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Scaling up the electricity access and addressing best strategies for a sustainable operation of an existing solar PV mini-grid: A case study of Mavumira village in Mozambique

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ABSTRACT

Access to electricity in a sustainable, affordable, and reliable manner is still a challenge, especially for rural communities in developing regions. In this study, we applied the HOMER Pro software for scaling up electricity and finding the optimum system that can satisfy the future electricity demand cost-effectively. Additionally, we analyzed the aspects that could influence the sustainability of the project, based on selected indicators, to address the best strategies for future improvements in the system performance. The main source of information for this research was the data collection in the study area through interviews with 35 individuals, including the owners of households, revenue collectors, and local governance selected based on their level of involvement and also their knowledge about the project. We focused on the solar PV mini-grid system installed in Mavumira village in Mozambique. Our results showed that among various configurations analyzed, hybrid solar PV/diesel/battery is the most appropriate system, as it presents the lowest cost of electricity (LCOE) of 0.47 $/kWh compared to other solutions, such as diesel-only with 0.63 $/kWh. Moreover, we found that in the future, the system will require less government subsidy than today's case, as the optimized future system is 1.3 times more expensive than the expected future tariff (0.37 $/kWh). By investigating the sustainability of the project, we found that, on a scale from 1 to 5, the economic and social indicators like economic activities and safety scored high (5 and 4, respectively), meaning that they are likely to ensure the project's performance over its lifetime, compared to the technical and institutional indicators like the reliability of power supply and effectiveness of local governance, which were attributed low-performance scores (1 and 2, respectively). These last aspects need to be adequately addressed, through local skills for operation and maintenance, to avoid failure in the system.

Introduction

Access to electricity has proven to be the engine for the social and economic development of many nations (Das et al., 2017a; Sayar, 2019a). However, in developing countries, many remote communities still lack affordable, reliable, and sustainable access to electricity (United Nations General Assembly, 2015). By 2020, it was estimated that 790 million people would have no access to electricity, mostly in developing Asia and sub-Saharan Africa, as compared to 1.2 billion in 2010 (IEA et al., 2020; Sustainable Energy for All, 2020; World Bank

Abbreviations: AC, Alternating current; CO_2, Carbon dioxide; CC, Cycle charging; DC, Direct current; DG, Diesel generator; FUNAE, Energy fund; GHI, Global Horizontal Irradiance; HOMER, Hybrid optimization model for electric renewables; HRES, Hybrid renewable energy systems; IRENA, International Renewable Energy Agency; km, Kilometer; kW, Kilowatt; kWh, Kilowatt-hour; LCOE, Levelized cost of energy; LF, Load following; NASA, National Aeronautics and Space Administration; MZN, Mozambican currency unit; NPC, Net present cost; O&M, Operation and maintenance; PV, Photovoltaic; RE, RE; RF, Renewable Fraction; W, Watt; VEC, Village Energy Committee.

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Custodian Agencies, 2020; IEA, 2021). Additionally, projections indicate that in 2030 the world will still have 680 million people without access to electricity (IRENA, 2018). In developing countries, most of the rural areas are sparsely populated, making grid extension far from being a reality due to their remoteness and geographical constraints. Off-grid renewable energy (RE) technologies seem to be the most feasible option for rural electrification, considering their technological, cost, and environmental benefits associated with resource availability (Zebra et al., 2021). Stand-alone renewables systems are intermittent and variable, which causes instabilities in power generation (Zebra et al., 2021; Rinaldi et al., 2020). Therefore, the application of alternative energy configurations, in particular hybrid renewable energy systems (HRES) with a storage device and backup power supply of diesel generators, are seen as the most appropriate options to overcome the intermittency nature of renewable resources and meet the energy demand in terms of affordability and reliability in developing countries. HRES have proven to be successful in several places around the world, particularly in Africa (Nnaji et al., 2019; Agyekum & Nutakor, 2020a) and Asia (Qun Liu & Xin Wang, 2009; Das et al., 2017b). Solar PV, hydro, biomass and wind are the most use renewable energy technologies, hybridized in most of the case with diesel backup because of their potential to increase the fraction of electricity produced by renewable and reduce diesel dependence on the system (Zebra et al., 2021; Niyonteze et al., 2020). The literature has addressed various tools for the design and size optimization of HRES, each with their features and limitations, for example, Hybrid Optimization Model for Electric Renewables (HOMER) deals with sensitivity analysis based on uncertainty parameters but does not model the frequency stability and voltage, while iHOGA has own meteorological database for many locations but does not perform sensitivity analysis (Agyekum & Nutakor, 2020a; Ringkjøb et al., 2018; Inês et al., 2021).

So far, in most studies, more attention has been given to the techno-economic viability of hybrid systems without considering social and other aspects that may hinder the functioning of these systems over the project lifetime, for example the community organization and involvement in the operation and maintenance (O&M) of the project. Additionally, there is limited research focusing on specific technical aspects behind the unreliability of power supply, such as failures and outages. However, these aspects are considered of great importance to ensure the successful implementation of the system.

In our recent literature review (Zebra et al., 2021), which focused on the main aspects behind the HRES implementation in different developing regions, we found that, in general, if well designed and implemented, HRES systems can result in an affordable, reliable, and sustainable solution for remote areas. Thereby, based on experiences from different developing countries on mini-grid deployment, we proposed a framework (see Fig. 1) indicating the main pre-conditions for successful implementation of these systems and clustered them into four stages: 1) government intervention through policy, regulations, and incentives, which is important as a starting point to attract private participation and finance for the deployment of HRES; 2) software tools like HOMER for the pre-feasibility and design of these projects to ensure that the systems meet the load demand cost-effectively; 3) social and other aspects at the local level, for example, the community organization and finally in stage 4) we addressed four operation models (community, utility, private, and hybrid-based) based on successful examples reported in the literature. The findings of our previous study (Zebra et al., 2021) highlighted that the feasibility of the project at the local level is highly determinant for rural projects to be sustainable, which should be linked to the community's ability to operate and maintain the project for

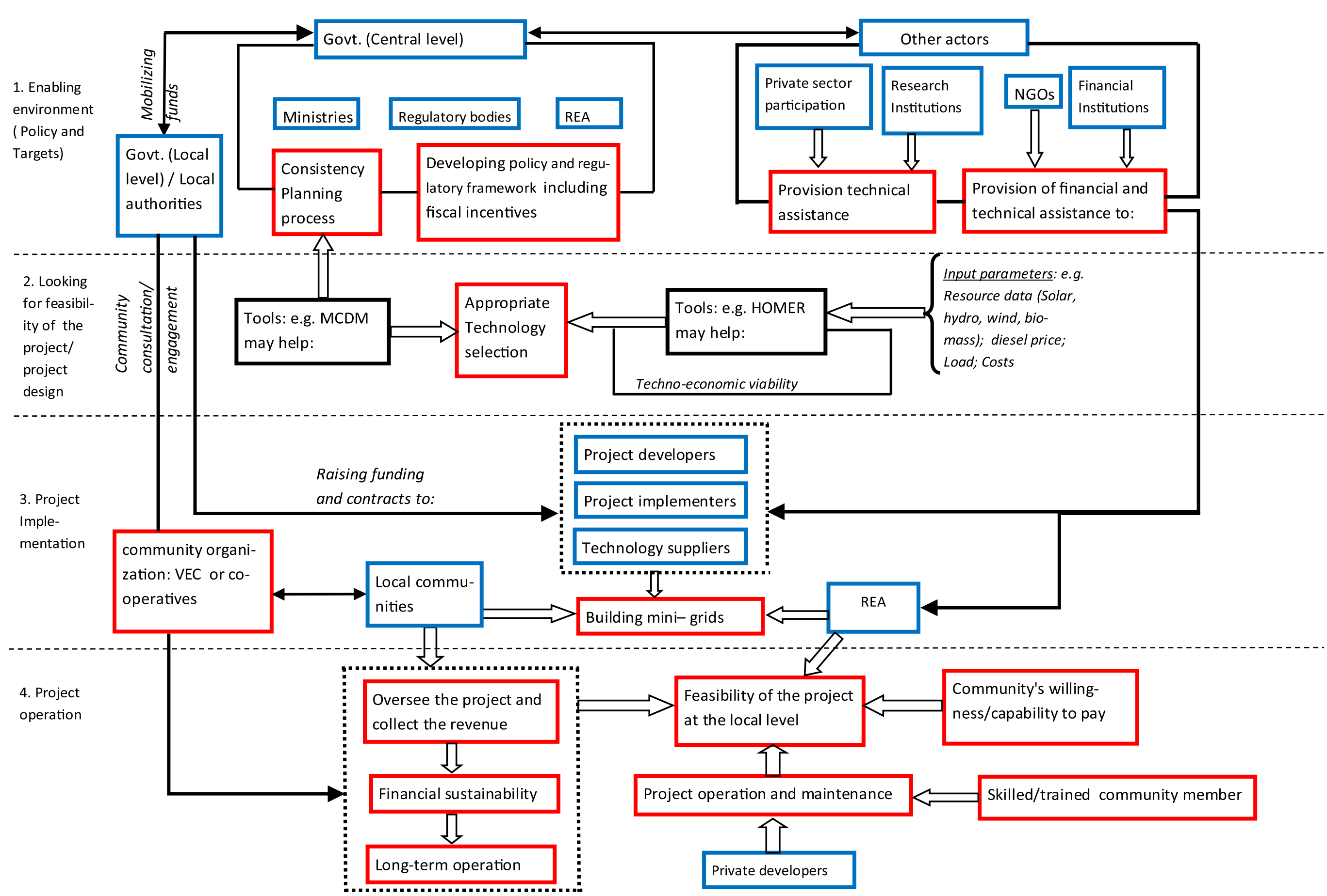

Fig. 1. Aspects influencing the mini-grid's integration in developing regions. Proposed by (Zebra et al., 2021).

rapid response to the issues, willingness to pay for electricity and revenue through the collection of payments to ensure the project's operation over its lifetime. Moreover, our study (Zebra et al., 2021) suggested that further studies should explore the application of HRES with sufficient battery storage to reduce the diesel fuel consumption in the system. However, the proposed framework is yet to be tested for a concrete project.

The present study thus aims to test the framework for a concrete solar PV project, which is operational in Mavumira village, hence, based on its experience enabling a greater understanding of the aspects that need attention for further improvement in its functioning to ensure the sustainability of the system throughout its lifetime and the system's expansion, cost-effectively, looking into the techno-economic feasibility of the project to respond to the growing demand. Our study focuses on a solar PV mini-grid installed in Mavumira village. Mavumira village is located in Sofala Province, Mozambique. This country is part of the 20 countries that have the most people lacking access to electricity (World Bank Custodian Agencies, 2020). Mozambique accounts for only 32.7 % of the population with access to electricity (Naidoo & Loots, 2020) despite its abundant energy resource like hydro, solar, wind, and biomass. Most of the capital cities are connected to the national grid, while the majority of rural areas are not connected and are dependent on polluting, *expensive*, and unsustainable energy sources such as traditional biomass for cooking, kerosene lamps, and diesel generators to satisfy their energy needs (Governo de Moçambique, 2014). Hence, the application of alternative energy, such as hybrid renewable energy systems with a backup power supply of diesel generators can be the best option to meet the energy demand in remote areas.

