Microgrids – Impact on the development of rural communities in Sub-Saharan Africa

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***Abstract*— This master's thesis explores the transformative potential of microgrids in promoting the development of rural communities in sub-Saharan Africa. Many regions in this area lack viable access to electricity, which has led to a focus on microgrid systems powered by photovoltaic technology and battery energy storage. With an approach centered on sustainability and access to clean energy, the research investigates the potential of these microgrids to address the lack of electrification in remote regions, in order to offer a reliable energy solution for 24 hours a day.**

The research will focus on 2 case studies of different sizes: the Municipality of Mussende and the commune of São Lucas, both located in the province of Kwanza Sul in Angola. The sizing, planning and implementation of microgrids in these regions will be studied in comparison with the expansion of the electricity grid.

The results show that the choice between grid extension and microgrids varies according to the scenario and local needs, in terms of distance from the grid and number of inhabitants.

This research provides valuable insights to inform decision-makers, researchers, and professionals involved in off-grid electrification within energy-deficient rural areas of sub-Saharan Africa.

Keywords— Microgrids, Rural Communities, Sub-Saharan Africa, Renewable Energies, Decentralized Energy, Sustainability

I. INTRODUCTION

The integration of distributed energy resources into low-voltage distribution grid is a crucial step in ensuring access to reliable and sustainable energy for all. One solution to the challenges presented by this integration is the development of microgrids, which can address the integration of geographically dispersed energy resources and avoid significant technical problems that could affect the security of the system [1]. Sub-Saharan Africa (SSA) has a rich mix of renewable energy sources, but most of this is either unused or underused to produce electricity from these sources. This problem has a lot to do with the fact that there is a lack of energy infrastructure that is adequate and the high cost to implement it. Lack of electricity is correlated with poverty, and as such, communities living in rural areas of sub-Saharan Africa need to be able to get affordable electricity so that it is beneficial in the long run for both sides. Since, in SSA energy resources are widely dispersed from each other and, communities live in large clusters, it is expected that the use of these resources to obtain and produce energy, will be distributed throughout the region [2].

Thus, the use of microgrids is justified and a wise choice for this area, as they are a standalone technology that can connect to the grid or operate as an islanded system. Microgrids, are a technology that offers a feasible and reliable solution compared to grid extension, as many of these areas are not easily accessible and are located far from the electrical grid [3]. The use of fossil fuels to produce electricity is something that nowadays is increasingly falling into disuse, being unattractive because it is not sustainable and, as is known, because its production process releases greenhouse gases into the atmosphere which, in turn, increases the total carbon footprint, causing overwhelming effects for the increase of global warming and the consequences associated with this phenomenon [4], [5]. Although the initial costs of installing renewable energy generation technology are high compared to fossil-fueled generators, when looking at the long-term situation there are factors that make the choice very advantageous for remote areas of sub-Saharan Africa, such as inaccessibility of sites and rising fuel prices [3].

However, not all renewable energies are suitable for all locations to be implemented. Renewable energies such as hydropower or geothermal are dispersed, while solar and wind energies, for example, are intermittent in nature. In addition, both wind and solar energy have variations in their intensity that are reflected in their production from place to place [6]. To interconnect these renewable energy technologies directly to the grid, there are associated challenges that need to be addressed. Energy services are crucial to human well-being and development. Without the necessary conditions for life, and reliable energy is one of them today, it is difficult to escape subsistence lifestyles and human poverty. Access to energy, especially for rural communities, represents a key aspect of population development. About 1.1 billion people worldwide (14% of the world's population) do not have access to reliable electricity or any form of energy. Of these people, about half live in SSA. As such, this lack of access to electricity in rural communities in sub-Saharan Africa means that these people have little choice but to live a subsistence life. This problem has been intensified in recent decades by the ever-increasing population growth, and as a resolution, the United Nations (UN) Sustainable Development Goals (SDGs) have recognized access to energy as a major challenge for global society. Thus, Goal 7 of the SDGs, guarantees "ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 [2], [7].

The following project will explore these issues and propose solutions for the successful integration of microgrids and renewable energy technologies in SSA, with a focus on addressing the unique challenges faced by rural communities. For this project, Angola was selected as the SSA country under study, along with two distinct locations within the country for project implementation.

The aim of this thesis is to propose solutions for the successful integration of microgrids and renewable energy technologies in sub-Saharan Africa, with a focus on addressing the unique challenges faced by rural communities, and for the analysis and comparison of different photovoltaic projects in rural communities in Angola, to understand how these projects can impact these locations in terms of obtaining reliable energy and when they should be used in place of expanding the grid.

II. SUB-SAHARAN COUNTRIES

A. *Population and Economic Growth*

The main factors that drive the demand and usage of energy are the growth of population and economic activity. Africa is undergoing changes, which will result in an increased need, for energy services in SSA in the next few decades. As of 2020 the entire continent of Africa accounted for one fifth of the population with more than 1.3 billion people living there. However back in 2000 Africa made up 13% of the worlds population indicating a higher and faster population growth rate compared to other parts of the world. Over the three years Africas population has been growing at an annual rate of 2.5% surpassing all other regions and doubling the global growth rate. In 2020 around 750 million individuals lived in areas across Africa making up 55% of the total African population. Consequently SSA remains one of the regions globally. As mentioned earlier rural populations in SSA have limited access to services such, as energy and face fewer economic opportunities [8].

B. *Electricity Access and Renewable Energy as an important role*

To attain universal electricity access in Africa by 2030, a substantial yearly increase of 90 million people, particularly in rural areas, is necessary. Rapid population growth in sub-Saharan Africa drives an annual access rate growth almost three times faster than pre-pandemic levels, primarily through standalone and mini-grid systems. Electricity demand, particularly in sub-Saharan Africa, significantly increases as both population and economy expand. Solar PV is projected to become the dominant electricity source in Africa by 2030 [8]–[10]. However, significant investment in infrastructure, transmission, and distribution is essential, and policy measures must improve operational efficiency. Electrification approaches vary, and modular decentralized systems have accelerated access. Expanding electricity demand, mainly in sub-Saharan Africa, is projected to be met by solar PV. Nonetheless, infrastructure investment and policy measures are vital, while microgrids are a key solution for electrifying remote communities cost-effectively, reducing fossil fuel dependence, and fostering development [8], [11], [12].

