Mini-Grid or Grid Extension? The Strategies for Electrification Schemes Concerning Population Density in Sub-Saharan Africa

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Abstract

Sub-Saharan Africa (SSA) is the second-largest continent in the world and homes an estimated quarter of the world's population. While the region has the fastest-growing population, it is dominated by scattered settlements between cities, towns, and villages. To date, SSA is the least electrified region in the world with lower electrification rates in its developed regions than in the least electrified regions in developed countries. This study uses Namibia, the least densely populated SSA country to assess the viability of mini-grids versus grid extension. Two main electrification options were considered within the presented work: grid extension and mini-grids. The study identified the key factors for fostering electrification in rural Namibia. The method applied in this paper follows various features starting from data collected from the field, literature review and geospatial approach to detailed analysis through techno-economic and social perspective. Summing up, the article presented the economic estimation for selected electrification options. Based on the analysis, the presented study attempted to provide a technical framework (based on the local boundary conditions). Even the LCOE is more subjective to various factors compared to grid-extension, it is recommended mini-grid for low-population off-grid. The derived result can serve as fundamental inputs for decision makers / policymakers to define the strategies for electrification schemes.

Keywords: electricity, grid extension, mini-grid, Namibia, population density, Sub-Saharan Africa

1. Introduction

1.1 Mapping out the scene

Access to electricity is considered one of the fundamental elements of human development (Sarkodie and Adams, 2020). In 2016, 1.1 billion people lacked access to electricity. At the end of 2021, the number of people without access to electricity dropped from 1.1 billion to almost 768 million. Around 60% of them live in sub-Saharan African (SSA) countries. Despite ongoing efforts of the electrification activities, ensuring access to affordable and reliable, sustainable, and modern energy for all (Sustainable Development Goal 7) is challenging. The current trajectory estimates that around 700 million people remain unelectrified until 2030, and the majority of them (600 million) will be from SSA (IEA, 2017; Falchetta et al., 2020). With a major electrical scarcity, it is difficult to foresee a developing modern economy or healthy and productive households. SSA holds the lowest energy access rates in the world. Around 13 countries in SSA have less than 25% electricity access rate. SSA's population is structured with approximately two-thirds of settlers in rural communities. However, it is the least electrified region in the world with about half of its population lacking access to not only electricity but also reliable electricity which both hinders the livelihood and productivity of the region. It is certain that grid extension cannot single-handedly thrust electrification rates and electrify the entire SSA. Electrification is even more crucial for low-population density countries in SSA. Because low population densities affect electrification schemes as there exist very long distances between regions and therefore pose infrastructural, time, economic, resource availability as well as technical awareness constraints (Trotter, 2016).

1.2 Introducing the special focus on Namibia

Namibia is a small country of about 2.5 million people. It lies along the coastline on the South Atlantic bordering South Africa, Botswana, Zambia, and Angola. The country identifies as the driest country in SSA with 70% of its population depending on natural resources for their livelihood (Schick and Pierre, 2021). Around 60% of Namibian electricity is imported from South Africa's Eskom and Southern African Power Pool (Marambire, 2020). Of the renewable primary energy resources, hydropower is highly exploited in Namibia. Due to climatic changes, hydrological regimes and capacity generation of the existing power plants are expected to reduce or vary (Ministry

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of Mines and Energy, 2020) especially with Southern African Power Pool (SAPP) failing to meet the demand of its primary customers in South Africa therefore reduction of imported electricity to Namibia. Namibia has electrification rates of 45% national wide and 19% for household settlements. At 3 people per km^2 with 79% of its population in rural settlements, grid extension is prone to the same constraints to reach its energy targets. Fig.1 represents the electrification timeline of Namibia put in place by the government to achieve universal electrification.

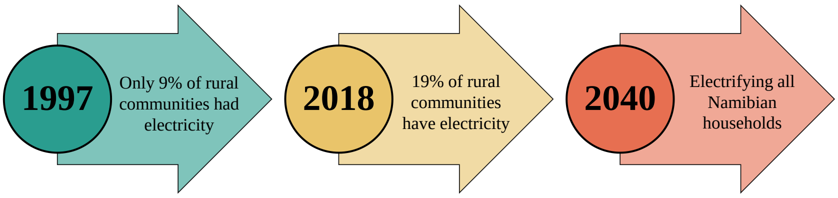

Fig. 1: Electrification timeline of Namibia (own illustration based on Buasai et al. (2019) and Ministry of Mines and Energy (2020))

Whilst the region is investing in formulating policies and regulations to increase its electricity access, often the remote and least developed areas are neglected. Namibian Ministry of Mines and Energy (MME) states within the rural electrification program that "*Rural electrification is part of the Government's economic development policy to expand the electricity supply infrastructure to rural areas to improve the socio-economic conditions of Namibian citizens and to create the necessary incentives for economic development in the targeted areas*" (Ministry of Mines and Energy, 2020). Recently, it was identified that the Ministry of Mines and Energy has a plan to electrify all Namibian households by the year 2040 (Pressreader, 2022). To achieve the target, Namibian energy policies approached several ways of electrification which are presented in Fig.2.

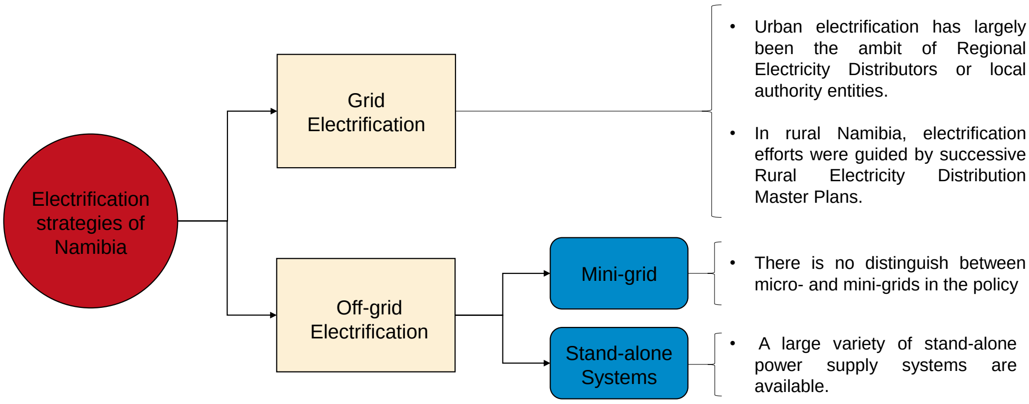

Fig. 2: Electrification strategies of Namibia (based on Ministry of Mines and Energy (2020))