Based on the proposed framework, we applied the HOMER software to find the best system configuration that can meet the future load demand cost-effectively and reliably by increasing the number of batteries and solar photovoltaic (solar PV) in the system, thus reducing diesel fuel consumption in the system. We also investigated how the system's sustainability can be improved, based on its current operational experience, considering aspects such as reliability of power supply to ensure the project's feasibility at the local level. Additionally, from our earlier literature review, we identified the main aspects affecting the sustainability of the energy project to inventory relevant indicators that were later refined and used to structure and compile the questionnaire used for the interviews, for data collection in the study area. HOMER software was applied for simulation, optimization, and then sensitivity analysis to investigate how the existing system can be scaled up and optimized to meet the increased future load demand of the village. This study is further extended to qualitatively investigate the social, economic, technical, and institutional impacts of the Mavumira mini-grid, making use of relevant indicators, such as the reliability of power supply, income generation activities, and community engagement, selected from the literature (Mainali et al., 2014; Buchmayr et al., 2021), to help investigate the aspects that could influence sustainability of the project after implementing the mini-grid. Three sustainability dimensions (environmental, economic, and social) are commonly applied in the literature to analyze the sustainability of rural electrification projects (Ilskog, 2008a; Mainali & Silveira, 2015; Hong & Abe, 2012; Ilskog & Kjellström, 2008). Technical and institutional dimensions have been added for the analysis of specific rural sectors (Khan, 2020; Purwanto & Afifah, 2016; Azimoh et al., 2017a; Katre et al., 2019). All these dimensions use specific indicators. However, in these studies, these indicators were not fully and uniformly analyzed. They vary from one to several indicators as the application of the indicators is highly dependent on the objective and scope of the work. For instance, the authors in (Ilskog, 2008b) listed 39 indicators used for assessing rural electrification projects, whereas the authors in (Mainali, 2012) assessed 16 crucial indicators. In our study, we selected 13 indicators (described in Selection of indicators section) for four dimensions (social, economic, technical, and institutional) to provide insights into the key aspects affecting the sustainability of the Mavumira project. We do not take environmental issues into consideration because they require a specific method to measure the impact, for example, the life cycle assessment method, and it was not considered under the scope of this study. The following research questions shall be answered in this study:

Q1: How can the electricity generation be scaled up and optimized to meet the increased energy demand in a reliable and cost-effective way for Mavumira village?

Q2: Which are the key aspects that could influence the system's sustainability, taking into account its social, economic, technical, and institutional dimensions?

Q3: Which strategies can be addressed to improve the future system's performance (based on a combination of the previous Q1 and Q2)?

This study is structured into four main sections. Section 1 presents the introduction of the topic. In Section 2, the materials and methods are described. Section 3 presents the results and discussions of the optimized hybrid system and the sustainability impact assessment of the installed mini-grid. And finally, in Section 4, conclusions and synthesis are provided.

Materials and methods

This study presents the design of an optimal energy system that can meet the future load demand of Mavumira, taking into account the load profile and resource availability while analyzing the social, economic, technical, and institutional impacts upon the arrival of the mini-grid. More details about the study area and the reasons for its selection are presented in Appendix A of this paper. The overall methodology applied in this research is depicted in Fig. 2. It encapsulates the following four main steps:

Step I – In this stage, we assessed the basic requirements for this study, which consisted of a literature review, highlighting results from (Zebra et al., 2021) as it integrates the main aspects for the successful operation of mini-grids and selection of relevant indicators (see Selection of indicators section) We used these indicators to prepare the questionnaire.

The questionnaire, which was divided into six main categories of questions, guided us during the interviews with different people in the study area, including the beneficiaries of electricity and the revenue collector. Further details about the questionnaire, including its structure, are presented in Questionnaire design and interviews section.

Step II – Based on the village electrical load profile obtained during the data collection in the study area (see HOMER Pro software method section), we estimated the future electrical load profile, considering an increase of up to 60 % by 2025 over the actual load. We used the HOMER Pro software tool for the techno-economic assessment to determine the best system configuration that can meet the future village load demand cost-effectively. The optimized system included hybridization of the existing solar PV mini-grid with diesel. The sensitivity analysis was performed to investigate the effect of solar and wind resources, diesel fuel price, the increased load demand, decrease in battery and solar PV capital cost on the system performance.

Step III – In this step, we used the results from the interviews conducted in the study area to assess the social, economic, technical, and institutional impacts after the implementation of the project in the village (detailed in Determining the assessment method and score for the indicators section). The results of this assessment help to address improvements to the system, for example, improving the system reliability to ensure the technical viability of the project over its lifetime.

Step IV – In this stage, based on the combination of the assessments conducted in Steps 2 and 3, we identified the best strategies to improve the future performance of the system and ensure the long-term sustainability of the project.

Selection of indicators

After reviewing the literature on sustainability assessment of energy

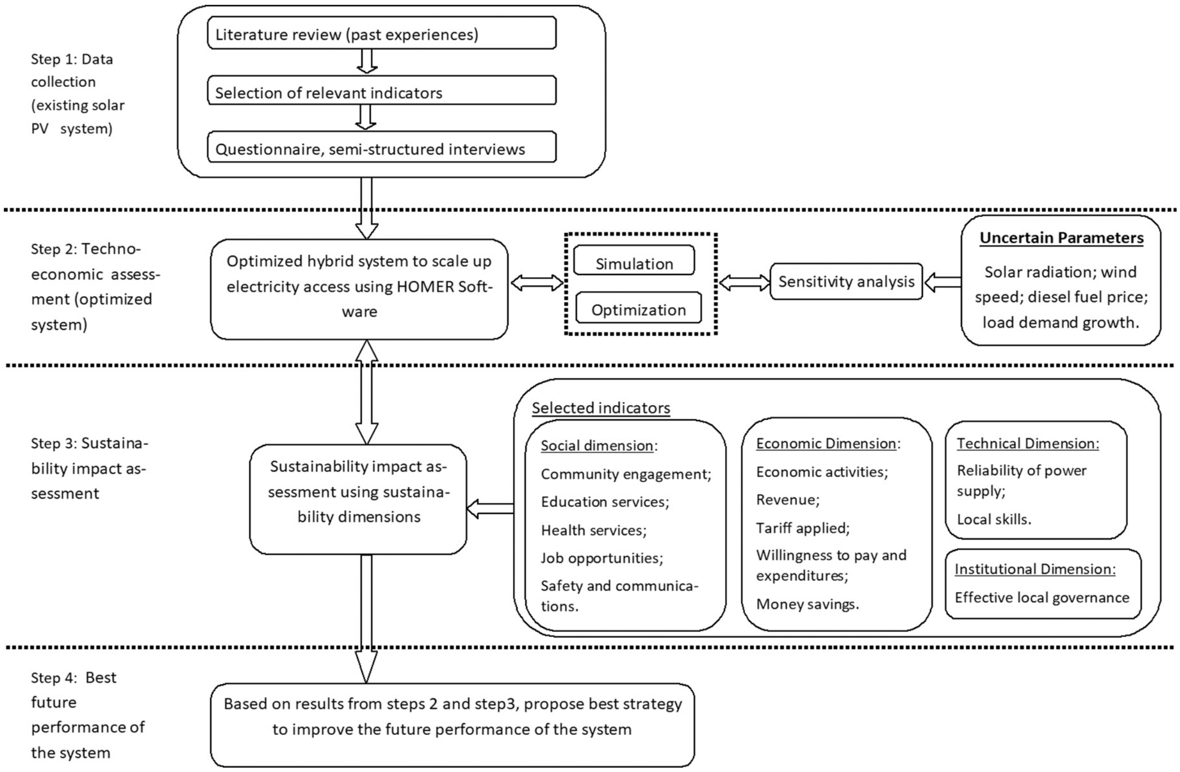

Fig. 2. Flowchart depicting the methodology used in the present study.

projects (Mainali et al., 2014; Buchmayr et al., 2021), we identified different indicators that were applied to analyze the impact of the rural project. The indicators were selected to investigate the project's sustainability at the local level to address recommendations for further improvements to the system performance. We assessed 13 set of indicators (community involvement, education services, health services, safety, job opportunities, economic activities, revenue, satisfaction with tariff, willingness to pay, money savings, reliability of power supply, skills, and local governance), clustered into four selected sustainability dimensions (social, economic, technical, and institutional). The selected indicators are considered relevant because: a) they apply to the characteristics of the project to be evaluated and to local-specific conditions; b) they can help investigate the aspects influencing the sustainability of the existing mini-grid and address future improvements to the system performance. Community involvement and job opportunities are important indicators under the social dimension of sustainability. This is because they are directly linked to the community's sense of ownership and participation, which is important to ensure the project's viability over its lifetime. Similarly, education services, health services, and safety indicators are also linked to the social dimension. The provision of electricity helps improve these services by increasing the study hours for the students, and shortness the long distance to the nearby health center. Economic activities and money savings are considered key indicators under the economic dimension. They are directly linked to the village's economic development through income generation activities and money savings, through savings, derived from fuel expenses. Likewise, the revenue, satisfaction with the tariff, and willingness to pay are also linked to the economic dimension. They contribute to ensure the project's financial viability and continuous O&M. Reliability of power supply and local skills availability are commonly used indicators within the technical dimension. The mini-grid project should be able to deliver the planned power output, and it requires local skilled capacities for O&M to avoid failures to the system. Under the institutional dimension, we considered the ability of local governance to manage the system without external influence for rapid response to the issues, avoiding failures.

Questionnaire design and interviews

After selecting relevant indicators to assess the impact of the Mavumira project, we developed a questionnaire used for interviews with relevant people and parties in Mavumira village. Interviews were the most important source of information for our study. They were conducted five months after the mini-grid commissioning in the village, in August 2019, to investigate the village load patterns to find the optimized system that can meet the future load and analyze the impact of the existing system to address future improvements to the sustainability of the sustainability. A semi-structured face-face format was used for the interviews, which provides the interviewee with the opportunity to raise new issues (Myers & Newman, 2007; Petty et al., 2012). Two people were involved during the data collection process, namely the researcher and a technician from FUNAE's provincial delegation appointed to assist in the process, which facilitated access to information. The respondents were selected based on their level of knowledge concerning the village's energy situation before and after the arrival of the mini-grid and also their involvement in the project. In total, 35 individuals were interviewed, of whom three people were revenue collectors (interviewed together at the same time), three were school teachers (interviewed together at the same time), the head of a health center, two nurses whose homes were within the same enclosure (interviewed together at the same time), one representative from local governance, seven owners of small shops (interviewed individually), and seventeen owners of households (interviewed individually). Additionally, an interview was carried out with the FUNAE's provincial delegation, as the system owner, to gather information on the functioning and management model of the mini-grid. The structure of the questionnaire is presented in Appendix B.

HOMER Pro software method

In the second step, we performed the techno-economic analysis of the hybrid system, considering an increase of 60 % in the future energy demand of the village over the actual load demand. The HOMER Pro software, developed by the National Renewable Energy Laboratory, was used in this study for the optimal planning and techno-economic evaluation of the system for off-grid application. HOMER Pro is a cost and system optimization tool that performs the simulation and optimization simultaneously, as well as a sensitivity analysis (Bahramara et al., 2016a; Lambert et al., 2006). The software is able to simulate a mix of dispatchable and non-dispatchable resources of energy, converters, and storage and is adequate for both grid-connected and off-grid projects. For simulation and optimization, HOMER Pro requires as the input data the meteorological data/resource availability (solar radiation, and wind speed) and village electrical load profile (Mavumira village), presented and described in Appendix C; equipment characteristics; search space (to define values, for example, capacity or quantity, for various components that are used to simulate the feasible configurations and determine the most efficient configuration in the system); and economic data (which includes investment cost, replacement cost per kW of the solar PV system, annual O&M costs, as well as fuel costs), and technical data to determine the optimal system configuration and cost analysis.