C. *Angola's case*

Angola's 2025 strategic objective aims to transform the nation into a prosperous, modern, and globally integrated country, prioritizing the energy sector's development to meet domestic and export demands. This initiative focuses on human development, economic growth, balanced national development, sustainable progress, and global competitiveness [9], [13]. This strategy, emphasizes widespread electricity access to enhance human development. Renewable energy capacity growth and private sector investments are integral to the National Energy Security Policy and Strategy, contributing to diversifying the national economy. The National Strategy for New Renewable Energies outlines plans for 500 solar-powered villages in unconnected communes and distribution of solar systems to the remaining population [13], [14].

Despite challenges in managing demand growth and expanding distribution coverage, electrification expansion in Angola is a critical objective. To achieve this, a substantial allocation of resources towards generation, transmission, distribution, and off-grid services is essential, as the government aims to reach 60% electrification by 2025 [13], [14]. An assessment suggests that this target might be realized by 2028 due to deceleration and high population growth. The expansion plan includes grid densification, infrastructure expansion, mini-grid deployment, and solar home system introduction. Currently, Angola's electricity access stands at 44%, with microgrids (46%) and grid connections (38%) being the most cost-effective approaches, while stand-alone systems extend coverage to remote areas, as it can be seen in Figure 1 [9], [15].

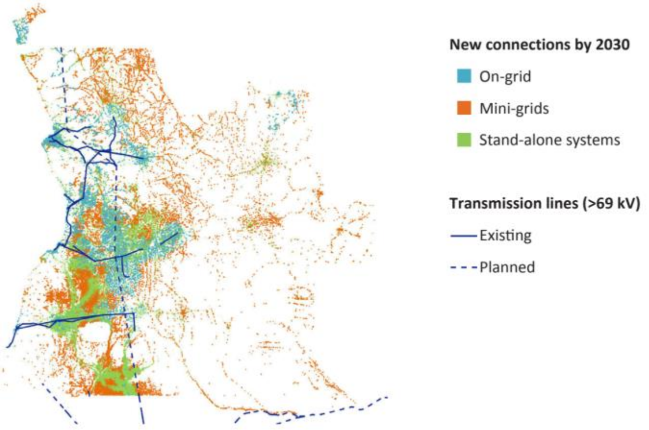


Figure 1 - Electricity Access in Angola by 2030 (Source: [9]*)*

The country's rapid economic and population growth have led to a significant increase in electricity supply and demand. The demand for electricity in Angola is projected to quadruple by 2025, reaching a load of 7.2 GW, driven by the goal to electrify 60% of the population [13]. Efforts are focused on provincial and municipal centers, where about 97% of domestic customers are expected to be located by 2025.
The anticipated demand growth will lead to a peak load of 7.2 GW and consumption of 39.1 TWh by 2025, driven by electrification, population expansion, growing wealth, industrialization, and electrified customer consumption. Over 3 million new consumers are expected within a decade, straining existing infrastructure [13] This project aims to provide off-grid microgrids as a renewable energy solution to meet Angola's increasing energy demand.

III. MICROGRID CONCEPT

Microgrids are small-scale, decentralized power grids that operate independently from the main centralized grid. They provide localized power generation and distribution, offering a solution for reliable, clean, and cost-effective energy production [16].

In regions like sub-Saharan Africa, where remote communities face challenges in accessing energy through the national grid, microgrids, particularly those using solar photovoltaics, are a promising solution. Solar energy is abundant and has a low Levelized Cost of Energy (LCOE), despite its intermittent nature. To ensure uninterrupted power supply, energy storage systems, like batteries, are essential. They store excess energy generated during the day for use during periods when energy production is not possible, such as at night [16], [17].

The successful operation of a microgrid depends on detailed modeling and analysis, including factors like battery sizing, daily load, battery model, discharge limits, autonomy, and operating conditions. These considerations help determine the microgrid's overall efficiency and equipment requirements [18]. Additionally, the cost of implementing the microgrid to local communities must be analyzed to make informed decisions about implementing these systems. Microgrids offer a viable solution for providing reliable and sustainable energy access to remote areas, especially in regions with abundant solar resources like sub-Saharan Africa [16], [17].

IV. CASE STUDY

A. *Methodology*

In order to study the application of microgrids in rural areas of Angola, two rural locations were selected and an opportunity to visit both of them was provided. In each of these locations, the feasibility study for implementing microgrids will be carried out, as well as all the sizing of these projects. One of the microgrids will be medium-sized and the other smaller, in order to compare two different realities, even though both are in rural areas. The proposed methodology shown in Figure 10 will be follow:

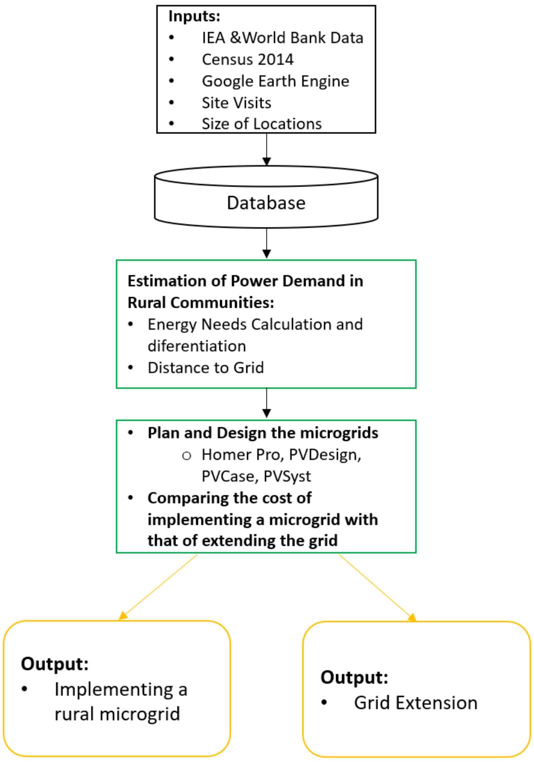


Figure 2 - Project Methodology and Organogram

B. *Selection of Locations*

Selecting the appropriate locations for implementing microgrids in Angola involved a comprehensive analysis of various factors. Initially, an assessment of Angola's energy grid and transmission infrastructure was conducted using Google Earth Pro, utilizing government-provided data in Figure 3. This analysis revealed that significant portions of Angola are either distant from the existing power grid or entirely lacking access to it, aligning with the 44% national electrification rate mentioned before [9], [13].