1.3 Gap in the research and key objectives

To achieve the electrification target, naturally, rural settlements would probably be approached through either mini-grid technology or grid extensions under the scheme of "rural electrification program". Stand-alone systems are designed for primary energy needs (i.e., home lighting, mobile charging, radio etc.). However, stand-alone systems are of limited energy access in rural settlements which are formulated with some business establishments due to the requirement of higher energy amounts, the vast range of appliances as well the ability to easily expand and develop their energy demand (Scott-George et al., 2021). The recent theoretical development mentioned that there are two classic approaches available for rural electrification. One suitable way is to extend the grid to remote areas and electrify the isolated regions. Another one is the installation of a mini-grid system for remote settlements. However, selection of the suitable options from the above-mentioned solutions is one of the critical tasks for the policymakers. This is significantly applicable to countries with a low population density because the rural areas are situated far away from the major energy production centers and isolated geographically. This can be considered as one of the results of the low electrification rate (especially in the rural regions) in Namibia.

The lack of studies focusing on electrification policies that take into consideration population density and distribution limits the insight into answering the question of whether grid extension surpasses mini-grids as an electrification approach. In the case of Namibia, for instance, the government set out a strategy to adapt off-grid schemes only to public institutions. However, there is a gap in the research that outline the strategies for the electrification schemes at the household-level / settlement level. To address the research gap, the presented study is the first attempt to provide a framework for the electrification scheme in Namibia (a low population density country) and thoroughly discusses the viability of the grid extension versus mini-grid on the country level. It brings forward results to this unaddressed comparative analysis with transferability to other SSA remote communities. Such study can serve as a fundamental base for decision makers / policymakers for adequate planning for the electrification strategies and targets.

2. Research Methodology

The method applied in this paper follows a multifaceted approach to achieve the key objective of the paper which is presented in Fig.3. The study starts with the problem statement by studying the energy situation in Namibia and the potential of rural electrification in the country. Based on that outlook, the presented article set a research question. To foster electrification, it is important to identify the key challenges / barriers to understanding the existing situation. Based on the expert opinion, geospatial data and literature review, the paper recognised the key electrification challenges for a typical rural settlement in Namibia. To actualise the technical framework, the article selected a typical rural settlement from SSA which holds a low population density and is situated far away from the national grid. For the presented study, Uutsathima was selected, and two main electrification options were considered: grid extension and mini-grids.

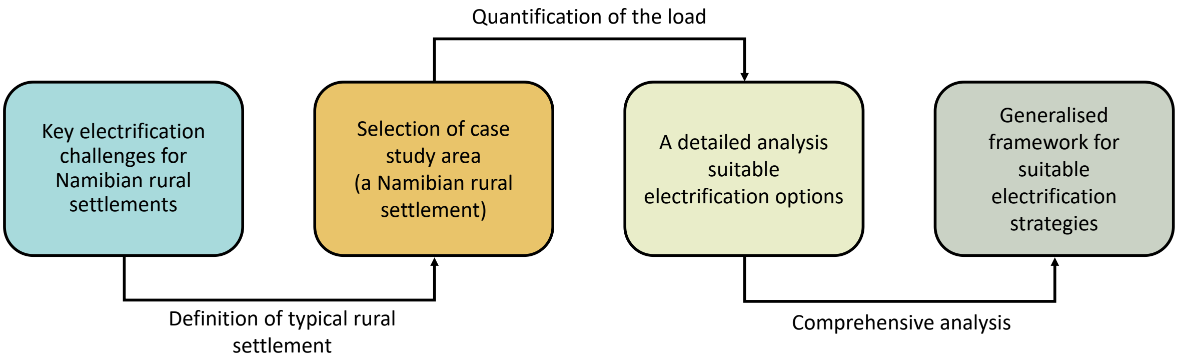

Fig. 3: Research methodology of the presented paper

The study brought out a comparative picture of suitable electrification options for rural Namibian settlement and provided a generalised framework on the country level (based on the on-site survey, technical analysis, literature survey and socio-economic indicators).

3. Derivation of key electrification challenges for rural settlements

Rural electrification in Namibia faced several challenges that deem typical electrification approaches impractical. This chapter intends to discuss the real challenges based on open-source geographic data, extensive literature, and field visits.

3.1 Population density

Population density gives an overview of how sparsely a country's population is distributed. In SSA, Namibia ranks last at three people per km^2. The population density affects infrastructure and economic efforts in grid expansion as it may deem it unaffordable and / or time-consuming. The distribution system network in low population density communities requires a vast distribution network coverage for the non-comparable amount of low energy consumption customers. This limits the value for electricity per square kilometer of coverage. Therefore, regardless of there being other alternatives such as generators and traditional exploitation of biomass energy, risks such as putting inhabitants' health at risk as well as limiting the economic activities carried out due to unreliable access still prevail. Especially with rising fuel costs, auxiliary solutions such as diesel gensets also do not put forth the best solution for rural inhabitants.

Gesto Energia (2018), identified that in Senegal the grid extension is recommendable in areas of higher population density as well as consumption. This is never the case for rural settlements, which explains the opaque grid extension efforts by various SSA member states' governments and ministries. Fig. 4 (b) illustrates the population density of Namibia. The interpretation of the map is that Namibia is substantially low populated with most regions appearing empty or unresized which may be interlinked with the dryness of the country. Apart from the northern region whose population is affected by the immigration of Angolans who fled their country in search of basic needs due to drought in Angola (Nhongo, 2021), the remaining of the country especially the rural regions have very small population densities. Likewise, the youths and working class of Namibia tend to migrate into urban and semi-urban regions in search of energy ergonomic conditions. Namibia, therefore, serves the best for the evaluation of grid extension versus mini-grid implementation feasibility in concern of population density.