In the optimization results, HOMER Pro simulates different configurations taking into account different numbers of batteries and sizes of other components such as solar PV, and converts from the search space to find the optimal solutions (Bahramara et al., 2016a; Suite & Co, 2016; Givler & Lilienthal, 2005; NREL & HOMER Energy, 2011).

Moreover, HOMER Pro was designed to deal with uncertain values for parameters such as intermittency and non-dispatchable renewable power resources (solar radiation and wind speed), cost of the components, load size, future fuel price, and expected load demand growth. The dispatch strategy was also analyzed in this study, as it significantly influences the outcome of the hybrid system configuration (Das & Zaman, 2019).

Components of the proposed hybrid system

This section describes the main system's components, including the assumptions and performance parameters considered for the design phase. It presents the system configuration for different load scenarios (Fig. 3). As previously mentioned, since 2019, part of the residents of Mavumira village have been connected through a 30 kW solar PV mini-grid (scenario a), which has led to a growth in the village's electricity demand due to the fast economic development. Therefore, in this study, we proposed to scale up the electricity to meet the increased load demand considering an increase of 60 % in 2025 (scenario c) over today's load demand (scenario b). The proposed system comprises solar PV panels, wind turbines, diesel generators, batteries, converters, and charge controllers as the main components. However, there are other elements that need to be considered, such as transmission and distribution lines covering a radius of up to 1 km away. More details of the system's components are presented in Appendix D, including the costs of the components of the system, equations used for the economic evaluation of the hybrid system, the sensitivity parameters assumed and dispatch strategy.

Determining the assessment method and score for the indicators

The literature addressed some methods to measure the sustainable indicators, which include expert judgment (Akinyele & Ighravwe, 2019), simulation outputs (Diemuodeke et al., 2019), hybridization of expert judgment and simulation output (Babatunde et al., 2019), and focus group analysis (Murtagh, 2013). In our case, to assign a score to each indicator, we applied the methodology proposed by (Katre & Tozzi, 2018), which was later tested by (Katre et al., 2019) to analyze the performance of a concrete project in India. The authors of (Katre & Tozzi, 2018) introduced a comprehensive framework and analytical methods to assess the sustainability of decentralized RE systems and illustrated its use, looking into dimensions described by a set of selected indicators, such as reliability, user satisfaction, efficiency governance, and community participation. The method proposed by (Katre & Tozzi, 2018) is based on scoring the indicators for each sustainability dimension, considering the importance of the indicator for the sustainability of the project. They used information collected through interviews with stakeholders, and each indicator (qualitative) was assigned the related score ranging from 1 (lowest) to 5 (highest), where (1) indicates the lowest sustainability impact, and 5 indicates that more likely the project performed well for that specific indicator. The method helps assess the indicators for rural electrification, allowing comparison among different dimensions of sustainability. It can be used to identify the weaknesses and strengths of the sustainability on a specific project and address solutions for future improvements. As previously mentioned, in our study, we applied the proposed method to score the set of selected indicators (see Determining the assessment method and score for the indicators section) based on their performance in the Mavumira mini-grid. The set of indicators and measurement units are described in Table 1. It was possible to set measurement units for some indicators; for example, the community involvement indicator was measured in terms of the level of community participation in the project (low/medium/high), health services and safety measured in terms of percentage of interviewees who reported improvements in these services, and the reliability of power supply measured in terms of the number of days that the system registered outages during a month. Each of the indicators was assigned a relative score according to the data obtained from the interviews with different people in the study area, as presented in Table 1. For example, for health services and safety indicators, we attributed scores (1 to 2) if the respondents reported no improvements or (4 to 5) if >70 % of respondents pointed out improvements in these services upon the arrival of electricity in the village. Under the reliability of the power supply indicator, we attributed the score according to the frequency and duration of outages, which varied from more than five days of outages per month (score 1) to no unscheduled outages (score 5).

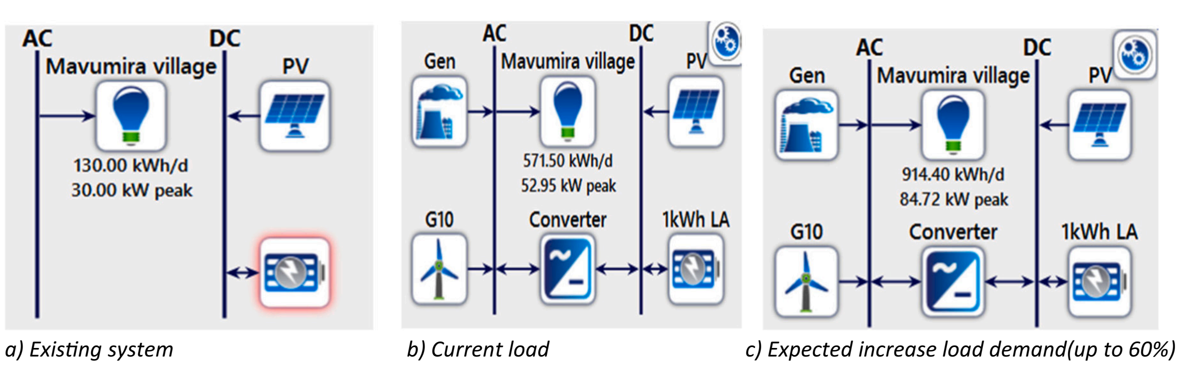

Fig. 3. System configuration for different load scenarios.

Table 1
Determining the score of the indicators.

Sustainability dimension	Indicator	Description of indicator	Measure (unit of measure)	Scoring the indicators
Social	Community involvement	Community involvement is important for the success of the project as it ensures a sense of community ownership, avoiding failures of the system. This is an important indicator and should be observed from an early stage of project development to ensure system O&M and, hence, the project's sustainability over its lifetime (Tomei & Gent, 2015; Sustainability, 2014).	Level of involvement of the community members in the project (low/medium/high)	This indicator was assessed through the level of involvement of the community member in the project. It scored low (1–2) if there was a very limited sense of community ownership and high (4–5) if the community members were regularly involved in the project.
	Education services	One of the benefits of access to electricity is the provision of better education services in rural areas as it increases the study hours during the night, providing the students more chances to improve their education performance (Riva et al., 2018a; Das et al., 2017c; Lenz et al., 2017).	Hours of additional study time (No improvements/about an hour of additional study/more than an hour of additional study)	The indicator was assessed based on increased hours of additional study. It was attributed a maximum score (4–5) if the respondents reported more than an hour of additional study time during the night and a minimum score (1–2) if there were no improvements in education services.
	Health services	Access to electricity is fundamental in improving health services, especially in remote areas. Besides reducing smoke emissions from kerosene, which are prejudicial to health, the health services can improve childbirths and reduce the long-distance travel to the nearest health centers (Riva et al., 2018a; Lenz et al., 2017; ARE, 2006; Mishra & Behera, 2016).	Percentage of respondents reporting improvements in health services (no improvements/about half of the respondents reported improvements/>70 % of respondents reported improvements)	This indicator was assessed in terms of improvements in health services. If >70 % of respondents reported improvements in access to health services, the indicator scored high (4–5) and low (1–2) if there were no improvements.
	Safety	This indicator represents an important aspect of the community as it improves the living conditions through the street lights, which allow people, especially women and children, to go outside at night (Practical Action, 2014).	Percentage of respondents reporting improvement in safety (no improvements/ about half of the respondents reported improvements/>70 % of respondents reported improvements)	This indicator was assessed in terms of improvements in safety during the nights. It was attributed a high score (4–5) if >70 % of respondents reported improvements in safety conditions cat night.
	Job opportunities	Job opportunity is an important indicator to measure the impact of electricity on the village's social and economic development since it can reduce unemployment as a result of new energy infrastructures and improve the life quality of the communities (Shaaban et al., 2018; International Renewable Energy Agency (IRENA), 2017). Potential jobs can be generated during the manufacturing, construction, and O&M phases (Gunnarsdottir et al., 2020; Okunlola et al., 2018).	N/A	The indicator job opportunity was assessed in terms of the existing local people directly employed during the operation of the project. We had limited access to information about the number of local staff employed during the construction phase of the project.
Economic	Economic activities	Access to electricity encourages the emergence of new businesses, thus increasing generation income activities, which is directly linked to economic development, providing the population with the means to pay for electricity (Das et al., 2017a).	Level of economic activities linked to electricity, e.g., no economic activities (if users are not reporting productive activities linked to electricity or report limited livelihood activities)/User are reporting use of electricity for some livelihood activity/ Expansion of economic activities (If the use of electricity is extended to several households).	Economic activities were assessed based on the level of generating income activities in the village after the arrival of the mini-grid. The indicator was attributed a low score (1–2) if there were no economic activities linked to energy use, score (3) if it is observed the use of electricity for some livelihood activity and a maximum score (5) was attributed if the expansion of economic activities was notorious.
	Revenue	Revenue is an important indicator for the sustainability of the mini-grid as it can be used to ensure the financial viability of the systems (Clausen & Rudolph, 2020).	N/A	This indicator was assessed in terms of local management of the revenue collected, which is an important aspect to ensure the long-term functioning of the project.
	Satisfaction with tariff	The tariff applied is an important aspect for the sustainability of the project. It should consider the user's capability to pay for electricity to ensure the financial viability of the project.	Percentage of respondents expressing satisfaction with the tariff (about 20–30 % of respondents expressed satisfaction/about 50 % of respondents expressed satisfaction/ >70 % of respondents expressed satisfaction)	The indicator was assessed based on the percentage of respondents who were satisfied with the tariff applied. It was attributed a low score (1–2) or high score (5) if 20–30 % and >80 % of the respondents, respectively, expressed satisfaction with the tariff applied.
	Willingness to pay	Readiness to pay for electricity is a determinant aspect of the system's viability to ensure the O&M of the project over its lifetime. The willingness to pay for electricity should be linked to income and people's expenditure to understand better how much the community can pay for energy services considering other expenses such as food and market, especially for	Ability to pay for electricity (incapable to pay at the moment of revenue collection and still debt/incapable to pay at the moment of revenue collection and facing difficulties in paying on the following month/incapable to pay at the moment of revenue collection but easily pay back on the following month/no difficulties to pay).	This indicator was assessed by considering the willingness of the local community to pay for electricity. It was attributed a high score (5) if there were no difficulties with regular payments and a low score (1–2) if the revenue collector reported difficulties

(*continued on next page*)

Table 1 (*continued*)

Sustainability dimension	Indicator	Description of indicator	Measure (unit of measure)	Scoring the indicators
		domestic consumers and can vary from large cities to small villages according to their electricity needs (Riva et al., 2018a; Sayar, 2019b; Lyndon & Tuckwell, 2013; UNIDO, 2017).		
	Money savings	Money savings is an important indicator to measure the impact of the project on the local communities. It helps to estimate how much the community saves by reducing the use of fossil fuels like diesel and kerosene.	N/A	This indicator was assessed based on the savings by replacing diesel and kerosene with electricity from a mini-grid. In our study, it was not possible to measure the savings in terms of the amount saved per month due to the lack of this information in the field.
Technical	Reliability of power supply	Reliability of power supply is defined as the capability of the mini-grid to deliver the planned, firm and secure power output to the consumers, thus avoiding failures. Ensuring the continued operation of the system will increase the community's satisfaction and hence the willingness to pay for electricity (Zebra et al., 2021; López-González et al., 2018; Shaaban & Scheffran, 2017; Wang et al., 2009; Reddy, 2015).	Frequency of outages (>5 days per month/2 to 5 days per month/1 to 2 days per month/ no unscheduled breakdowns)	The reliability indicator was assessed based on the number of days per month the system registered outages. It was attributed a low score (4–5) if the system registered more than five days of electricity disruption per month and was considered high impact (score 5) if the system registered zero outages.
	Skills	Most of the mini-grid projects implemented in developing countries face many challenges in terms of scarcity of their local technical capacity for rapid response to the issues to avoid long periods of breakdowns in the system. The lack of local skilled capacities for O&M of the systems is one of the principal aspects against the sustainability of many projects; especially if it is related to newly developed technologies such as RE mini-grids, which have not been massively introduced in the country (Palit et al., 2013; Taele et al., 2012; World Bank, 2017).	N/A	This indicator was assessed based on the availability of local, skilled persons trained for rapid response to the issues in case of failure to avoid long periods of breakdown.
Institutional	Effectiveness of local governance	One of the aspects that positively influences the success of off-grid electrification projects is strong governance at the local level, which can be influenced by the ability of local governance to manage technical and financial issues (Katre et al., 2019; Bhattacharyya & Palit, 2016).	Level of the effectiveness of local governance (very ineffective/medium effectiveness/effective/very effective).	This indicator was assessed in terms of the effectiveness of local governance. It was attributed a low score (1–2) if the local governance played an ineffective role in managing the system, including the O&M issues, and a high score (5) if the governance role was very effective in the sense that local authorities demonstrate the ability to take over the technical and financial issues without external support.

