging from 575 MWh/year to 611 MWh/year compared to the 433 MWh/year in 2021. These cases also consider the installed battery capacity to be in full operation condition. Using HOMER Pro, optimal mini-grid extension results (c.f. Table 4) were attained for each case.

Table 4. Tsumkwe mini-grid expansion capacities.

Case	PV Capacity (kWp)	Battery Capacity (kWh)	Additional Generation (kWh/year)	Annual Generation (kWh/year)
25%	86	-	142,777	575,223
15%	158	-	178,723	611,169
0%	419	1292	225,392	657,838

It is significant to note that only in case 3 (i.e., 0% capacity shortage fraction) is additional battery storage required. In such, mini-grid expansion with battery storage expansion, assuming the currently installed is fully operational, would be able to meet the current electrical energy demand of the Tsumkwe off-grid community. For cases 1 and 2, the diesel generator would be sufficient to meet the remaining demand. Based on these findings, economic calculations including diesel fuel consumption were calculated (c.f., Table 5).

Table 5. Techno-economic details for mini-grid capacity expansion in Tsumkwe.

Case	TNPC (€ million)	LCOE (€ million)	Diesel use (litres)	Carbon emissions (kg)
25%	0.47	0.20	24,300	63,666
15%	0.53	0.23	14,400	37,728
0%	2.20	0.41	-	-

For case 3, there is a considerable surge in TNPC because of the capacity addition of the battery storage system. However, this case presents an advantage in that there is no diesel use and carbon emissions. Especially in the case of remote off-grid communities where diesel attainment can be challenging, this case was necessary to consider.

4.2. Gam Electrification Enhancement

The following sub-sections describe the two scenarios for enhancing the energy supply in Gam as was done for Tsumkwe.

4.2.1. Grid Extension

The distance from Mangetti Dune to the Gam is 143 km. The same approach as for Tsumkwe is followed in the techno-economic analysis. These parameters provide the financial context for evaluating the viability and sustainability of the grid extension.

Grid extension with battery storage system

Upon performing an analysis in MS Excel to calculate the amount of electricity supply from the grid, the demand shortage to be meet was found to be 11,602 kWh/year. Likewise, the economic analysis was performed. Less electricity supply from the grid and a long distance of 143 km to cover are reflected in the high LCOE. Approximately 95% of the demand is covered by the mini-grid, considering that battery systems will back up the mini-grid during the night and when there are no solar production hours. Table 6 represents the details of the national grid extension scenario to Gam.

Grid extension without battery storage system

In this sub-scenario, it is assumed that there will be no use of battery storage systems after extending the grid since the community will have a connection to the national grid as a backup. Hence, in this case, the demand considered will be more than in the previous case. Any excess electricity production from PV would be completely fed into the grid. The electricity supply from the national grid covers the gap during the night and during the day hours when there is no solar production. After performing an analysis, the electricity supply from PV, in this case, is 149,110 kWh/year. Since the electricity supply is higher than in the previous case, while utilizing the same infrastructure, the LCOE is much lower. The grid would supply 54% of the total energy demand while the rest is from PV production.

Table 6. Techno-economic details for grid extension to Gam.

Scenario	Electricity demand (kWh/year)	TNPC (€ million)	LCOE (€/kWh)
With batteries	11,602	4.56	36.86
Without batteries	149,110	4.56	2.87

4.2.2. Mini-Grid Capacity Expansion

The installed mini-grid system in Gam is currently undersized and can therefore not fulfil the total electricity demand of the community. The possibility of expanding the generation capacity of the mini-grid system was evaluated. For capacity expansion planning of the mini-grid, a set of criteria, must be met by the expanded system capacity. The annual electrical energy demand of 276,238 kWh as of 2021 is used in this analysis. In 2021, an energy shortage of 11,602 kWh in 2021 was observed. This translates to a capacity shortage fraction of 4.2%.

To address this 4.2% capacity shortage within the system, an optimization for the mini-grid capacity expansion was performed in HOMER Pro. Since the value of the current capacity shortage is only 4.2%, this optimization focused only on one case for capacity shortage, i.e., 0% and a minimum

renewable fraction of 100%. Table 7 shows the technical details of the expanded system capacity. A 52 kWp mini-grid capacity expansion would meet the demand of the Gam off-grid community without the need to install additional battery capacity. This indicates also that Gam has a deficiency in PV generation to charge the batteries enough to meet the nighttime demand. This eases the expansion as no additional battery infrastructure would be required, considering batteries are the expensive mini-grid components.

Table 7. Gam mini-grid expansion capacity.

Case	PV Capacity (kWp)	Battery Capacity (kWh)	Additional Generation (kWh/year)
0%	52	-	11,602

This case also does not rely on diesel and therefore no emissions are projected (i.e., within system operation). The economic details are shown in the table below.

Table 8. Techno-economic details for mini-grid capacity expansion in Gam.

Case	TNPC (€ million)	LCOE (€ million)	Diesel use (litres)	Carbon emissions (kg)
0%	0.17	1.41	-	-

4. Discussion

Comparison of scenarios for Tsumkwe

The national grid extension to Tsumkwe is evidently the most expensive option for enhancing electrification. In the case of mini-grid capacity expansion, the cases 25% and 15% capacity shortage fraction prove a reduction of the LCOE to about half the current value, however due to the carbon emissions and reliance on diesel the two options are not the most sustainable, considering that the off-grid community may again have an increased demand in the coming years. The 0% capacity shortage fraction presents a slightly reduced LCOE but presents the cleanest and sustainable solution as there is no dependence on the diesel generator. The TNPC however then is higher than the other cases.