Recognizing the widespread need for such projects across Angola, the selection of the study's location was guided by practicality and data availability. Given that Angolan Census data is organized by province, and comprehensive nationwide data is not easily accessible, it was decided to focus on provinces where data could be obtained. These considerations led to the choice of provinces highlighted in green in Figure 3.

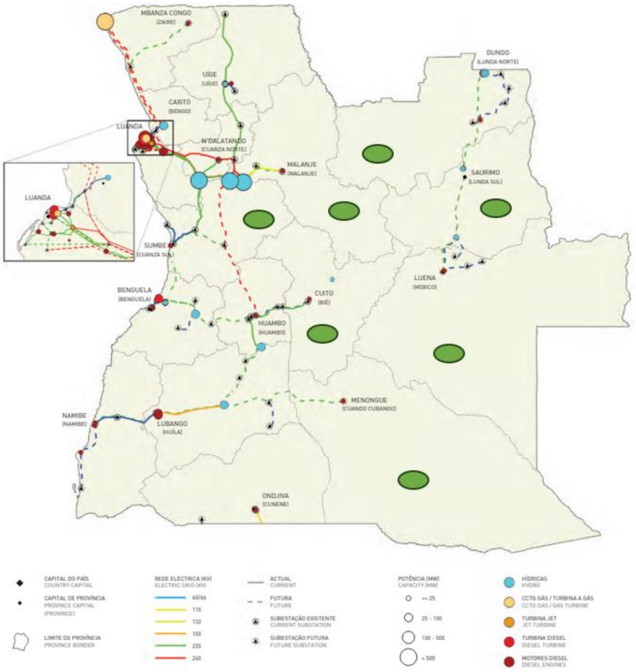


Figure 3 - Power Generation and Grid Transmission in Angola (Source: [13]*)*

Kwanza Sul, chosen for this study, was determined to have better and more comprehensive data available, which was critical for the research. However, it's important to note that the methodology used can be applied to any other province in Angola or sub-Saharan African countries. This province was selected, not only for its data accessibility but also because it was possible to visit rural areas within Kwanza Sul during the research, enabling the collection of precise information about the local population's energy requirements.

Following the province selection, the study considered the choice of cities and communes. To facilitate effective project size comparisons, a medium to large municipality (Mussende) and a relatively small commune (São Lucas) were selected for the study. These locations allowed for meaningful assessments of microgrid implementations within varying community sizes.

C. Size of Locations

Access to the Kwanza Sul province censuses provides valuable information about the population residing in these areas. However, based on the experience of other projects already completed in Angola, this data does not correspond to the current reality because the censuses were conducted in 2014 and are not always consistent with the data of today. A rough estimate of the number of houses in each of these communities was therefore made using Google Earth Engine software and a code owned by MCA. Based on the data from Google Earth Engine, it was then possible to get a more approximate data of how many houses are present in these locations, with 12 939 in Mussende and 1 334 in São Lucas. As such, these locations are as intended, two locations of different sizes so that the impact on different rural communities can be seen. In order to obtain data on the number of inhabitants in each of these localities, the Census of Kwanza Sul had to be used to find out the average number of inhabitants per house in this region.

Figure 4 - Average household size by municipality (Source: [19]*)*

As both Mussende and São Lucas are part of the Municipality of Mussende, using the data provided by the Census shown in Figure 4, we can use 4.9 as the average household size in these locations. It is therefore possible to determine a more approximative estimate of the population of these two rural communities by using the information from the house count and the average number of occupants of each house in the Municipality of Mussende.

D. Energy Needs

For the purpose of sizing these microgrids appropriately, it is required to estimate the population size of these communities as well as their energy requirements. Therefore, it was feasible to determine the population in each of the villages as well as their energy requirements in terms of power consumption using the inputs from the preceding section and others depicted in the organizational chart in Figure 2.

The World Bank and the International Energy Agency (IEA) anticipated that Angola would use 442.3 kilowatt-hours (kWh) per capita consumption of energy in 2020 [20], [21]. However, after conducting fieldwork during a three-month expedition through Angola's interior, during which these communities and many others like them were visited, it was concluded that there are significant differences between the ways in which these populations consume energy and that they can be divided into two categories based on their per capita energy consumption:

- For communes with a population of more than 25,000 people, a simultaneity coefficient of 70% was assumed based on a per capita consumption of 442.3 kWh. It was assumed that only 70% of users would be consuming the maximum amount of energy simultaneously rather than all users reaching a daily maximum. Due to this supposition, the per capita consumption was decreased to 309.6 kWh.
- A basic energy calculation was conducted for each of these dwellings in the less developed communes, both in terms of the population and the amount of trade and industry present, establishing a basic consumption kit per house, providing a figure of about 1.43 kWh consumption per house per day. This amount corresponds to a basic consumption kit that includes a refrigerator, two outlets, two chargers, and two light bulbs. This results in a per capita consumption for the province of Kwanza Sul of 106.4 kWh per capita.