Results and discussions

Techno-economic optimized analysis of the proposed hybrid system

Optimization analysis

In our assessment, we followed two main steps. First, we conducted a load survey in the study area to find the village load patterns based on the existing mini-grid and estimate the current village load demand. Second, hybrid system configurations with different capacities were optimized to find the optimum combination that can supply electricity to the Mavumira community at the lowest levelized cost of electricity (LCOE), considering an increase of 60 % in the future energy demand of the village, as presented in Fig. 3. The scaled annual average of 914.4 kWh/day and a peak load of 84.72 kW were considered for future projections over the actual scaled annual average of 571.5 kWh/day and peak load of 52.95 kW. The optimization analysis demonstrated that the best-performing energy system architecture that can meet the future peak load of 84.72 kW, corresponding to an increase of up to 60 % of the actual load demand in Mavumira village, is the hybrid solar PV/diesel/ battery system. HOMER optimized for the lowest NPC system, which comprises a 200-kW solar PV system, 94.0 kW diesel generator, and 600 batteries (generic 1 kWh lead-acid each), and the size of the converter is 45.8 kWh, at the scaled annual average of 571.5 kWh/day. However, we considered the LCOE as the main economic output for our analysis to compare the costs of different system's components and select the most appropriate technology. Additionally, the LCOE allows the comparison of parameters such as the tariff. Thus, our optimum future system comprises a 300 kW solar PV system, a 94.0 kW diesel generator, and 800 batteries (generic 1kWh lead-acid each), and the size of the converter is 72.9 kWh. The system presents the lowest LCOE of 0.47 $/kWh at the scaled annual average of 914.4 kWh/day, as presented in Table 2. In addition to the cost-effectiveness of the best performing system, the RE fraction is 77.3 %. The diesel generator supplies the remaining percentage of the annual load of 22.7 %, which shows minimum diesel dependence in the optimum system.

Comparing the obtained results with previous studies, we found that the LCOE of our optimized system (0.47 $/kWh) is within the range of previous studies, despite the relative variations associated with aspects such as resource availability and the scale of the projects. For example, our previous review study (Zebra et al., 2021) analyzed the LCOE of various mini-grids, in general, and mini-grids for different scales, including future projections, based on reports from international organizations and scientific journals. The results indicated that by 2025 the LCOE for a mini-grid will vary between 0.30 $/kWh to 0.57 $/kWh over the 0.47 $/kWh to 0.92 $/kWh of 2015, without considering local government incentives or subsidies. While a study by (IRENA, 2016a)

Table 2
Comparison of the optimized results with the best future case.

	Optimized today's case		Optimized best future case based on HOMER		Our best future case	
	DG only	Solar PV/DG	DG only	Solar PV/DG	DG only	Solar PV/DG
Battery capital cost multiplier (%)				0.85		0.85
Diesel fuel price ($/L)	1.20	1.20	1.20	1.20	1.40	1.40
Solar PV capital cost multiplier (%)				0.60		0.60
PV capacity (kW)		100		200		300
Battery capacity (units)		200		600		800
Converter capacity (kW)		40.6		45.8		72.9
DG capacity (kW)	59	59	94	94	94	94
Capital costs ($/kWh)	0.01	0.13	0.02	0.19	0.01	0.17
Replacement costs	0.08	0.09	0.13	0.13	0.08	0.12
Fuel costs ($/kWh)	0.43	0.24	0.49	0.13	0.46	0.14
O&M costs ($/kWh)	0.07	0.06	0.12	0.07	0.07	0.05
Salvage costs ($/kWh)	−0.001	−0.003	−0.002	−0.006	−0.001	−0.013
NPC ($)	1.59	1.40	2.03	1.37	2.70	2.05
LCOE ($/kWh)	0.59	0.52	0.75	0.51	0.63	0.47
Tariff ($/kWh)	0.14	0.14	0.37	0.37	0.37	0.37

indicated that the LCOE of a solar PV-diesel mini-grid, which serves 100 customers, varies from 0.46 $/kWh to 0.74 $/kWh, in sub-Saharan Africa.

The cost summary for each system's components, considering today's case (current load) and future case (higher load + lower PV + lower battery), including the grid costs for 1 km, are presented in Fig. 4. According to (Maatallah et al., 2016a), the cost of the grid extension for 1 km on-air is 21,742.40 USD. Thus, using Eq. (D.4.4) (see Appendix D) and assuming that the replacement cost of the grid is always zero, we found that the current LCOE of the grid is 0.11 $/kWh, while future projections indicated that the LCOE of the grid would be 0.07 $/kWh. By comparing the optimized future system and today's system, we found that the LCOE of the optimized future system presents the lowest LCOE of 0.47 $/kWh if compared to the LCOE of today's system, which presents the LCOE of 0.52 $/kWh. Despite an expected future decrease in solar PV and battery capital cost, we found that the optimized future system presents high PV and battery costs as a result of an increase in solar PV capacity and battery quantities in the system, from 100 kW to 300 kW and from 200 units to 800 units, respectively, to satisfy the increasing village load demand. As seen in Fig. 4, the diesel generator is more expensive than other system components such as solar PV and batteries. Therefore, a diesel-only system is economically less feasible than the hybrid solar PV/diesel/battery system due to its high LCOE. Moreover, in the future case, the system will rely less on diesel fuel than in today's case. Thus, the community will be less exposed to the instability of the diesel fuel prices in the future.

Operation strategy and an economic analysis of the system were also considered. In terms of the system's operation strategy, LF is used as the optimal generator-dispatching strategy. While LF is in use, the excess electricity from renewable power sources is used to charge the batteries. The diesel generators only serve the required load in the absence of RE sources and battery power. The use of renewable resources is thus maximized and the operating hours of the generator is reduced, which results in the use of a minimal amount of diesel fuel in the system.

Effect of number of batteries on the system performance

The batteries play an important role in ensuring the hybrid system's stability when intermittent RE experiences failure (Halabi & Mekhilef, 2018). During the optimization analysis, the implications of battery storage for the system performance were studied, considering its impact on the renewable fraction (RF) and costs, as presented in Fig. 5. For the analysis, we considered the system to be optimized at 300 kW solar PV, 94.0 kW diesel, 72.9 kW converter, and 800 batteries. We varied the batteries from 0 to 1200 (in 200 intervals). The results showed that by increasing the number of batteries, the fraction of energy produced from RE sources on the load increased considerably, making the system more reliant on renewable technologies, which suggests less use of diesel fuel in the system. Furthermore, it can be seen from Fig. 5 that by increasing the number of batteries by up to 800 units, the LCOE decreases, making the system economically more viable for that condition. This consequently reduces the operating hours and diesel fuel consumption in the system considerably and provides a good indicator of the system's sustainability in the future. In contrast, the NPC increases when >800 units of batteries are used, which suggests investigation for further research.

Tariff implementation

In this section, we present a comparison the tariff applied to the existing system with the LCOE of the optimized system to analyze its economic viability, considering today's load and the improved future systems, as seen in Fig. 6. Currently, the mini-grids implemented in Mozambique apply the government-subsidized electricity tariff set to make access to electricity more affordable for domestic consumers. The current tariff charged by the national utility company is 8.44 MZN/kWh, equivalent to 0.14 $/kWh (1USD = 62.2 MZN as of August 2019).

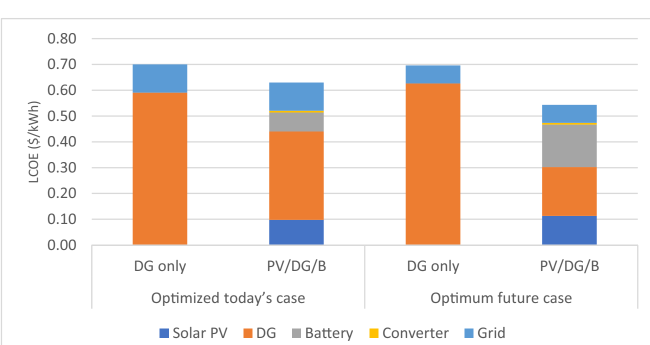

Fig. 4. Cost summary for each system's components (today and future case).

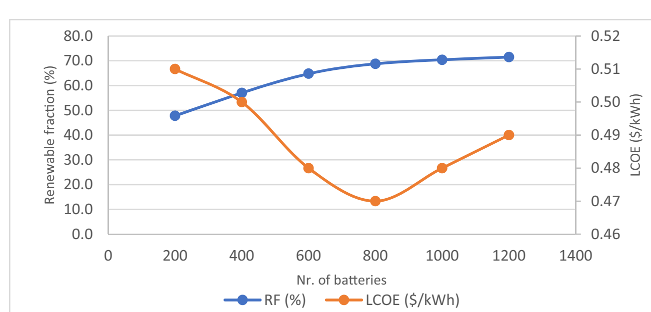

Fig. 5. Impact of batteries on the system performance (RF and LCOE).

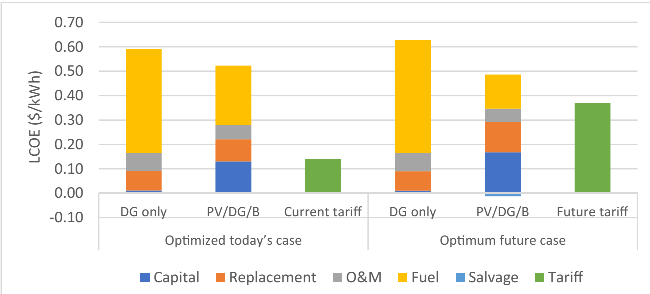

Fig. 6. Comparison of the LCOE of different configurations with the tariff.