3.2 Limited availability of the transmission network

While rural regions, worldwide, are mainly defined by low population, low economic activity and recreational engagement, geographical outlook, among other factors, rural regions of SSA are predominantly interlinked with poor infrastructure and low to no electricity access. In SSA, less than 6 out of 10 households are connected to the main grid while less than 43% always enjoy a reliable supply of electricity without blackouts.

Rural residents have half the probability of that urban residents to have access to the main grid (Lee et al., 2022). To argue this fact, this paper presents a map (c.f. Fig 4 (c)) of Namibia which represents the transmission line of the national electricity grid. The map indicates that the grid is mainly concentrated in the central part of the country where the capital city, Windhoek lies. Contrary to that region, the northern, western, and southern parts are hardly within the reach of the grid. While this may again be interlinked with the absence of residence, arguably, this neglects most of Namibia's rural settlers whose geographical location denies them of their prerequisite need of access to clean and reliable electricity.

To define the non-electrified areas more specifically in-line with the availability of transmission network, Fig. 4 (d) represents the night light imagery applied which is defined by light emissions and the absence of the light emissions.

3.3 Low income

Residents of rural SSA communities are mainly associated with small-scale economic activities. In fact, the economic engagement in rural settlements is characterized by daily income-generating activities that can only sustain short-term needs rather than economic growth or savings. Rural regions mainly have a set of business establishments such as local kiosks selling basic household groceries, a few modern shops offering cellphone charging services and cold beverage, milling shops, and the most dominating are local alcohol shops for recreational purposes. In 2019, agriculture accounted for half the jobs in SSA and industries - mining industry - came at 13% in 2019 (United Nations Conference on Trade and Development (UNCTAD), 2021), however rural engagement in such activities remains very limited and if at all then food crop agriculture is predominant.

In Namibia, around 45% of the population live in multidimensional poverty / low-income. The low-income scenario is even more intense in rural Namibia (Namibia Statistics Agency, 2021). The lack of access to modern and reliable energy has contributed to the limitation of economic engagement of rural residents (Gesto Energia, 2018). Rural residents are linked with low income and are therefore unable to pay the electricity costs. Fig. 4 (e) illustrates the average household income in Namibia which indicates a higher generation in Windhoek (mainly in Khomas region) and a reduction of income as the map stretches towards the north and south of the country into rural regions.

3.4 High electricity costs

Despite the unavailability of the grid and high costs accompanied with grid extension, costs of electricity in rural SSA are often higher than the average earner can comfortably afford. Of the Southern-African Development Community (SADC), Namibia had the second highest electricity tariff of 0.167 € cents/kWh even though this was argued to be the most cost-reflective tariff in the region in 2018. Between 2017 and 2018, the tariff experienced a 6% increase for household consumers (Electricity Control Board (ECB), 2018). However, these reflective but expensive tariffs are also understood to grant and secure the viability and longevity of the energy solutions. On the 6^{th} of May, 2022 the ECB in Namibia announced an increase for bulk electricity tariffs by 7.30%, and placed residential prepaid electricity at 0.087 €/kWh in the year 2022/23 (New Era, 2021).

The Ministry of Mines and Energy, in Namibia, reports that the existing tariff for rural low-income consumers is exclusive of capital and operation costs. This way the cost of electricity is reflective of the economic status of the consumers. However, the ministry identifies that capital and operational subsidies are crucial to compensate for the high supply costs which may be achieved through external funding to reduce or eliminate the risk of electrification failure in rural regions. The high electricity costs are, therefore, at present a burden for the government, operator, and consumer (Ministry of Mines and Energy, 2021).