After carrying out field research in both locations, it was concluded that Mussende could be considered to consume 309.6 kWh per capita, while São Lucas would have a per capita consumption of 106.4 kWh. The number of inhabitants for each of the regions was calculated using the data presented in section C above, giving a population of 63 401 for Mussende, and 6 571 for São Lucas. It was therefore possible to calculate the energy requirements for each of the regions as follows:

$$Energy\ Needs = \frac{Consumption\ per\ capita \times Population}{\text{Days per year}} \tag{1}$$

$$Energy\ Needs\ per\ day = \frac{(442.3\ \times 0.7) \times 63401}{365} = \\ = 53.8\ MWh/day\ in\ Mussende \tag{2}$$

$$Energy\ Needs = \frac{106.4 \times 6571}{365} = 1.9\ \text{MWh/day}\ in\ São\ Lucas \tag{3}$$

E. Sizing of Microgrids

To facilitate the sizing of the two microgrids, the strategic choice was made to ground these microgrids on the utilization of decentralized photovoltaic parks complemented by battery energy storage systems (BESS). This approach enables the provision of clean, uninterrupted, and sustainable energy supply around the clock. Several software tools, thoughtfully provided by MCA, were employed to conduct this case study with enhanced efficiency and real-world relevance.

The decision to deploy microgrids founded on decentralized photovoltaic parks integrated with BESS serves as a technologically advanced solution designed to address the energy challenges facing the respective regions. It ensures an uninterrupted and sustainable energy supply, thereby enhancing the quality of life and socio-economic development prospects for the communities under consideration.

F. *HOMER Pro*

HOMER Pro, an advanced energy system modeling software, is essential for optimizing microgrids in Sub-Saharan Africa's rural areas. It considers various energy resources, including solar panels, wind turbines, diesel generators, and storage systems, to create efficient, reliable, and cost-effective energy solutions. It aids in determining the required photovoltaic and battery capacity to fulfill local energy needs. Users provide project details, and the software generates outputs for analysis [22].

Both the Mussende and São Lucas projects share similar characteristics concerning their load diagrams and energy consumption patterns. In both cases, the choice was made to employ photovoltaic solar energy systems complemented by battery storage.

In both projects, the load diagrams reveal distinct energy peaks occurring between 5 a.m. and 8 a.m. and between 7 p.m. and 10 p.m., closely aligned with the daily routines of these communities. An example of one of these load diagrams, in this case, the one from São Lucas is depicted in Figure 5. These patterns are intrinsically connected to the daily lives of the residents. Mornings see early agricultural activities in the fields, contributing to the morning energy peak. Similarly, evenings witness residents returning home, considering the lack of public lighting beyond the city limits, leading to the evening energy peak [23]. These contextualized load profiles highlight the importance of designing microgrid solutions that synchronize with the specific energy consumption patterns of Mussende and São Lucas. Such tailored designs optimize energy availability and utilization, aligning with the unique needs of these communities.

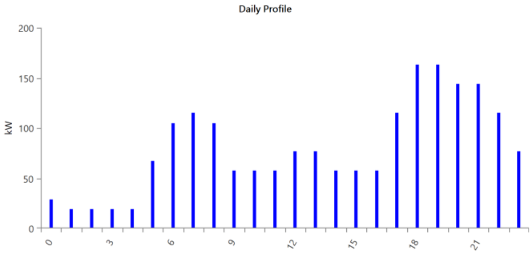


Figure 5 - São Lucas load diagram to HOMER Pro (Source: [22]*)*

Based on the inputs for both Mussende and São Lucas, the software optimizes solutions that are uniquely suited to each location's energy needs and available technologies. In the case of Mussende, this entails a photovoltaic park with a capacity of 28 MWp and an approximate battery storage capacity of 54 MWh, ensuring continuous energy supply throughout the day. In contrast, the São Lucas project, with its lower energy requirements, calls for a more modest configuration. It comprises a 1 MWp photovoltaic park and a 3 MWh battery storage capacity, providing a reliable and sustainable energy source to the São Lucas community throughout the day. These tailored configurations account for the specific energy consumption patterns of each locality, ensuring optimized energy availability and utilization.

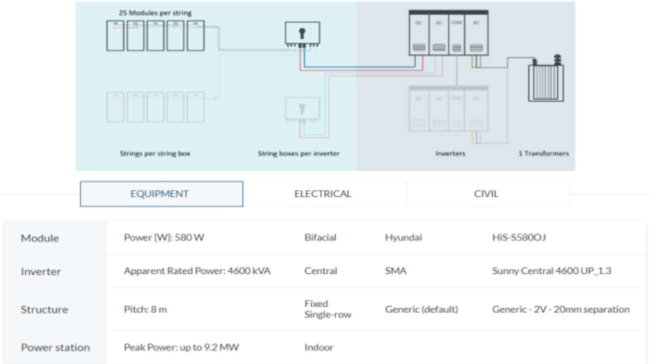
G. *PVDesign*

PVDesign software plays a crucial role in designing and optimizing solar PV systems for this project. It aids in sizing and configuring PV installations by considering location-specific factors like shading, panel orientation, and component efficiency. This software is essential for ensuring the efficient and effective deployment of microgrids in rural Sub-Saharan Africa [24].

To utilize PVDesign, appropriate land selection for photovoltaic parks is vital. Google Earth Pro was used to provide location inputs. Strategic land selection prioritized level terrain, proximity to populated areas and main roads, and accessibility to the future distribution network. This careful planning and site selection are critical for optimizing photovoltaic installations in rural regions.

Following the selection of sites for the installation of photovoltaic parks, the PVDesign software necessitated several technical decisions for both photovoltaic installations. These decisions encompassed equipment choices as well as electrical and civil engineering options. Figure 6 provides an overview of some of the key equipment selections employed in the Mussende project, along with a simplified electrical diagram illustrating the technical choices underpinning this photovoltaic system. These technical selections and equipment choices are critical components of the photovoltaic system design process.

Selecting the right inverter is critical for the efficiency of a PV microgrid. It should match the microgrid's specific characteristics, including solar power generation, load profiles, environmental conditions, and grid stability requirements. In this context, Grid Forming inverters are crucial for a decentralized microgrid. They can establish and maintain the microgrid's electrical grid, ensuring autonomous operation in off-grid areas. Grid Forming inverters offer features like black start, resynchronization, and virtual inertia, making them ideal for this project in isolated areas, where a stable grid may be absent. [25].