However, the tariff applied by the government does not reflect the costs, and it is expected to grow over the years in the base case. For example, in 2018, the tariff was adjusted for an increase of 30 % over the year 2017, and in the short-term, it would be expected to increase by approximately 15 % by 2019, 17 % by 2020, and 21 % by 2021, making it cost-effective, while in the mid-term and long-term (2022–2043), the tariff expects an adjustment every year based on the price index and electricity supply costs to sustain the operation costs (Electricidade de Mocambique, 2018; Ministry of Mineral Resources and Energy, 2018), as presented in Fig. 7. To analyze the impact of future costs on the tariff, we assumed that the tariff projected for 2025 would be 0.37 $/kWh. Our results showed that the LCOE of the optimized today's system (current load) is approximately 3.7 times higher than the current tariff applied to the existing system of 0.14 $/kWh, compared to the LCOE of the optimized future system, which is approximately 1.3 times higher than the projected future tariff of 0.37 $/kWh. This means that the optimized future system would still rely on government subsidies to make it affordable for local communities. However, the required future subsidy is lower than today's subsidy. Our results also demonstrated that the diesel fuel price highly influences the costs of the systems. Moreover, the future optimized system showed that the capital and replacement costs have a significant contribution to the LCOE of the system if compared to other costs, such as fuel and O&M costs. However, as mentioned before, the costs of technologies (solar PV and batteries) are expected to decrease even more in the future with further improvements in production. This suggests that the system will depend even less on diesel fuel prices in the future, providing cost-effective and reliable electricity for the community of Mavumira.

Electricity production of the system

The total electricity production of the optimum system to meet the load demand of 914.4 kWh/day and peak of 84.72 kW is 333,756 kWh/yr, of which 77.3 % of this production is generated from solar PV, and 22.7 % is generated from diesel generators. This means that the use of diesel fuel will be minimal in the system. The monthly electric power production of the system is presented in Fig. 8. As shown, solar PVs generate the largest percentage of electricity compared to diesel generators. The capacity factor of solar PV is 13.5 %, which is relatively high when compared to the capacity factor of diesel generator of 12.7 %.

In terms of electricity generation, this system generates 459,929 kWh/yr excess electricity, which translates into 19.6 % of its total generation capacity and must be dumped because it cannot be utilized to supply the load or charge the batteries. It may be due to the impact of the high solar radiation in the system, which will result in a reliable power supply due to excess electricity that serves as a substitute for times of insufficient sun.

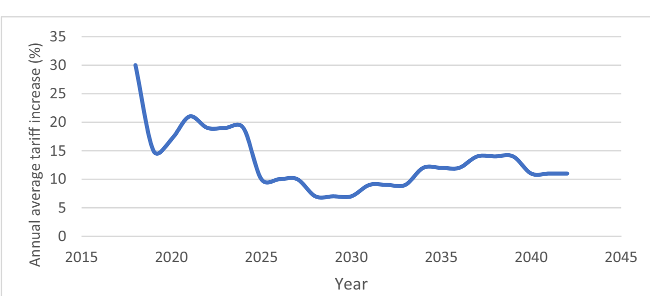

Fig. 7. Expected adjustment in the tariff. Based on (Ministry of Mineral Resources and Energy, 2018).

Sensitivity analysis of the optimized system

Effect of solar scaled average and diesel fuel price on the LCOE. Diesel fuel price is one of the variables that influences the total NPC and LCOE of the optimal system due to the fluctuations in the global fuel price (Gsma, 2010). The effects of diesel fuel price and solar radiation on the LCOE are plotted on the surface presented in Fig. 9. For each of the given prices and solar scaled averages, there is a corresponding LCOE. Solar scaled average and diesel fuel prices were found to have an effect on the LCOE, whereby an increase in the diesel fuel price makes the system economically less attractive; for example, by keeping the solar radiation constant at 4 kWh/m^2/day and increasing the fuel price from 1.0 $/L to 1.40 $/L, the LCOE will increase by approximately 9 %. In contrast, keeping the fuel price constant at 1.40 $/L and increasing the solar radiation from 4 kWh/m^2/day to 6.15 kWh/m^2/day can significantly decrease the LCOE and the NPC from 0.53 $/kWh to 0.49 $/kWh, and consequently, reduce the diesel consumption in the system. These results were obtained at a minimum wind speed and load demand of 4.09 m/s and 914.4 kWh/day, respectively. Solar PV contributes to generating electricity in lower LCOE. This makes the hybrid solar PV/diesel/battery system an optimum system that can satisfy the village's load demand under the studied conditions.

Effect of wind speed scaled average and diesel fuel price on the LCOE. The effect of wind speed (m/s) and diesel fuel price ($/L) in the LCOE was investigated in the surface plot at constant solar radiation, scaled annual average, battery, and solar PV capital cost of 4 kWh/m^2/day, 914.40 kWh/d, 0.85, and 0,60, respectively, as presented in Fig. 10. The results demonstrated that using wind energy in the hybrid system does not seems to be feasible for small systems like the Mavumira system because NPC is insensitive to lower wind speed values compared to solar energy values. It is observed that the LCOE varies depending on the wind speed and diesel fuel price. For example, for wind speeds above 4.7 m/s, the LCOE decreased from 0.53 $/kWh to 0.51 $/kWh, which allows the system to include wind turbines, while for wind speed below 4.7 m/s, the LCOE remain constant at 0.53 $/kWh, thus favoring only the hybrid solar PV/diesel/battery system. This finding in line with the fact that the country has limited wind resources compared to the solar resource, with average wind speeds between 4 and 6 m/s measured at 80 m in height, based on the data released from the RE Atlas of Mozambique (Gesto Energy, 2014; Mokveld & von Eije, 2018; Management & Esbensen, 2017). For comparison, the maps of solar and wind potential for Mozambique are shown in Appendix E. The finding is also in line with past studies; for example, a study by (Johannsen et al., 2020) indicated that for small wind speed below 4.5 m/s, the hybrid solar PV/wind system is less feasible compared to hybrid solar PV/diesel. These authors also found that for wind speed above 6 m/s, the diesel generator should be neglected, which is good to consider for further research in areas with high wind speed. Similarly, the authors in (Hazelton et al., 2014) compared the benefits of several hybrid mini-grid configurations and revealed that many studies recommend hybrid solar PV/diesel over hybrid combinations with wind turbines because solar PV is more cost-effective than small wind turbines for remote applications. However, it is not yet certain whether this is true under all conditions. We think that in various countries like Mozambique more integrated studies that take

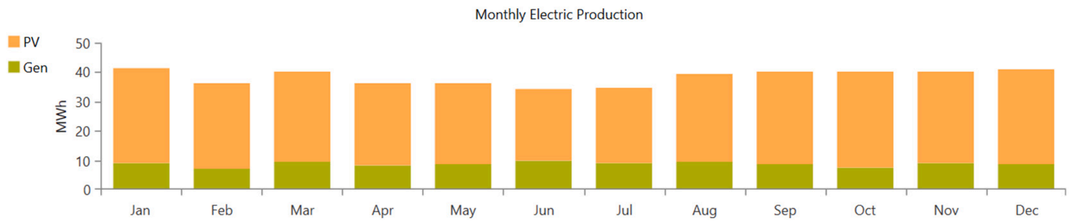

Fig. 8. Monthly electric power of components of the system.

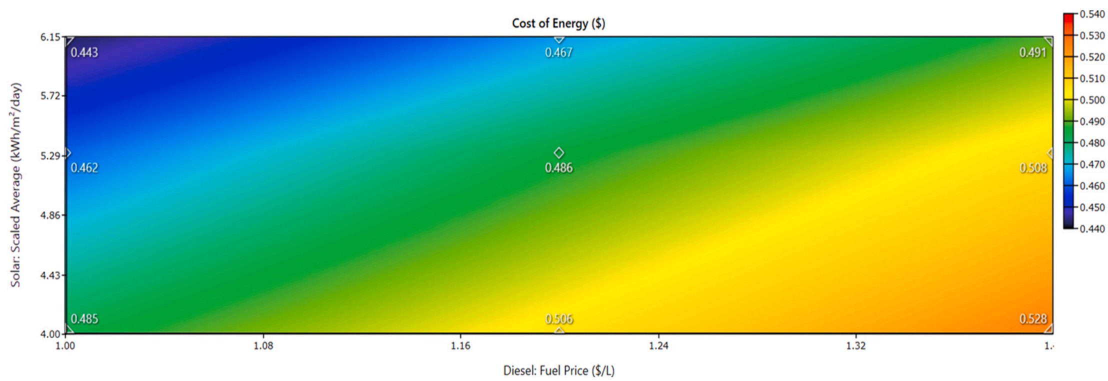

Fig. 9. Effects of solar scaled average (kWh/m^2/day) and diesel fuel price ($/L) on LCOE ($).

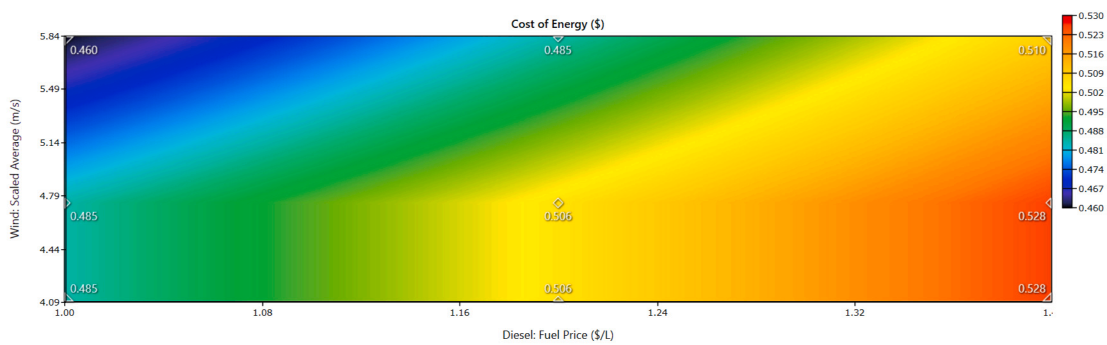

Fig. 10. Effect of wind scaled average (m/s) and diesel fuel price ($) on the LCOE ($).

into account economic and local technical aspects are needed.

Effect of scaled annual average and diesel fuel prices on the LCOE. This section presents the results of the analysis of the effect of the load demand growth and diesel fuel price on the NPC with the LCOE superimposed. The load demand was set and investigated, considering the growth of 60 % at minimum solar radiation, wind speed, solar PV capital cost multiplier, and battery capital cost multiplier of 4 kWh/m^2/day, 4.09 m/s, 0.60, and 0.85, respectively, as presented in the surface plot shown in Fig. 11. The total LCOE was shown to be sensitive to the scaled annual average and diesel fuel prices. The results revealed that

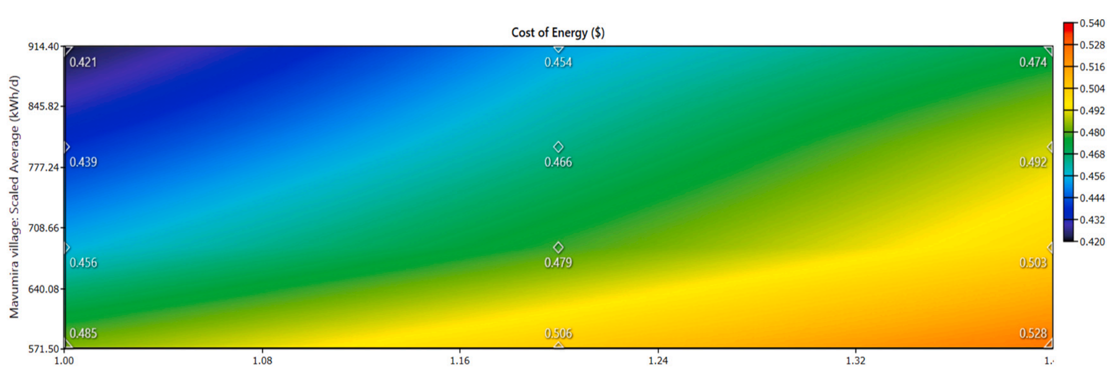

Fig. 11. Effects of scaled annual average (kWh/day) and diesel fuel price ($/L) on the LCOE ($).

keeping fuel consumption constant, at 1.40 $/L, will reflect a decrease in the LCOE from 0.53 $/kWh to 0.47 $/kWh as the scaled annual average rate increases. Moreover, maintaining the scaled average constant at 914.4 kWh/day while increasing fuel consumption results in an increase in LCOE from 0.42 $/kWh to 0.47 $/kWh. Hence, the LCOE increases when the diesel fuel price increases and decreases when the load demand increases.