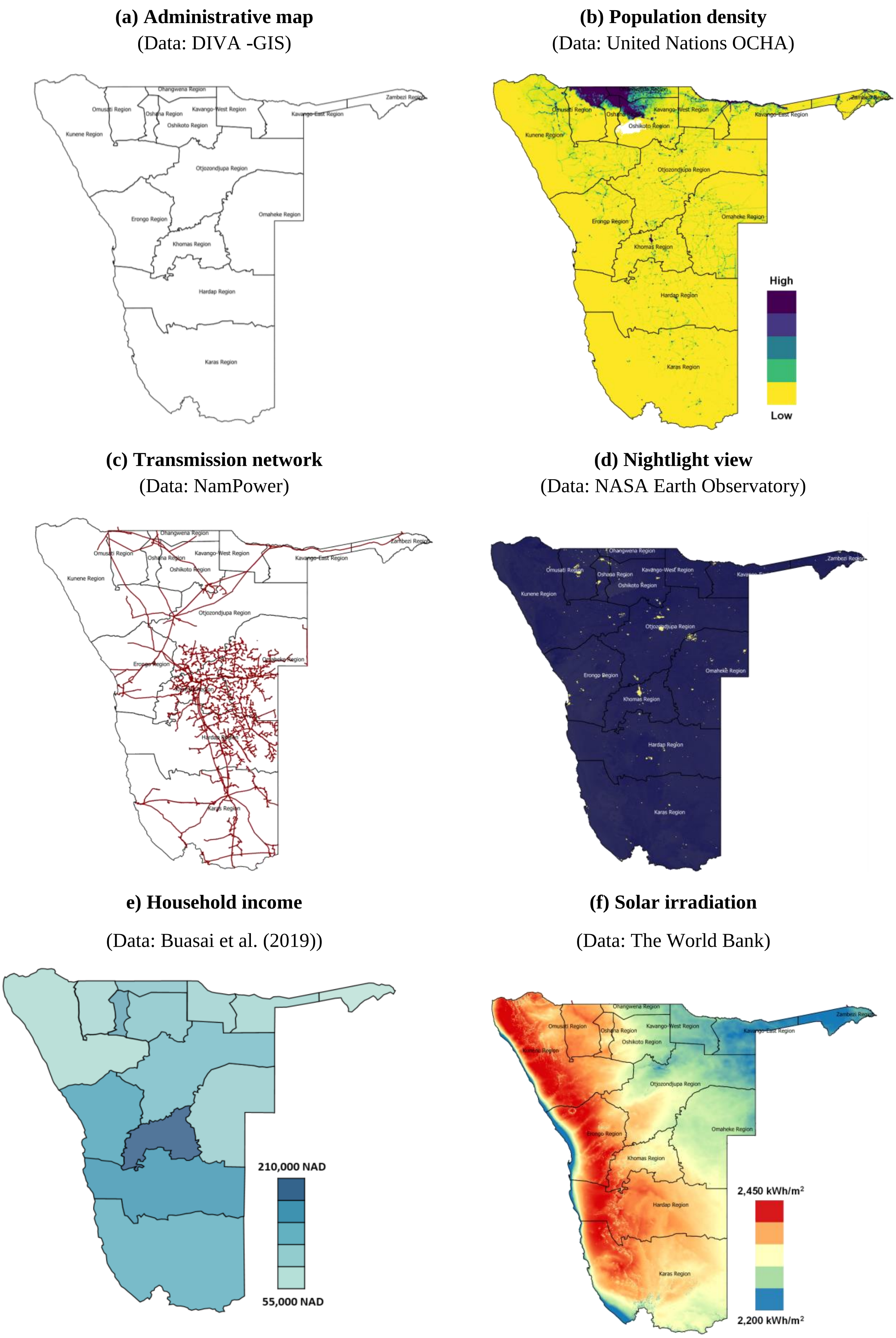

Fig. 4: The selective geographical datasets for Namibia (own illustration based on the GIS data mentioned respectively)

3.5 Less exploitation of solar energy for electrification

Namibia is one of the sunniest countries in the world, as shown in Fig. 4 (f), with solar irradiation ranging from 2,200 to 2,460 kWh/m2 annually. Despite this, over 60% of the country's energy is imported, and most rural areas are without electricity. Only three off-grid regions, Gobabeb, Tsumkwe, and Gam, have installed pilot mini-grids using solar energy. This indicates a lack of solar energy utilization for electrification. This paper focuses on solar energy as an alternative electricity source, particularly for mini-grids, in Namibia, which has a low population density and substantial potential in solar irradiation and photovoltaic technology.

4. Typical rural Namibian settlement - Uutsathima

A typical SSA rural settlement is characterized as a large constellation of very distributed settlements. Often the areas are with large open land or a small population density with minimal business engagement. While the areas belong to a governmental structure, seldom do they benefit from development and budgetary schemes as they are the least prioritized regions. Services such as education, health, electricity, clean water, and infrastructure such as roads are very limited in rural regions of SSA. The rural settlements in Namibia have identical structure to those in the SSA region and all over the country. This paper goes further to select a rural settlement in Namibia for precise and realistic findings. This chapter describes Uutsathima, a typical Namibian rural settlement and its electrical condition, consumption, and demand which is used to design and recommend electrification options for a low population density community.

4.1 General setup of Uutsathima

Uutsathima, Namibia is a rural village located in the north-eastern part of Namibia in the Omusati region at 18° 27´ 36´´ S, 14° 50´ 24´´ E. Fig. 5 shows its geographical information orientation. As of 2022, Uutsathima's households and business settlements are still mainly unelectrified, while a few businesses use diesel generators or solar panels for phone charging services. The households use either candles, paraffin, or solar-powered lanterns for lighting purposes while they all use wood stoves and charcoal for cooking.

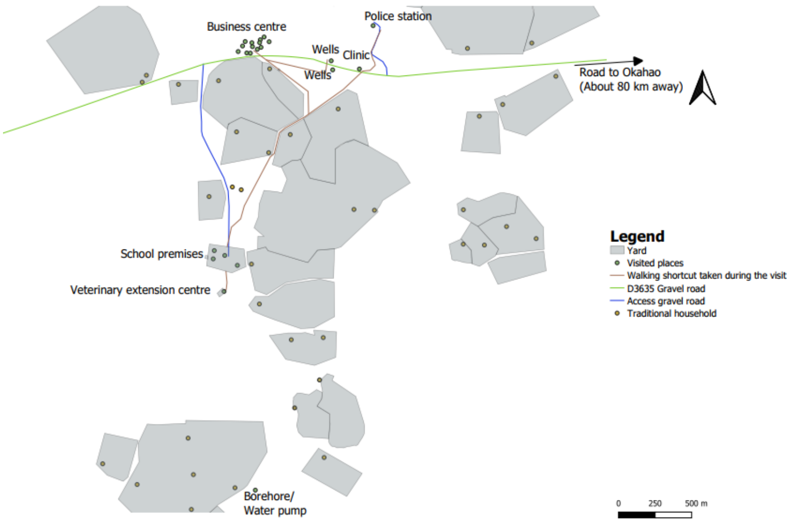

Fig. 5: Geographic information system (GIS) representation of Uutsathima village

The village is mainly sub-categorized into households, businesses, and public settlements. The business centre of Uutsathima is comprised of 50 local alcohol shops, 10 local shops, 4 modern shops as well as a milling shop. The public institutions include a police station, a school with teachers and students' residence, a clinic, and a veterinary centre. The village also has a water pumping station that uses a Lister-peter diesel powered surface pump to fill in the village water storage tanks. This paper recognizes the prerequisite lack of electricity access to the households and business settlements as a barrier to their general livelihood and herein utilizes the situation to analyse and answer the question of which option between grid extension or mini-grid implementation best fits the electricity access coverage when population density comes in question. To do that, the electrical consumption of Uutsathima is studied.

4.2 Load profile of Uutsathima village

Low-income resident dominated rural settlements of SSA are characterized by limited electrical demand and access as well as few electrical appliances based on the significance of demand. The Global LEAP, an international association that promotes the world's best off-grid appliances, identifies lighting, mobile charging, radio, television, and music sound systems as the most electrical applications by order of significance (Narayan et al., 2020).