Module	Power [W]: 580 W	Bifacial	Hyundai	HiS-S580OJ
Inverter	Apparent Rated Power: 4600 kVA	Central	SMA	Sunny Central 4600 UP_1.3
Structure	Pitch: 8 m	Fixed Single-row	Generic (default)	Generic - 2V - 20mm separation
Power station	Peak Power: up to 9.2 MW	Indoor		

Figure 6 - Simplified Electrical Diagram and Main Equipment Used in Mussende Project (Souce: [26]*)*

The PVDesign program was able to produce the desired results for the Mussende and São Lucas projects after all the equipment selections made in the preceding section were completed. When it comes to sizing and developing photovoltaic projects, this software provides us with a ton of outputs, including: a preliminary PV system layout, an analysis of energy production, an electrical diagram, a bill of materials, an analysis of shading, economic viability and system performance, as well as detailed reports on these outputs. However, only some of the data generated by this program were considered in this case study because it was possible to work with other, more specialized software in other areas of PV system sizing.

Therefore, after accomplished all the aforementioned steps, the layout generated by PVDesign could then be exported to Google Earth Pro, to gain a more comprehensive understanding of the integration of these parks within both sites. This design was also exported in .dxf format, to serve as the foundational framework for the final layout, to be developed using the PV Case software.

H. PVCase

PVCase software is essential for designing solar panel mounting systems that adapt to local terrain and maximize energy generation efficiency. It integrates with AutoCAD, making it easy to incorporate solar layout information into detailed engineering and architectural projects. PVCase is highly compatible with PVSyst, a recognized tool for photovoltaic system analysis, ensuring accurate performance analysis. This integration allows advanced features from PVCase to optimize system layout and sizing based on the terrain, contributing to more effective solar projects [27], [28].

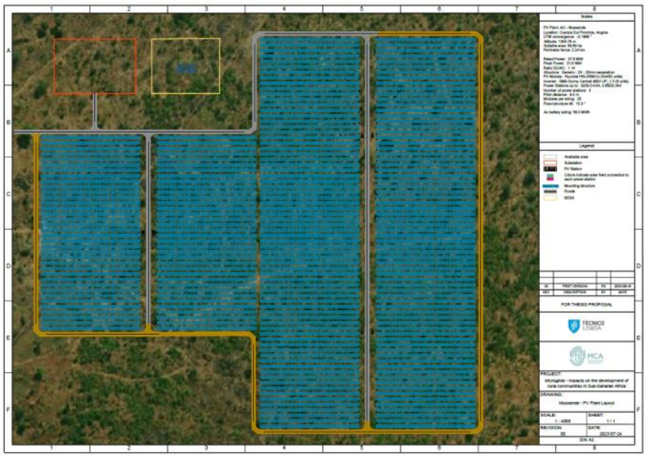


Figure 7 - Mussende PV Park Layout (Source: PVCase)

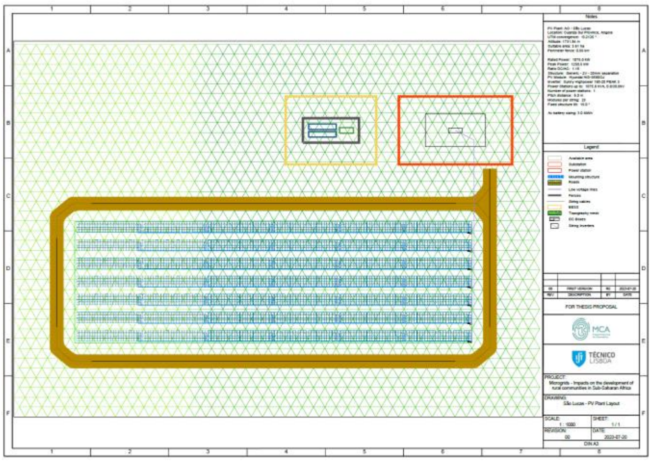


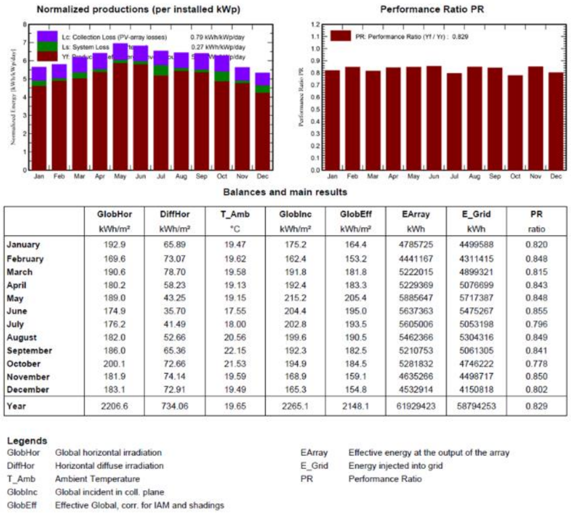
Figure 8 - São Lucas PV Park Layout (Source: PVCase)

Figure 7 and Figure 8 in PVCase show layouts for Mussende and São Lucas PV Parks. The software enabled earthwork adjustments, civil engineering corrections, and road design for balanced inverters. It integrated with Google Earth for topographical analysis. After creating layouts, they were exported for 3D integration with PVSyst, a powerful combination for solar project development.

I. PVSyst

Finally, PVSyst, a key software, is used for comprehensive analysis and financial assessment of solar energy projects. It accurately simulates solar system performance under various conditions. PVSyst was instrumental in validating data for photovoltaic and battery-based systems, supporting effective microgrid planning and operation [29]. This software's energy report forms the basis for the final considerations on the studied hybrid systems.

To generate the final energy report, the process included selecting the meteorological database, entering key parameters, and performing shading analysis using PVSyst. The integration of PVCase layout into PVSyst allowed for precise adjustments in tilt angles and azimuth orientations based on topography. The next steps involved addressing detailed losses and running the simulation. Notably, two simulations were conducted: one for the PV system and another for the hybrid system. The PV system was analyzed separately before evaluating the hybrid system with batteries. The main results are summarized in Figure 9 and Figure 10.