Effect of scaled annual average and wind scaled average on the LCOE. This section presents the results of the effect of the wind speed scaled average and the scaled average (demand growth) on the LCOE. The surface plot presented in Fig. 12 clearly shows that from a particular consumption rate and increasing wind speed, the LCOE decreases by approximately 6 %, thus favoring wind usage in the system. However, by maintaining scaled wind at a constant rate of 4.09 m/s, the LCOE decreases from 0.53 $/kWh to 0.47 $/kWh with increasing demand. In this regard, the optimal system to satisfy the increasing load demand is the hybrid solar PV/diesel/battery system.

Effect of solar PV capital cost and diesel fuel price on the system performance. In this study, we performed a sensitivity analysis on the solar PV capital cost and diesel fuel price to investigate their impact on the performance of the system. We assumed the solar PV capital cost multimeter as a sensitivity variable of 1 to 0.6, which means the capital cost falls from 2500 $/kW to 1250 $/kW. Since the solar PV lifetime is the same as the project lifetime, we neglected the value for the replacement cost because the solar PV does not need to be replaced. As mentioned previously, diesel fuel prices vary from 1.0 $/L to 1.40 $/L. The results displayed in Fig. 13 reveal that the solar PV capital cost highly influences future system performance. It shows that keeping the diesel fuel price constant at 1.40 $/L and reducing the PV capital cost by up to 60 % results in a decrease of approximately 11 % in the LCOE from 0.53 $/kWh to 0.47 $/kWh, while an increment in diesel fuel price from 1.0 $/L to 1.40 $/L results in an increase of approximately 12 % in the LCOE, from 0.42 $/kWh to 0.47 $/kWh. This will favor more solar PV integration into the system, making the system less reliant on diesel in the future.

Effect of battery capital cost multiplier on the system performance. The impact of the battery capital cost multiplier on the number of batteries, the solar PV capital cost, and LCOE was analyzed by varying the battery capital cost multipliers from 1 to 0.85 (a decrease of 15 %). The results are presented in Figs. 14 and 15. They reveals that a reduction of the battery capital cost by 15 % will result in a decrease of the LCOE from 0.48 $/kWh to 0.47 $/kWh, while the solar PV capital cost and the number of battery variations are very insignificant for that particular condition. Therefore, reducing battery costs means a greater opportunity of reducing diesel fuel consumption in the system, which will allow the community to be less exposed to fluctuations in the cost of diesel.

Sustainability impact assessment of Mavumira project

This section presents the discussion of the results of the sustainability impact assessment of Mavumira project based on data collected from interviewees in the study area. The results of the interviews are detailed in Appendix F, and specific scores for the indicators are presented in Table 3. One of the purposes of mini-grid projects is to provide electricity for rural communities, ensuring their social and economic development. In this study, we investigated the social, economic, technical, and institutional impacts of the mini-grid using selected indicators (described in Selection of indicators section). A score was determined for each indicator based on the interviewees' responses to produce an overview of its impact on each dimension of sustainability. Our results showed that electricity provided the communities with better health, education, and safety services, as these indicators scored high (4). For example, access to health services allows students to increase their study hours. Moreover, the economic activities indicator scored high, as a result of the income-generating activities in the village, hence providing the community members with the means to pay for electricity despite the high tariff applied by the government. Therefore, the money is retained in the village, contributing to the village's socio-economic development.

In contrast, the community involvement indicator was attributed a low score (2) as the community members had very limited participation in the project, making it challenging to ensure a sense of ownership. Moreover, when comparing the results from the Mavumira mini-grid with the success stories in developing countries, there is a noticeable contrast. For example, in Nepal, Indonesia, Sri Lanka (Zebra et al., 2021; ESMAP, 2017; Bhandari et al., 2018), and Namibia (Azimoh et al., 2017b), the community-based model has been successfully adopted. This model included community organization in the Village Energy Committee (VEC) and also the community's ability to operate and maintain the system. In these countries, the local communities have been trained to own and operate the systems, which has positively impacted the sustainability of the projects. The satisfaction with the tariff indicator was attributed a low score (2) because >30 % of the respondents showed dissatisfaction with the tariff currently applied, taking into account that they are low-income consumers and the fact that there is no tariff differentiation among the high- and low-income electricity customers, making it hard for the low-income communities to pay for electricity. However, despite the high tariff, we see a positive impact regarding the community's ability to pay for electricity, facilitated by the pre-paid metering system adopted, which allows the communities to purchase electricity according to their capacity to pay, and the fact that they are satisfied with the electricity. The unreliability of the power supply was considered the most critical aspect as it presented the lowest score. We found that despite its short operational time, the system registered a long period of outages. For example, the beneficiaries reported that the outage took two months to be fixed, which is associated with the lack of local skills for rapid response to the issues.

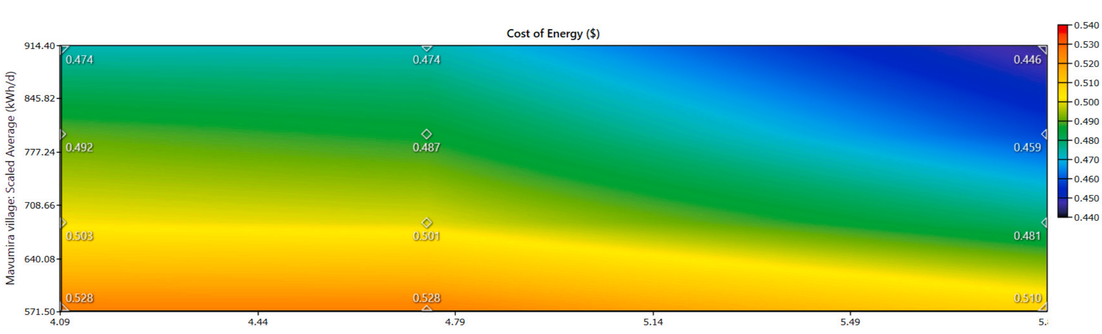

Fig. 12. Effects of scaled annual average (kWh/day) and wind scaled average (m/s) on the LCOE ($/kWh).

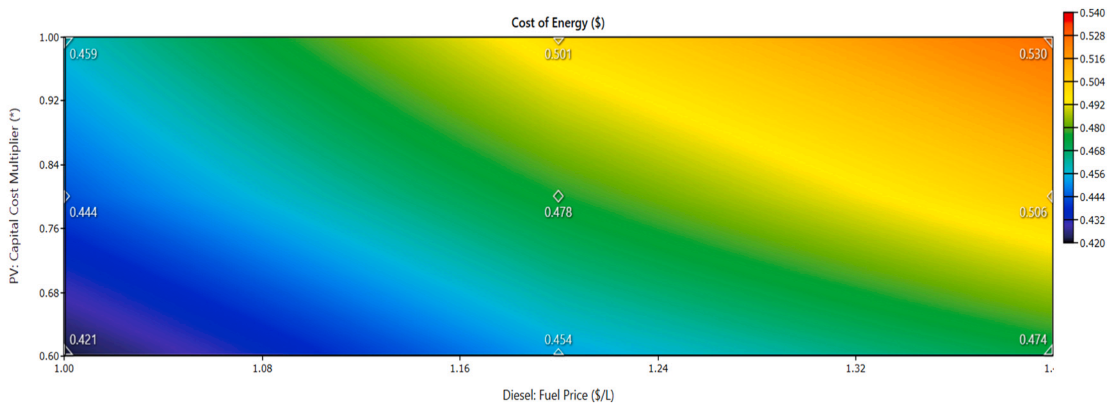

Fig. 13. Impacts of solar PV capital cost multiplier and diesel fuel price on LCOE.

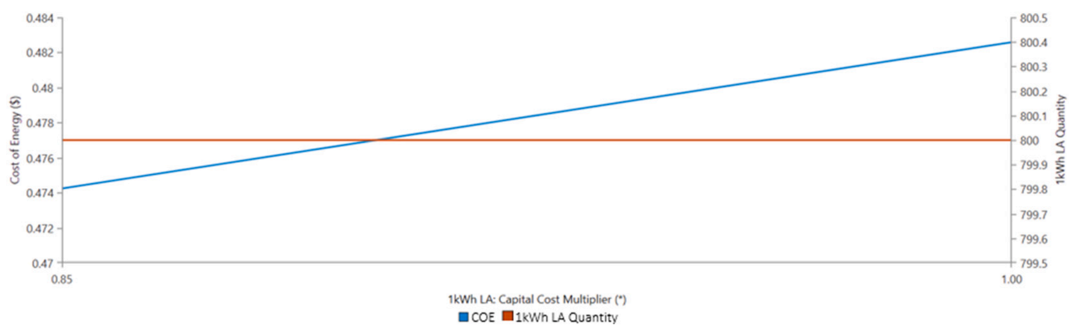

Fig. 14. Impact of battery cost multiplier on the number of batteries and the LCOE.

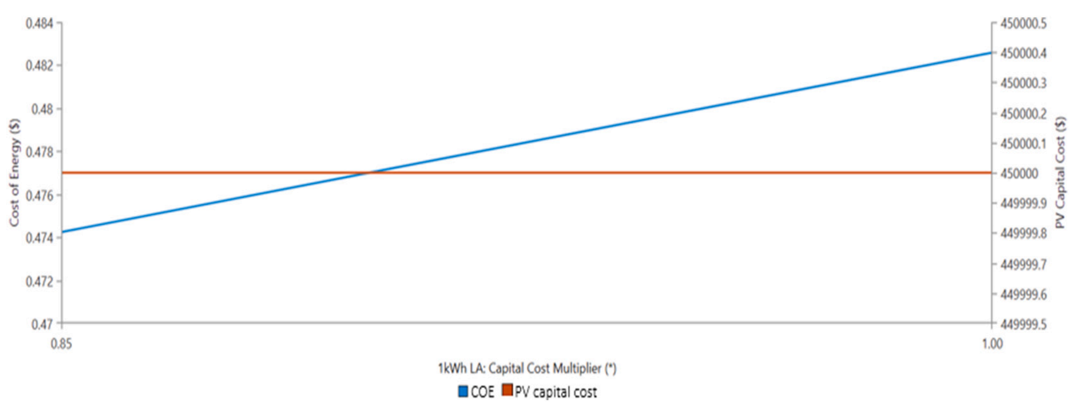

Fig. 15. Impact of battery cost multiplier on the solar PV cost multiplier and the LCOE.

Therefore, if not adequately addressed, this indicator could hinder the sustainability of the project.

Overall, when assessing the project's impact, we found some aspects that can help address the sustainability of the project at the local level. From the above analysis, it can be concluded that indicators assessed under economic and social dimensions (economic activities, willingness to pay, health services, education services, and safety) scored high for sustainability when compared to indicators assessed under the technical and institutional dimensions (reliability of power supply and effectiveness of local governance), which scored low (1 and 2) for the sustainability of the project. This is because the local technical capacity for O&M of the systems and rapid response to the issues were not observed in the village, which caused a long period of breakdown in the system. However, these dimension play a key role in ensuring the reliability of the power supply. Therefore, if not adequately addressed, it may contribute to the system's failure. Moreover, it is important to transfer the experiences learned from successful examples, such as the community organization model adopted in Nepal and Namibia, to help ensure the sustainability of the Mavumira project.