In Uutsathima, the same electrical demand and behaviour was observed through an on-site survey. A social and technical survey was done, to distinguish the customer clusters, the appliance ownership across the categorized clusters and their power rating, as well as the consumption behaviour -as influenced by related economic or domestic activities- on an hourly basis. This survey was done over a research stay which included interviewing, questionnaire filling as well as on-site survey and energy audit of available appliances across the electrified public institutions. Due to minor economic engagement and existence of only one business centre, all establishments including the public institutions were audited. As the households were completely unelectrified, random sample household respondents were interviewed. Data was therefore collected on existing appliances and projections for the appliance ownership in unelectrified consumer categories based on the respondents' information. The collected data was used to create load profiles for all distinct appliances and settlements using a MATLAB algorithm. Using the collected data, each appliance, its rated power, and the vector for the hourly usage is loaded into MATLAB and an independent appliance load profile is created. This MATLAB loop runs over all appliances in each settlement with the corresponding usage vector. Once the loop is completed over one consumer/ settlement, the aggregated load profile is computed for each settlement/ consumer. MATLAB then aggregates the individual settlement/ consumer load profiles into the Uutsathima village load profile presented in Fig.6.

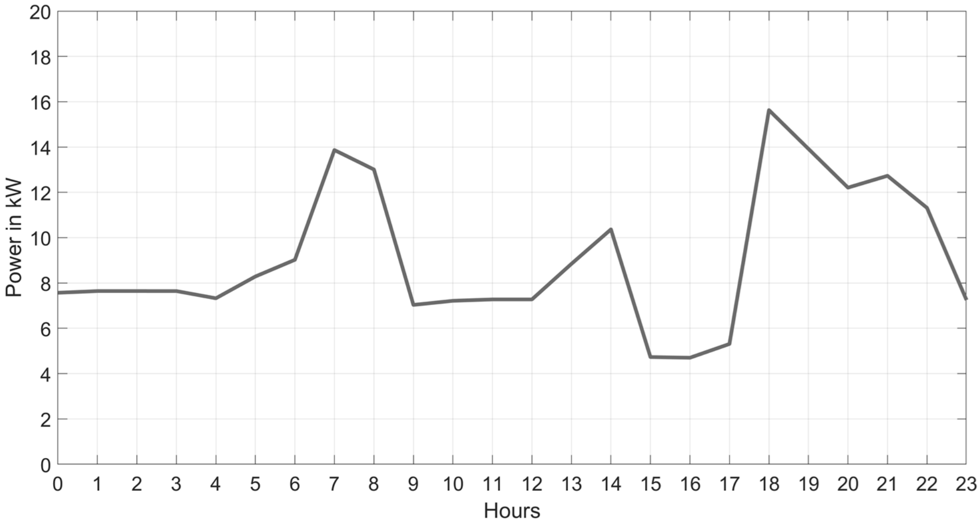

Fig. 6: Aggregated electrical load profile of Uutsathima village

The load profile of Uutsathima village represents the aggregated demand of all settlements within the village. Fig. 6 shows a morning peak mainly due to household consumption and the water pump turned on at 7:00 AM. Reduced activities at households, schools, and veterinary residences demonstrate a drop in consumption, leaving minor consumption and the water pump until the pump is switched off. In the evenings, the village exhibits higher demand due to increased residential activities, milling activities and alcohol sales at the business centre. The daily peak power and average energy consumption are 15.629 kW and 217.804 kWh/day, respectively.

The load profile depicts that the village has higher demand in the evenings than during the day which this study considers an indicator of the need for sufficient storage capacity. Therefore, since the consumption of energy is highest in the evening, that implies that during peak production hours, the charging of the batteries is crucial. To avoid extreme diesel consumption by running the diesel generator and/or evening and nighttime electricity black outs, this paper further suggests excluding the 6 kW water pump in the load profile. As is the pump is currently operated6 hours during peak production times (i.e., from 08:00 AM until 02:00 PM). This complements the storage capacity and assures reliable supply in peak hours. Since the water pump is currently diesel powered, the recommendation is to maintain it or replace it with a solar powered pump and operate it independent of the mini-grid serving other consumers. Fig. 6 shows the load profile of Uutsathima village with a decreased demand in the afternoon and is therefore used to examine the two electrification approaches.

5. Detection of potential electrification options

After quantifying the settlement electrical load, this chapter throws light on how to meet that load through suitable electrification. In that regard, two main electrification options were considered grid extensions and mini-grids. This chapter further presents a comprehensive analysis of both electrification options. Due to limited availability / unavailability of information on the economic dimensions, cost estimation was considered based on the literature review. However, the robust technical information provided in the presented article (i.e., load profile of a typical settlement, required size of mini-grid, the distance of the settlement from the available grid etc) will allow the scientific community to develop accurate economic analysis as a future scope.

- Mini-grid-based electrification:

  Based on the load profile generated for Uutsathima village, a mini-grid to meet the demand of the village was sized using PVsyst (Webgenève, 2022). The simulation results will allow understanding the size of the mini-grid for Uutsathima village. Based on the size, a rough estimation was made for LCOE for electrification through mini-grid.

- Grid-extension based electrification:

  For grid extension into Uutsathima, two key factors were considered. The closest grid point to Uustathima was found through consultation with the Namibian Energy Institute (NEI). Then, assuming a standard cost of grid extension per km, a rough capital investment for extension was attained.

5.1 Mini-grid for Uutsathima

The developed load profile became an input for the simulation through the PVsyst. Fig.7 represents the detailed technical results of the simulation results for electrification through mini-grid. The mini-grid annual energy production is 52 MWh/yr.