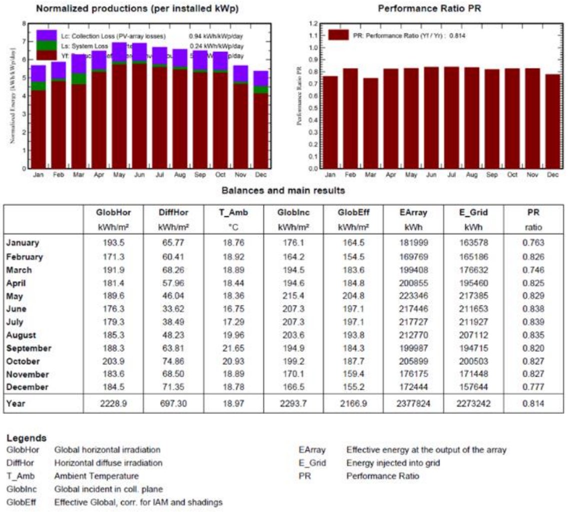
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	192.9	65.89	19.47	175.2	164.4	4785725	4499588	0.820
February	169.6	73.07	19.62	162.4	153.2	4441167	4311415	0.848
March	190.6	78.70	19.58	191.8	181.8	5222015	4899321	0.815
April	180.2	58.23	19.13	192.4	183.3	5229369	5076699	0.843
May	189.0	43.25	19.15	215.2	205.4	5885647	5717387	0.848
June	174.9	35.70	17.55	204.4	195.0	5637363	5475267	0.855
July	176.2	41.49	18.00	202.8	193.5	5605006	5053198	0.796
August	182.0	52.66	20.56	199.6	190.5	5462366	5304316	0.849
September	186.0	65.36	22.15	192.3	182.5	5210753	5061305	0.841
October	200.1	72.66	21.53	194.9	184.5	5281832	4746222	0.778
November	181.9	74.14	19.59	168.9	159.1	4635266	4498717	0.850
December	183.1	72.91	19.49	165.3	154.8	4532914	4150818	0.802
Year	2206.6	734.06	19.65	2265.1	2148.1	61929423	58794253	0.829

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Figure 9 - Main Results of Mussende PV System (Source: PVSyst)



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	193.5	65.77	18.76	176.1	164.5	181999	163578	0.763
February	171.3	60.41	18.92	164.2	154.5	169769	165186	0.826
March	191.9	68.26	18.89	194.5	183.6	199408	176632	0.746
April	181.4	57.96	18.44	194.6	184.8	200855	195460	0.825
May	189.6	46.04	18.36	215.4	204.8	223346	217385	0.829
June	176.3	33.62	16.75	207.3	197.1	217446	211653	0.838
July	179.3	38.49	17.29	207.3	197.1	217727	211927	0.839
August	185.3	48.23	19.96	203.6	193.8	212770	207112	0.835
September	188.3	63.81	21.65	194.9	184.3	199987	194715	0.820
October	203.9	74.86	20.93	199.2	187.7	205899	200503	0.827
November	183.6	68.50	18.89	170.1	159.4	176175	171448	0.827
December	184.5	71.35	18.78	166.5	155.2	172444	157644	0.777
Year	2228.9	697.30	18.97	2293.7	2166.9	2377824	2273242	0.814

Legends

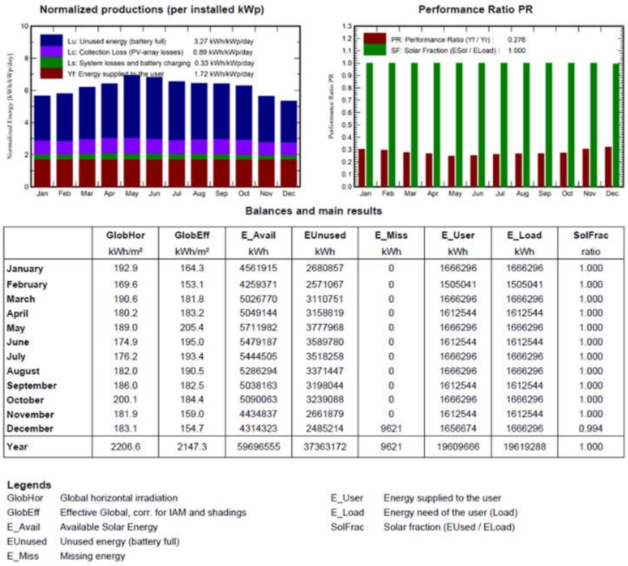
GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Figure 10 - Main Results of São Lucas PV System (Source: PVSyst)

Figure 9 and Figure 10 show that the photovoltaic projects in Mussende and São Lucas were well dimensioned and that there was an efficient conversion of solar energy into electricity. In Mussende, the PV system produced an average of 5.14 kWh/kWp/day, with losses of around 1.06 kWh/kWh/day and a Performance Ratio (PR) of 82.9%. In São Lucas, the system produced around 5.11 kWh/kWp/day with losses of around 1.18 kWh/kWp/day and a PR of 81.4%. These results confirm that the photovoltaic system is well dimensioned and has a high performance, so that it is possible to move on to integrate this system with the batteries and analyze the results obtained for the hybrid system.

To transition from the PV system to the hybrid system in PVSyst, the first step involved adding lithium-ion batteries to the equipment section. These batteries were incorporated into the projects to meet their energy storage needs as determined by HOMER Pro. Following the equipment update, the load diagrams, specifying energy appliance requirements, were introduced in PVSyst. The load diagrams now accounted for individual appliance power and usage times. The energy requirements were calculated as 53,751,473 kWh/day for Mussende and 1,903,796 kWh/day for São Lucas. The remainder of the project remained unchanged, allowing for the simulation of both projects with the hybrid system to analyze the results.