Study limitations

It is important to mention that the analysis presented in this study are subject to the following limitations:

- First, despite its powerful metric in assessing the techno-economic viability of hybrid systems, HOMER does not consider the grid calculations for off-grid systems. It considers grid systems connected to the main-grid or off-grid systems where a grid extension is an option. Moreover, the software does not perform the entire environmental analysis. It can only calculate total emission based on the emission factors for components and fuels entered into the system. Therefore,

Table 3
Scored indicators for sustainability dimensions.
This table presents the selected indicators for each sustainability dimension, including the score reached for each indicator. These indicators were selected to evaluate the sustainability of the mini-grid implemented in Mavumira village. The score was attributed to each indicator based on the information collected during the interview with different people in the village. For a particular indicator, the highest score (5) indicates the best sustainability impact, and the lowest score (1) indicates the lowest performance in terms of system's sustainability. A low score was attributed to the community engagement indicator because this particular indicator was not observed in Mavumira village. In contrast, the economic activities receive a maximum score as a result of an increase in new business activities after the arrival of electricity, while the satisfaction with tariff applied scored low, reflecting the high tariff applied for low-income consumers.

Sustainability dimensions	Indicators	Score	Remarks on score
Social	Community involvement	2	This indicator scored low (2) in the sustainability impact attributed to a lack of community involvement, which results in limited or no sense of community ownership of the mini-grid. The community members were not involved during the decision-making, construction, and operation of the project.
	Education services	4	This indicator was attributed a high score (4) as a result of the improvements in the education services in the village, specifically, the increased study hours. The respondents reported that the students have more hours to perform their tasks.
	Health services	4	The health indicator was attributed a high score (4). The respondents reported improvements in terms of better health services. Specifically, childbirth became possible and safe in the village.
	Job opportunities	N/A	N/A
	Safety and communication	4	The safety indicator was scored higher under the sustainability assessment of the Mavumira project, as the electricity brought access to streetlights in the village allowing people, especially women, to walk in the streets during the evenings.
Economic	Economic activities	5	Economic development was given the best performance indicator, with the highest score, as a result of the emergence of new economic activities linked to electricity.
	Satisfaction with tariff	2	This indicator scored low sustainability impact by the community members due to the high tariff applied for electricity. According to the respondents, they pay the same tariff as the customers connected to the national grid, which is considered high, considering their economic activities.
	Willingness to pay and expenditure	5	This indicator scored higher as the result of the adoption of the pre-paid metering system allowing the local communities to pay according to their purchasing capacity, which also facilitates regular payments.
	Revenue	N/A	N/A
	Money savings	N/A	N/A
Technical	Reliability of power supply	1	The system's reliability scored low in the sustainability performance attributed to the failure registered in the system. According to the respondents, the system registered two months of breakdown a few months after its installation with power outages that lasted for several hours.
	Local skills	N/A	N/A
Institutional	Effective local governance	2	This indicator was attributed to low performance (score 1) as the local government has a very limited role in the project. According to the interview with the representative from the local government, the local government is not in a position to take care of the system or to respond to small issues related to the technical or financial viability of the system. External intervention is necessary to keep the project going.

additional simulation tools such as Life Cycle Assessment are needed to complete the environmental sustainability analysis of the system.

- Second, there were limitations regarding the cost inputs in the HOMER software as we had no access to local costs for the components of the systems. As mentioned in HOMER Pro software method section, the costs of components vary considerably. For example, the cost for a generic 10 kW wind turbine was considered $20,000 for a study conducted in Kenya and $45,000 for a study conducted in Ethiopia. For our study, we resorted to costs available in the HOMER software library and previous publications in developing countries such as Kenya. It would have been more realistic if we had used local costs considering the incentives available in the country and the costs associated with transport.
- Third, regarding the sustainability indicators, we found limitations associated with the lack of data available at the local level and the method to attribute the specific score (on a scale from 1 to 5) to measure the following indicators: job opportunities, revenue, savings, and local skills. Nevertheless, these limitations do not significantly affect the results of our study, as the aim was to understand the main aspects influencing the performance of the mini-grid, taking into account its impact on the local community development.

Conclusions and synthesis

The purpose of this study was to determine the best system configuration that can meet the future village load demand cost-effectively using HOMER software while analyzing the aspects that could influence the sustainability of the Mavumira project based on the selected indicators. Finally, the results were combined to address the best strategies to improve the future performance of the system. In the following sections, the major results drawn in response to the three research questions addressed in this study are presented.

Techno-economic assessment

The first research question addressed in this study was to find the optimized system that can meet the increased energy demand in a cost-effective and reliable manner for Mavumira village using HOMER software.

- Our analysis shows that the hybrid solar PV/diesel/battery is the optimal system that can provide a cost-effective and reliable power supply to meet the future increased load demand of Mavumira village. The system presents the lowest LCOE of 0.47 $/kWh compared to other combinations, like the diesel-only, which presents 0.63 $/kWh. Moreover, despite relative variations in the LCOE, which could be associated with aspects like the scale of the project, the obtained results are within the range of previous studies; for example, a study by (Zebra et al., 2021) indicated that by 2025 the LCOE for a mini-grid will vary between 0.30 $/kWh to 0.57 $/kWh, without considering local incentives.
- The LCOE of the optimized system considering today's load is 3.7 times higher than the current tariff applied to the mini-grid. However, by varying parameters such as the load demand, solar PV, and battery capital cost, we found that the LCOE of the optimized future system will be 1.3 times higher than the projected tariff, which makes the future system more cost-effective than the current system. Moreover, considering parameters like local incentives, the LCOE of the optimized future system can be further reduced, making it more affordable for the community.
- Sensitivity analysis was conducted to analyze the influence of the number of batteries on the system performance. We found that the LCOE is sensitive to the variations in solar radiation, wind speed, solar PV and battery capital cost, and demand growth. For example, by keeping the diesel fuel constant at 1.40 $/L while scaling up the current load demand from 571.5 kWh/day to 914.4 kWh/day, the LCOE reduces by approximately 11 %, which indicates that in future the system will become more cost-effective thus demonstrating the effect of the economy of scale.
- The findings of this study equally demonstrated that the solar PV and battery capital cost are sensitive to the LCOE, as a reduction in the solar PV capital cost by 60 % and battery capital cost by 15 % leads to a decrease in the LCOE of approximately 11 % and 2 %, respectively. Therefore, with the expected decrease in solar PV and battery capital cost, the system would rely less on diesel fuel, favoring the solar PV. This is a good indicator of the future economic viability of the system. Furthermore, it is also clear that, if implemented, the proposed system would reduce the risk of exposure to diesel price fluctuations in the future, since the government is gradually removing subsidies to the cost of diesel. Favoring the use of RE technologies will benefit not only the local communities but also the economy of the country as the diesel consumption will decrease significantly and hence reduce the diesel subsidies paid by the government.
- Sensitivity results also show that for wind speed below 4.7 m/s, there is no change in the LCOE, which indicates that it becomes less feasible to include wind turbines in the system under those particular circumstances.

Sustainability performance assessment

The second research question addressed the aspects that could influence the system's sustainability, analyzed through selected indicators related to four sustainability dimensions (social, economic, technical, and institutional) to investigate the aspects to address future improvements in the project's sustainability.

- The analyses revealed that, on a scale from 1 to 5, the selected indicators for the social and economic dimensions, for example, education services (extending study hours during the night) and economic activities (creating new economic activities), had scored high (4 and 5, respectively) for the sustainability of Mavumira project. This means that these dimensions are likely to ensure the best project's performance over its lifetime. On the contrary, indicators for technical and institutional dimensions, for example, the reliability of power supply (frequency of outages) and effective local governance (local government capacity for rapid response to technical and financial issues), scored low (1 and 2, respectively), which means that more attention is needed to achieve project sustainability in these dimensions.
- The findings of this study have shown that the project performed very well for the economic activity indicator, as it presents the highest score (5) when compared to other indicators, like the reliability of power supply, effective local governance, and community involvement. This is because the arrival of electricity in the village favored new income-generating activities, which allowed the communities to pay for the electricity. Moreover, based on pre-paid metering, the payment structure adopted allowed the communities to pay according to their purchase capacity, facilitating revenue collection. These aspects could contribute to ensuring the project's financial viability. On the contrary, the effective local government and community involvement indicators scored low (2), which illustrates their inability to respond to technical or financial issues. If not adequately addressed, for example through training schemes and community organization through VEC for rapid response to the issues, these indicators can contribute to failures in the system and consequently hinder the sustainability of the Mavumira mini-grid.

Synthesis and strategies

The third research question addressed the best strategies to improve the future performance of the system. To answer this question, a synthesis is proposed based on the combination of the results from Q1 and Q2.

- Overall, by reducing the solar PV and battery capital cost while increasing the load demand, the LCOE of the future optimized system could be significantly reduced (0.47 $/kWh) compared to the LCOE of the current system (0.52 $/kWh). Additionally, the O&M and fuel costs of the optimized future system are lower (0.06 $/kWh and 0.14 $/kWh), than the current optimized system (0.05 $/kWh and 0.24 $/kWh). Therefore, if implemented, the optimized hybrid system will rely more on RE, reducing the total fuel consumption in the system. Hence, the local communities will save money and time spent on diesel transportation. We considered this one of the key strategies for economic development because the community will be less exposed to diesel fluctuation prices, and the money will be retained in the village. It can also be considered an opportunity to encourage RE to be added to the system, making it more sustainable.
- The system overload was reported as one of the reasons for the power outages, which indicates the need for further improvement in the system's performance. Therefore, the optimized system suggested the hybridization of solar PV with a diesel generator backup to compensate the fluctuations and increase the system's capacity, thus ensuring higher reliability and continuous power supply. As a result, the system performance will improve, allowing the connection of more appliance devices to avoid failures due to the system overloading, which is currently the main suspected cause of outages. Moreover, the hybridization will introduce more complexities to the system, implying more components like solar panels and batteries. So, this strategy also requires more involvement and training schemes for the local communities for O&M of the system to avoid failures in the system, thus favoring the local job opportunities indicator and hence increasing their interest in the project.
- From the interviews in the study area, we realized that people were not satisfied with the current tariff applied, which is far from

reflecting current energy costs as the government subsidizes it. Our analysis found that the LCOE of the optimized future system, estimated without considering local subsidies, is 1.3 times higher than the expected future tariff of 0.37 $/kWh. However, with the gradual removal of government subsidies and the decrease in technology costs, for example the fall in solar PV capital cost of up to 57 % by 2025, the optimized future system will become more cost attractive and competitive to the utility-scale. This will significantly impact the electricity tariff in the future, making the mini-grids more affordable for rural communities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Description and reason for selection of the study area

Mavumira village, the target area for this research, is located in the administrative post of Estaquinha, Chissinguana locality, district of Buzi in Sofala Province. The geographic location of Chissinguana is presented in Fig. A.1. According to the census of 2017, the population of Sofala Province has grown significantly over the last decades, from 1,289,390 in 1997 to 1,642,920 in 2007 and to 2,221,803 in 2017 (Instituto Nacional de Estatistica, 2010). By 2017, Mavumira village had 1700 inhabitants out of 23,867 inhabitants of Chissinguana locality. The size of the household is considered between six to eight family members. The village is located 285 km away from Beira (provincial capital of Sofala), 85 km from the Buzi district headquarters, and approximately 35 km from the main grid. According to (Suri, 2020), a village should be located 10–15 km away from the substation to avoid frequent voltage fluctuations. Mavumira village is connected through poor road infrastructures with the potential to become disconnected during the extended rainy season. The climate is characterized by rainy and dry seasons.