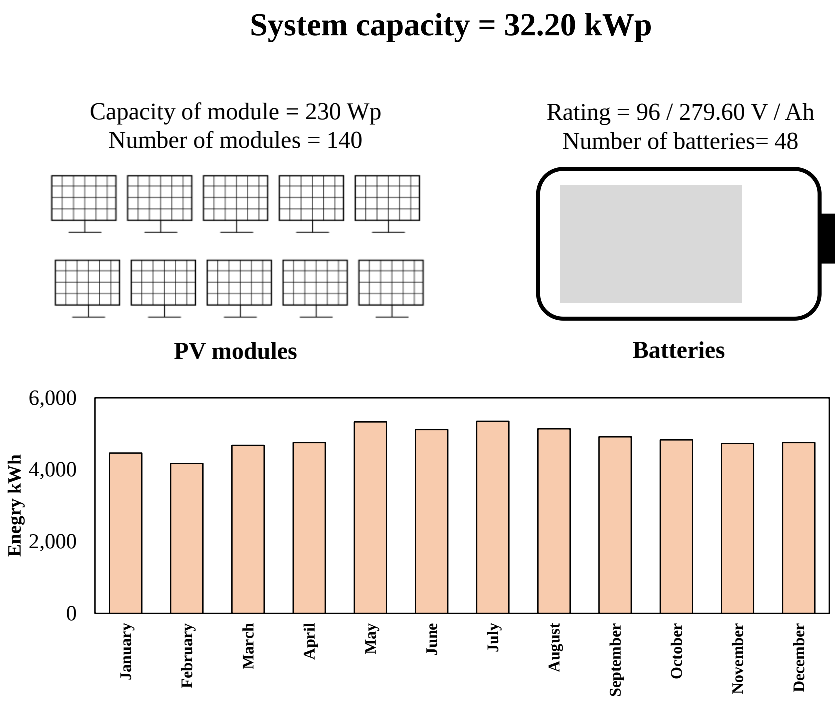

Fig. 7: Technical specification for the suggested mini-grid and monthly Uutsathima PV mini-grid electricity generation

By considering the abundant solar energy resources, the presented simulation study considered the solar PV-based mini-grid for electrification. However, as the presented article deals with the general blueprint and technical framework, Fig. 8 represents the LCOE of various mini-grid technology for the scientific community. One can study Come Zebra et al. (2021) for in-depth economic assessment of mini-grid for off-grid electrification in developing countries. By considering the enormous potential of solar energy as well as the robustness of the solar-based mini-grid, the presented article selects the solar PV-based mini-grid. In the case of Uutsathima as the system size for the mini-grid is 32.20 kWp, the estimated LCOE is 0.55 €/kWh based on the literature review.

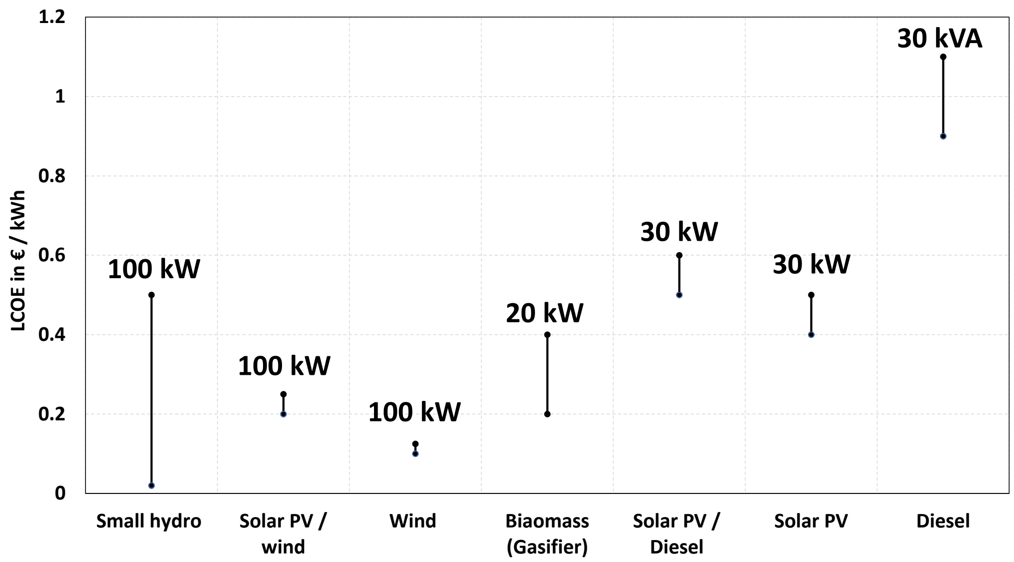

Fig. 8: LCOE (€/kWh) of mini-grid and hybrid mini-grid options at different scales based on Come Zebra et al. (2021)

5.2. Grid-extension for Uutsathima

The United Nations sustainable development goal 7 (SDG 7) motivated governments in SSA to formulate solutions in efforts to increase energy access. In the case of electrical energy, most governments enacted grid extension as a premium solution. However, connection costs remain high for an average-earning household. Economically advantaged households are twice likely to get connected to the grid in comparison to a poor household, the percentage probability is 83% to 43% (Lee et al., 2022). Whilst these connections imply only in the case that the grid is within proximity, the corresponding governments also face significant investment cost implications in grid extension.

In 2019, the cost of grid extension was reported by the World Bank to range up to 35,080 €/km (Sessa et al., 2021). Research showed that 87% of new connections are within 5 km of the existing distribution network and 77% within 2 km (Sanghvi, 2020). This implies that for villages, such as Uutsathima, whose closest grid distribution network is tens of kilometres away, the economic feasibility of grid extension is impractical especially with little to no budget allocation by the responsible ministries and governments. Okahao is the closest semi-urban town to Uutsathima. 20 km from the town is the nearest grid point to both Okahao and Uutsathima. An approximate of 60 km lies between the grid point and Uutsathima. At the rated cost of extension per km as per Sessa et al (2021), a grid extension investment of approximately 2.1 million euros would be required to Uutsathima. In instances that member countries of SSA have extended their grid into rural regions, electricity costs continue to surpass the economic capability of rural abilities to purchase despite their willingness to pay for electrical energy.