To fully understand the feasibility of the grid extension to Tsumkwe, the value ‘break-even’ is introduced. This would showcase the distance in km to which grid extension from Mangetti dune would still be economically viable when compared to mini-grid capacity expansion costs. Beyond the intersection of TNPC of grid extension and mini-grid capacity expansion, grid extension is expensive compared to the other options. In the case of Tsumkwe, the break-even grid extension distance is 68.87 km, which implies that extending the main grid beyond 68.87 km (c.f., Figure 7) is not economically feasible. Since the required distance to extend the grid is 82 km, this rules out grid extension as the best electrification enhancement scenario.

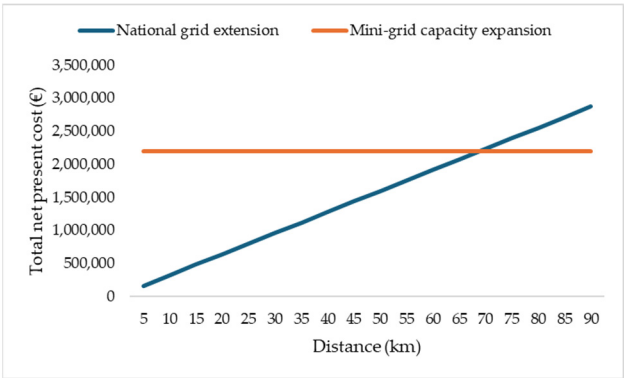


Figure 7. Break-even grid extension distance for Tsumkwe.

Comparison of scenarios for Gam

In Gam, grid extension is seen to be the most expensive scenario with a TNPC of € 4.56 million. Especially extending the grid with battery storage in Gam, as this means high extension costs for very little generation. In both cases (i.e., with and without the battery storage), the LCOE is too high to be economically feasible for implementation. Among the evaluated scenarios, mini-grid expansion presents the lowest LCOE even though still higher than the current LCOE (i.e., 1.41 €/kWh compared to 0.91 €/kWh).

In the case of Gam, the break-even grid extension distance is 5.2 km (c.f., Figure 8), whereas the required distance to extend the grid is 143 km. Extending the national grid to Gam beyond 5.2 km is not economically feasible.

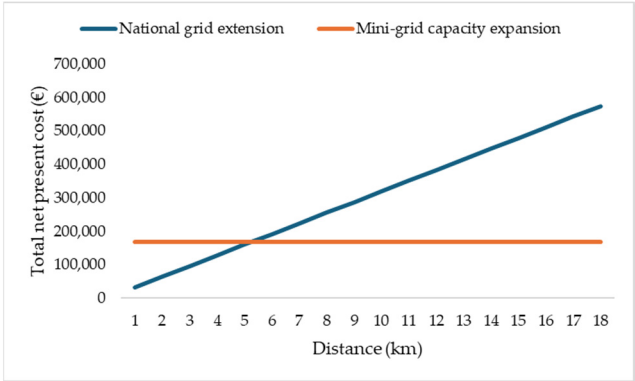


Figure 8. Break-even grid extension distance for Gam.

5. Conclusions

Electrification of off-grid communities in SSA is crucial but lacks the follow-up upon electricity demand increasing. With time, mini-grids become undersized and fail to meet the communities' electricity demand and therefore interventions and innovative strategies are required to enhance the electrification of these communities to eradicate energy poverty. Grid extension and mini-grids, especially solar based, remain the top rural electrification strategies in SSA. This paper therefore analyses the feasibility of grid extension and mini-grid expansion to enhance electricity supply of existing mini-grids (case studying Tsumkwe and Gam in Namibia). Considering that the mini-grids are also equipped with batteries, the grid extension enhancement strategy also examines extension without batteries. This stems from the fact that batteries on site are already deteriorated and some act like loads rather than storage. This paper examines both the technical and economic factors thus ensuring sustainability and affordability. The analysis for both Tsumkwe and Gam shows that grid extension is very expensive and in fact only an extension of 68.87 km and 5.2 km from Mangetti Dune respectively would be economically feasible. As for mini-grid capacity expansion, this scenario presents economically feasible options especially for Tsumkwe as the attained LCOEs are lower than the current LCOE. In the case of Gam, the LCOE remains higher than the current one. It can therefore be concluded that mini-grid expansion presents the best electrification enhancement scenario for off-

grid communities however, it is crucial to do community specific analysis to obtain the exact indicators for feasibility. In the case of Tsumkwe, for instance, this paper presents three possible implementation solutions. However, for Gam this paper fails to present an economically saving solution unless strategies such as subsidies were put in place. The methodology used can be adapted to any SSAn off-grid community provided the specific values are changed respectively. This paper uses assumptions stated in the methodology chapter, due to lack of data in some cases. Further research can be done with actual data to better compare grid extension to mini-grid expansion in established off-grid communities. Likewise, one may go further to consider subsidizing options to support mini-expansion.

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