The inclusion of BESS in the PV system resulted in underutilized energy production throughout the year, with Mussende generating 1.72 kWh per kWp per day and São Lucas producing 2.18 kWh per kWp per day. Energy losses remained similar to the PV system without BESS. The primary reason for this underutilization was the battery system's sizing, as energy consumption by the populations was insufficient to fully discharge the batteries at night. The presence of unused energy in both systems contributed to their lower-than-expected performance, resulting in performance ratios of 27.6% for Mussende and 34.6% for São Lucas. These results can be seen in Figure 11 and Figure 12.



Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	192.9	164.3	4561915	2680857	0	1666296	1666296	1.000
February	169.6	153.1	4259371	2571067	0	1505041	1505041	1.000
March	190.6	181.8	5026770	3110751	0	1666296	1666296	1.000
April	180.2	183.2	5049144	3158819	0	1612544	1612544	1.000
May	189.0	205.4	5711982	3777968	0	1666296	1666296	1.000
June	174.9	195.0	5479187	3589780	0	1612544	1612544	1.000
July	176.2	193.4	5444505	3518258	0	1666296	1666296	1.000
August	182.0	190.5	5286294	3371447	0	1666296	1666296	1.000
September	186.0	182.5	5038163	3198044	0	1612544	1612544	1.000
October	200.1	184.4	5090063	3239088	0	1666296	1666296	1.000
November	181.9	159.0	4434837	2661879	0	1612544	1612544	1.000
December	183.1	154.7	4314323	2485214	9621	1656674	1666296	0.994
Year	2206.6	2147.3	59696555	37363172	9621	19609666	19619288	1.000

Legends

GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		
E_Miss	Missing energy		

Figure 11 - Main Results of Mussende Hybrid Project (Source: PVSyst)

Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	193.5	164.5	126796	63809	0	59023	59023	1.000
February	171.3	154.5	118348	61752	400	52911	53311	0.992
March	191.9	183.6	139389	76314	660	58364	59023	0.989
April	181.4	184.8	140542	79713	680	56440	57119	0.988
May	189.6	204.8	156629	92856	0	59023	59023	1.000
June	176.3	197.1	152715	90959	0	57119	57119	1.000
July	179.3	197.1	152599	88893	0	59023	59023	1.000
August	185.3	193.8	148994	85750	284	58739	59023	0.995
September	188.3	184.3	140073	78535	0	57119	57119	1.000
October	203.9	187.7	144217	80763	0	59023	59023	1.000
November	183.6	159.4	123065	62126	333	56786	57119	0.994
December	184.5	155.2	120043	58942	1655	57368	59023	0.972
Year	2228.9	2166.9	1663409	920412	4012	690939	694951	0.994

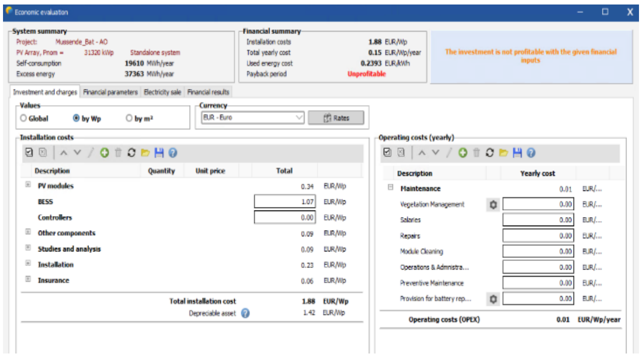
Legends

GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		
E_Miss	Missing energy		

Figure 12 - Main Results of São Lucas Hybrid Project (Source: PVSyst)

J. *Levelized Cost of Energy*

The Levelized Cost of Energy is crucial for assessing the economic viability of energy systems, including remote microgrids. It calculates the average cost per unit of energy produced over the system's lifetime [30]. PVSyst software was used for LCOE calculations, considering project costs, financial parameters, and the impact of BESS on decentralized microgrid costs. The decentralized system incurs additional BESS costs and associated maintenance expenses not found in direct grid injection systems.



System summary
Project: Mussende_Bat - AO
PV Array, Pnom = 31320 kWp Standalone system
Self-consumption 19610 MWh/year
Excess energy 37363 MWh/year

Financial summary
Installation costs 1.88 EUR/Wp
Total yearly cost 0.15 EUR/Wp/year
Used energy cost 0.2393 EUR/kWh
Payback period Unprofitable

The investment is not profitable with the given financial inputs

Values
○ Global ● by Wp ○ by m²

Currency
EUR - Euro

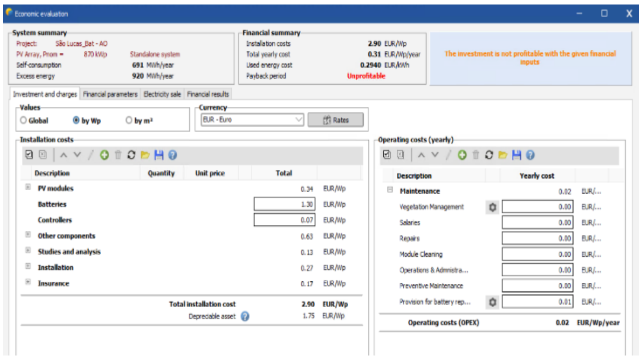
Installation costs

Description	Quantity	Unit price	Total	
PV modules			0.34	EUR/Wp
BESS			1.07	EUR/Wp
Controllers			0.00	EUR/Wp
Other components			0.09	EUR/Wp
Studies and analysis			0.09	EUR/Wp
Installation			0.23	EUR/Wp
Insurance			0.06	EUR/Wp
		Total installation cost	**1.88**	**EUR/Wp**
		Depreciable asset	1.42	EUR/Wp

Operating costs (yearly)

Description	Yearly cost	
Maintenance	0.01	EUR/...
Vegetation Management	0.00	EUR/...
Salaries	0.00	EUR/...
Repairs	0.00	EUR/...
Module Cleaning	0.00	EUR/...
Operations & Adminstra...	0.00	EUR/...
Preventive Maintenance	0.00	EUR/...
Provision for battery rep...	0.00	EUR/...
Operating costs (OPEX)	**0.01**	**EUR/Wp/year**