6. Outlook / Discussion

6.1 Recommended technical framework for electrification in Namibia

Previous research is available that used different methodologies / decisive matrices for electrification of the non-electrified regions. However, in particular, for Namibia, there is a lack of scientific knowledge available about decision-making. Hence, based on the literature review and discussion with the energy experts in the field, the presented technical framework attempt to quantify the derived key challenges and portrays the robust technical framework for electrification which can be considered as a novel contribution. The presented analysis will serve as the fundamental input for the policymakers / decision-makers to design the electrification plan for Namibia.

Naturally, high population density in the village / community is immediately interlinked with higher load density (i.e. kW demanded / km^2). Ochs and Gioutsos (2017) mentioned that "*Areas with higher load densities require less low-voltage line materials and labour for their installation, which reduces distribution costs and often swings the economic favourability towards mini-grids. Cost savings are found to diminish at around 400 people per square kilometre*". However, Namibia is already a low population density country and therefore it is difficult to transfer the results to Namibia. The author suggests that further research work needs to be carried out here to quantify the population density as a decision making for Namibia for available electrification options. It is recommended that the living area / settlement near power transmission lines within the proximity of 5 to 25 km is cost-effective for electrification through grid extension (Szabó et al., 2011; Bertheau et al., 2017; Ochs and Gioutsos, 2017). Fig 4 (c) already presented the recent transmission network of Namibia. One can easily identify the unelectrified region through that and try to measure the distance from the nearest grid point. This approach will now give a better understanding that grid extension is a feasible option or not from the cost-effectiveness. Compared to solar home light systems, mini-grids are usually installed in the range of 10 kW to 10 MW and therefore provide large-scaled loads (Come Zebra et al., 2021). Naturally, the large cumulative load cut down the cost and makes the mini-grid generation economically viable. Based on the previous analysis, Fig. 9 presents a suitable electrification option selection for Namibia.

Considering that Namibia's tariffs exclude capital and operational costs for grid extension for rural unelectrified regions implies that from the implementation phase developing countries such as Namibia, function at an economic disadvantage. Unaffordability of electricity cannot be solved by incurring losses therefore, secure models should be adapted. The literature review showed that in most of the cases, LCOE of mini-grid is low compared to grid extension. However, the LCOE considers all-around investment and operations costs and if subsidization and cross-subsidies are adopted, this could see a decrease in price for rural consumers.

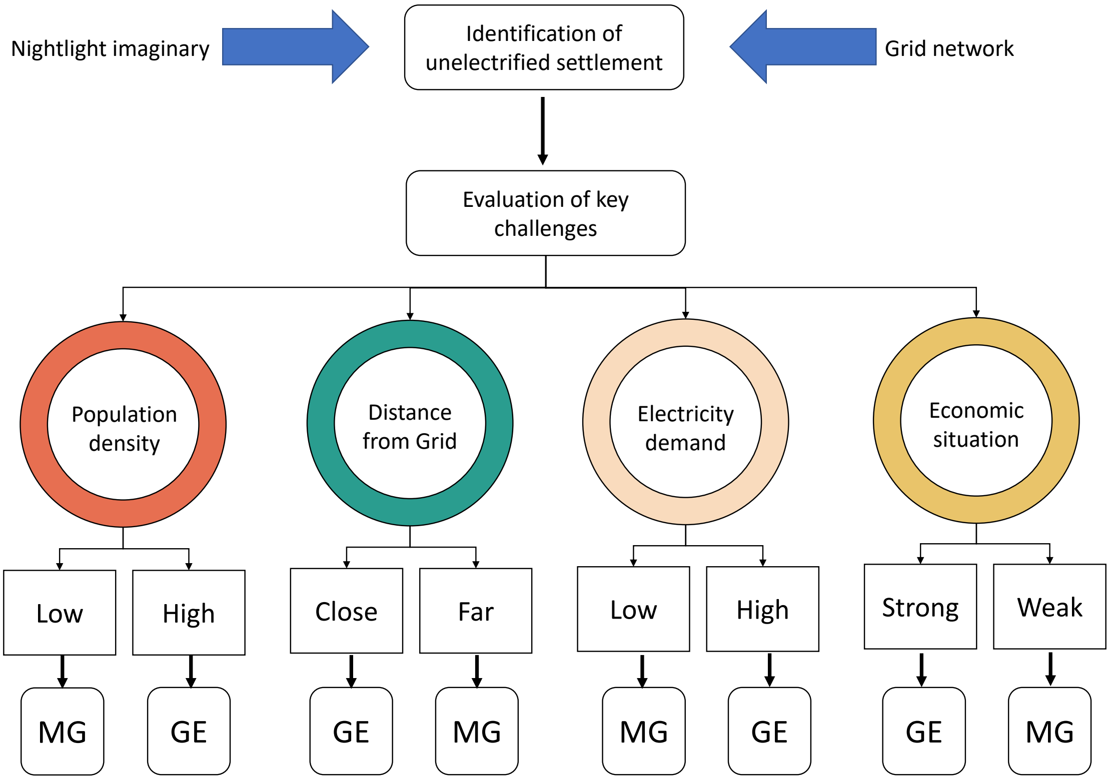

Fig. 9: A derived technical framework for deciding electrification schemes that can help to provide best-served electrification approach to electrify Namibia (MG = Mini-grid and GE = Grid extension)

6.2 Limitations of the study

The presented study provides a conceptual framework that was generalized and scaled up to the country level based on the on-grid and mini-grid assessment. Hence, the study will not only be limited to Uutsathima (settlement level) but, instead, the results were applied to Namibia (on the country level). However, the decision for suitable electrification can not only be made from the advantages and disadvantages of the technology. There is an immediate need to consider the key challenges / local factors which were derived in the presented article.

6.3 Comparative analysis of both electrification options in the context of SSA

This chapter provides a comparative overview of the pros and cons of both the selected electrification options in through the assessment in the local context. This overview will help an international reader to understand the individual electrification option closely.