Figure 13 - Economic Evaluation of Mussende's hybrid project (Source: PVSyst)



System summary
Project: São Lucas_Bat - AO
PV Array, Pnom = 870 kWp Standalone system
Self-consumption 691 MWh/year
Excess energy 920 MWh/year

Financial summary
Installation costs 2.90 EUR/Wp
Total yearly cost 0.31 EUR/Wp/year
Used energy cost 0.2940 EUR/kWh
Payback period Unprofitable

The investment is not profitable with the given financial inputs

Values
○ Global ● by Wp ○ by m²

Currency
EUR - Euro

Installation costs

Description	Quantity	Unit price	Total	
PV modules			0.34	EUR/Wp
Batteries			1.30	EUR/Wp
Controllers			0.07	EUR/Wp
Other components			0.63	EUR/Wp
Studies and analysis			0.13	EUR/Wp
Installation			0.27	EUR/Wp
Insurance			0.17	EUR/Wp
		Total installation cost	**2.90**	**EUR/Wp**
		Depreciable asset	1.75	EUR/Wp

Operating costs (yearly)

Description	Yearly cost	
Maintenance	0.02	EUR/...
Vegetation Management	0.00	EUR/...
Salaries	0.00	EUR/...
Repairs	0.00	EUR/...
Module Cleaning	0.00	EUR/...
Operations & Adminstra...	0.00	EUR/...
Preventive Maintenance	0.00	EUR/...
Provision for battery rep...	0.01	EUR/...
Operating costs (OPEX)	**0.02**	**EUR/Wp/year**

Figure 14 - Economic Evaluation of São Lucas hybrid project (Source: PVSyst)

With regard to LCOE, the values for these stand-alone systems are 0.24 EUR/kWh for Mussende and 0.29 EUR/kWh for São Lucas, as shown in Figures 13 and 14.

In São Lucas and Mussende, where there is no access to the national electricity grid and the alternative is the use of small diesel generators, it is important to note that the average LCOE for this type of energy in SSA countries is approximately 0.4 EUR/kWh [31]. Therefore, it can be concluded that both projects are economically viable, since their LCOEs are below this reference value.

In addition, the implementation of these projects not only makes financial sense, but also contributes to the transition from a fossil energy source subject to interruptions to a renewable and sustainable energy source, improving access to energy in these communities.

However, it should be noted that this project is only possible because the sale of energy in Angola is carried out directly by government entities and is financed by the state. The cost of energy in Angola is very low, around 0.036 €/kWh, so if the sale of energy were to be considered, it would be very difficult to get close to these figures.

K. Comparison between grid extension and microgrid

The research methodology adopted in this study plays a crucial role in the strategic evaluation of whether to extend the electricity grid or implement isolated microgrid systems in two regions of Angola, Mussende and São Lucas. To make informed choices, it was essential to assess the costs associated with grid extension, encompassing considerations such as the distance to the nearest substation and the requisite voltage, which translated into estimated costs of approximately €57.62 million for Mussende and €69.5 million for São Lucas.

However, the economic feasibility of these alternatives was further scrutinized using the Levelized Cost of Energy (LCOE) as a central metric. The LCOE calculations factored in each location's energy demands, contemplated a 25-year project lifecycle, and thoughtfully considered the impact of population growth. This meticulous LCOE-based analysis unveiled distinctive outcomes for Mussende and São Lucas.

In the case of Mussende, extending the grid emerged as the more cost-effective option due to its economic viability. The economic model indicated that choosing a microgrid solution for Mussende could lead to an approximate €70 million increase in project costs, pointing toward grid extension as the practical choice. On the contrary, the scenario in São Lucas firmly favored the microgrid approach, presenting substantial cost savings of around €64 million when compared to grid expansion.

While Mussende leans towards grid extension based on economic considerations, São Lucas resoundingly demonstrates the potential of the microgrid alternative. It offers not only significant economic advantages but also aligns with a sustainable energy solution. In both cases, a future comprehensive electrification plan is deemed essential to realize the full potential of these projects, entailing the establishment of comprehensive distribution grids, deployment of electrical infrastructure, and enhanced public lighting. These initiatives hold the key to maximizing sustainable energy access, fostering holistic development, and elevating the overall quality of life for the residents in these regions.

V. CONCLUSION

In conclusion, this research offers a comprehensive analysis of the potential of microgrids for rural electrification in SSA, underpinned by their technical, economic, renewable resources in these countries and sustainability aspects. The results of this study highlight the universal applicability of these conclusions in various rural regions of SSA, as long as the contextual parameters are taken into account, offering a methodology for sustainable energy solutions that can easily be replicated. A key aspect for the success of this type of project is the crucial role of grid-forming inverters. The ability of these inverters to emulate the functionality of a traditional power grid, along with the ability to operate autonomously in areas without access to the grid, increases the reliability and resilience of these systems.

The case studies carried out for Mussende and São Lucas have demonstrated the potential of microgrids not only in electrifying and making reliable energy available to these rural communities, but also in achieving the socio-economic development of these regions, fostering a better future for the lives of these people. The economic analysis showed different results, demonstrating that the choice between applying microgrids and extending the grid depends on the local context. For the case of Mussende, the most favorable choice in economic terms would be grid extension, however, it would not be a purely renewable resource solution. São Lucas, on the other hand, had a different result, emerging as a very viable example for the deployment of microgrids, offering both a significant economic advantage and the realization of a purely sustainable system thus serving as proof of the transformative power of these systems.

Furthermore, it can be pointed out that the impact of applying microgrids transcends the mere electrification of these regions, as it has the potential to catalyze the overall development of these rural communities, promoting the creation of new jobs, education, access to health care and the adoption of new technologies that come with access to reliable energy. As long as the implementation of these microgrids is aligned with the socio-economic context of each country, local resources and regional policies, the future prospects of this type of project for the SSA energy landscape look promising. Thus, this study contributes to the discussion on rural electrification, emphasizing the paramount importance of applying microgrids in driving sustainable development and ensuring access to energy for all, so that there is a more prosperous future for rural communities in all regions of SSA.

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