Tab. 1: Comparative overview of mini-grid and grid-extension technology

	Advantages	Disadvantages
Mini-grid	• Utilization of local resources • Community based solution • Integration of productive use cases • Enables "link" to (national) power grid • Depending on location: Lower LCOE as compared to grid extension	• High investment costs / Investor required • Regular maintenance is mandatory • Limited correlation between demand / capacity • Requires battery storage and / or backup generator
Grid-extension	• Low maintenance costs • "Technology-agnostic" • Battery storage optional • A robust, reliable solution	• (Very) high investment costs • (Very) long implementation time • Not (necessarily) linked to the expansion of renewable energy

7. Conclusion

The presented research article tried to answer the research question "what is the suitable electrification strategy for rural Namibia?". Therefore, this study conclusively identifies the selection possibilities between mini-grids and grid extension for rural electrification in Namibia. The results were obtained by consideration of the vision, goals, and efforts of the Namibian electrification and energy policies. The research looked at how to bring electricity to rural areas in Namibia. The study found two options that could work: mini-grids and grid extension. The study compared the benefits and challenges of each option, which could save money and make electricity available faster. The standard option in developed countries is the grid connection for almost all households. This highly capital and rigorous electrification option may take a longer time for developing countries to achieve fast electrification. At the same time, mini-grid technology is a well-established (technically) option. However, it requires sufficient high local demand density. However, it does not disregard the role of grid extension and therefore identifies regions that are least scattered, further from existing transmission plants and with denser load to utilize grid extension. Consideration of population increase, as well as an increase in economic activities, may, in the future, increase the demand and therefore the inflexibility of mini-grid expansion can be limiting but policies such as integrating them into the grid once it arrives may be the ideal solution. The study recommends studying the demographic influence of areas as well as sizing off-grid networks as per demand to avoid surplus generation, losses, or high costs. Summing up, the presented article derived a general framework to demonstrate where which technology will be feasible based on the key criteria discussed in the article. Due to this demographic similarity in remote areas of SSA, the findings of this study can be transferred to any member country. One may further analyze the utilization of other standalone off-grid systems such as solar housing to classify which electrification scheme fits for further scattered and less dense settlements.

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9. References

Bertheau, P., Oyewo, A., Cader, C., Breyer, C., Blechinger, P., 2017. Visualizing National Electrification Scenarios for Sub-Saharan African Countries. Energies 10 (11), 1899.

Buasai, S., ElShahks, B., Kelsey, B., Whitehorn, L., 2019. Data Portal for Rural Electrification in Namibia, 2019.

Come Zebra, E.I., van der Windt, H.J., Nhumaio, G., Faaij, A.P., 2021. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews 144, 111036.

Electricity Control Board (ECB), 2018. Electricity Supply Industry Statistical Bulletin Rural Electrification in Namibia 2018.

Falchetta, G., Pachauri, S., Byers, E., Danylo, O., Parkinson, S.C., 2020. Satellite Observations Reveal Inequalities in the Progress and Effectiveness of Recent Electrification in Sub-Saharan Africa. One Earth 2 (4), 364–379.

Gesto Energia, 2018. Senegal's SE4ALL Rural Electrification. Action agenda and investment prospectus.

IEA, 2017. Energy Access Outlook 2017.

Lee, H.E., Kim, W.Y., kang, H., Han, K., 2022. Still lacking reliable electricity from the grid, may Africans turn to other sources.

Marambire, A., 2020. Sustainable finance. An essential tool to enable access to affordable and clean energy in Namibia.

Ministry of Mines and Energy, 2020. Republic of Namibia - National Electrification Policy. First Draft. https://www.ecb.org.na/images/docs/Economic_Regulation/1st%20DRAFT%20-%20National%20Electrification%20Policy%20-%20Rev%202%20-%2020200916.pdf. Accessed 23 April 2022.

Ministry of Mines and Energy, 2021. National Electrification Policy. Final Draft.

Namibia Statistics Agency, 2021. Namibia Multidimensional Poverty Index (MPI) Report 2021, Windhoek, Namibia. https://ophi.org.uk/wp-content/uploads/Namibia_MPI_report_2021.pdf.

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

New Era, 2021. Electricity price to surge… NamPower granted 7.3% tariff increase. https://neweralive.na/posts/electricity-price-to-surge. Accessed 5 September 2022.

Nhongo, K., 2021. Namibia Under Pressure from Angolan Migrants Fleeing Drought. https://www.bloomberg.com/news/articles/2021-10-07/namibia-under-pressure-from-angolan-migrants-fleeing-drought. Accessed 6 September 2022.

Ochs, A., Gioutsos, D., 2017. Rural Electrification in Sierra Leone: The Role of Mini Grids vis-à-vis Stand-alone Home Systems and Grid Extension.

Pressreader, 2022. Tsumkwe West residents receive electricity, Namibia.

Sanghvi, A., 2020. National Electrification Strategy. Implementation Plan and Mechanisms for achieving Universal Electricity access (2020-2030). Terms of Reference.

Sarkodie, S.A., Adams, S., 2020. Electricity access, human development index, governance and income inequality in Sub-Saharan Africa. Energy Reports 6, 455–466.

Schick, A., Pierre, I., 2021. Namibian bush encroachment in context. An ecological perspective on current and future drylan greening.

Scott-George, A., Li, C., Tang, Y.K., Saha, S., Bin Ali, M.T., Marma, A., Pal, S., 2021. A review on the sustainability of solar home system for rural electrification. E3S Web Conf. 294, 2003.

Sessa, V., Bhandari, R., Ba, A., 2021. Rural Electrification Pathways: An Implementation of LEAP and GIS Tools in Mali. Energies 14 (11), 3338.

Szabó, S., Bódis, K., Huld, T., Moner-Girona, M., 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ. Res. Lett. 6 (3), 34002.

Trotter, P.A., 2016. Rural electrification, electrification inequality and democratic institutions in sub-Saharan Africa. Energy for Sustainable Development 34, 111–129.

United Nations Conference on Trade and Development (UNCTAD), 2021. Reaping the potential benefits of the African Continental Free Trade Area for inclusive growth.

Webgenève, 2022. PVsyst (Version 7.2) Photovoltaiv software. https://www.pvsyst.com/. Accessed 12 September 2022.