Mavumira has limited access to electricity. It is sparsely populated, therefore making grid extension economically less attractive. Hence, a hybrid renewable system could be an option to satisfy the village's load demand. Overall, in the Buzi district, there are two mini-grids installed, which are owned and operated by Energy Fund (FUNAE) in the locality of Inhamuchido and Chissinguana, with capacities of 6 kW and 30 kW, respectively, as depicted in Fig. A.1. A 30 kW solar PV mini-grid with batteries storage devices, which partially provides electricity to Mavumira village, is the only sustainable electricity source and has been operational since February 2019.

Mavumira village was chosen as the case study for the following reasons. First, based on its operational experience, the existing 30 kW solar PV mini-grid provides good insights into the main barriers and success factors that could help analyze the main aspects affecting the sustainability of the project. Second, its remote location (35 km away from the main grid) makes it less feasible and economical to extend the grid. Third, RE resources are available. Fourth, the Mavumira mini-grid is one of the first mini-grids implemented in Mozambique, making it a good representative sample among the mini-grids with similar characteristics installed in the country. Fifth, the results from this can be used as a benchmark to address best strategies to improve the performance of the systems in the future and could help decision-makers and designers in selecting the appropriate technologies to meet the electricity demand at the lowest net present cost (NPC), considering that Mavumira has a similar load profile to many other villages in Mozambique. Moreover, we realized that access to electricity brought rapid development to the village, which resulted in an increased energy demand to which the existing system could not respond.

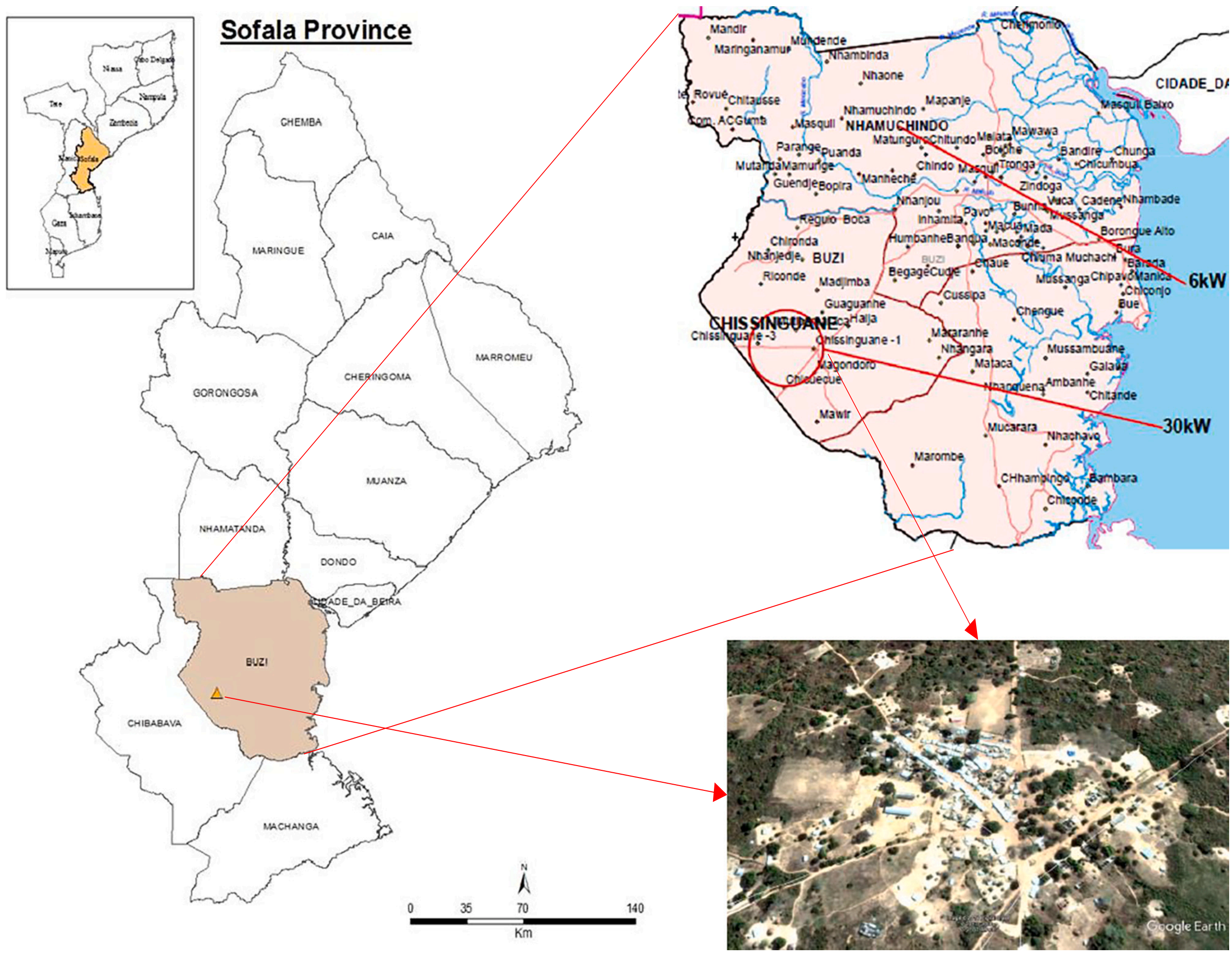

Fig. A.1. Geographical location of the study area (Mavumira village).

Appendix B. Interview protocol

This Appendix presents the questionnaire used for data collection in Mavumira village. The questionnaire is divided into six categories grouped under the social, economic, technical, and institutional sustainability dimensions. The first category was related to the respondent's general information, including their name and position. The second category addressed questions to investigate the village electrical load profile taking into account the total households in the village and the number of beneficiaries from the existing system. Third, under the social dimension, we investigated community involvement by addressing questions related to existing community organization and their level of participation in the project to ensure the O&M of the system. Fourth, under the economic dimension, we analyzed the village's economic development after the arrival of the mini-grid by addressing questions related to the creation of income-generating activities, existing payment methods, and the willingness to pay for electricity to ensure the financial viability of the project over its lifetime. Fifth, under the technical dimension, we investigated aspects such as the reliability of the energy supply considering the frequency and duration of outages to ensure the project's technical feasibility over its lifetime. Last, under the institutional dimension, we investigated the role of the local governance in managing the system without external intervention or support. It should be noted that the information regarding tariffs, willingness to pay, system operation, and maintenance was obtained by conducting interviews with people from FUNAE (at the provincial level), two appointed local revenue collectors (at the local level), local authorities, and the beneficiaries of the electricity. This information was used for the impact assessment of the mini-grid through selected indicators (Selection of indicators section). In addition, information related to specific load profiles was obtained during the visits to the installed system and analyzed using HOMER software (HOMER Pro software method section) to evaluate the techno-economic performance of the proposed system.

Table B.1
Questionnaire.

Type of impact	Interview protocol
1. General information of the respondent	
Name of the respondent, contact, and position	
Size of population	
Number of households	

(continued on next page)

Table B.1 (*continued*)

Type of impact	Interview protocol
Average number of family members per household	
How long have they been connected to the electricity from the mini-grid?	
Which electricity was available before the implementation of this project?	
2. Village electrical load	
Current capacity installed and number of beneficiaries	
Total number of households in the village	
3. Social dimension	
Community involvement	How is the community organized? Is there any Village Energy Committee or community cooperatives?
	Are the community members involved from an initial stage, including in the decision-making process of the project development? If yes, when? How?
	Are the community members designated for the O&M of the system?
Education	To what extent does electricity impact the education services in the village?
Health	To what extent does the electricity impact the health services in the village?
Safety and communication	To what extent does electricity impact the safety of the village?
Job opportunities	How many community members are directly employed in the project (from the construction until the operation stage)?
4. Economic dimension	
Economic activities	What are the sources of income/productive activities in the village (before and after the arrival of the mini-grid)?
Tariff applied (satisfaction with tariff)	Is the tariff official/approved by the government?
	Who sets the tariff?
	Which type of meters (pre-paid or post-paid) is applied in the project?
	How much do the users pay for electricity?
	Is there any tariff differentiation depending on the type of consumption (residential, commercial, or public), or is it a flat rate?
	Are the community members satisfied with the tariff applied?
Willingness to pay and expenditure	Are the consumers willing to pay for electricity? Is there any difficulty in revenue collection?
Revenue	Who collects the revenue?
	How often is the revenue collected?
	What is the revenue collected used for?
Money-saving	How much does the community save by replacing diesel and kerosene after the arrival of the mini-grid?
5. Technical dimension	
Reliability of power supply	Is the system delivering the planned output? If not, why?
	How many hours per day/month did the system register outages?
	Is there any equipment that has already been replaced in the system? Why?
Local skills	Are there local people with the skills to operate and maintain the system?
	Are the community members benefiting from any training? When?
6. Institutional	
Local governance	Is the local government involved in the project, including the decision-making process?
	Is the local governance organized to manage the system without external support?

Appendix C. Village electrical load profile and resource availability

C.1. Village electrical load profile

The load profile is important to estimate a village's present and future load demand for the optimal design of the system (Suri, 2020; Bahramara et al., 2016b). The electrical load was calculated, taking into account that the village has 340 households (residential and small shops), including one school, one health center, and one administrative office. The total installed capacity of 130 kWh/day supplies 63 households, which results in 2.063 kWh/day for each household, including one school, one health center, one administrative office, forty-one (41) small shops, nineteen (19) residences, and one carpentry business. The system also supplies electricity to ten (10) streetlights. The peak load was estimated at 52.95 kW and the scaled annual average at 571.5 kWh/day consumption of the houses, along with a load factor of 0.45. The peak load and scaled annual average consumption of the houses were estimated based on the remaining 277 households (residential and small shops) without access to electricity. Random variability (day-to-day of 10 % and time-step inputs of 20 %), were added to the load profile to make it more realistic. However, for the purpose of this study, we considered an increase of 60 % (20 % interval) in the load demand, which corresponds to the peak load that was estimated as 84.72 kW and the scaled annual average of 914.4 kWh/day over today's load demand.

Considering that the majority of the population rely on agriculture and trade as their principal source of income, during the day, most of the community members are not at home, and electric appliances are turned off. Thus, the maximum demand is observed at night (between 18:00 and 21:00) and in the morning (between 05:00 and 07:00).

Mavumira village has a total of 340 households out of the existing 5101 in Chissinguana locality, which means that the remaining 5038 households in Chissinguana (277 in Mavumira village) do not have access to any form of electricity. The small shops are either coupled to the households or have the same load as the residential load and do not have appliances that consume large quantities of electricity. For this reason, we considered the same load characteristics for the analysis. In the village, the primary energy demand comes from the residential, commercial (small shops), and community load (health center, school, administrative office, and streetlights). In general, the village demands electricity for lighting, refrigerators, and communication sets. The electrical appliances used in the village were estimated at 5 W (mobile phones), 90 kW (TV sets), 60 kW (radio), and 100 W (refrigerators) for domestic, commercial, and community purposes. However, commercial (small shops) and residential households represent a large number of electricity consumers, with 41 and 19 connections, respectively.

C.2. Resource availability

The availability of RE resources is important aspect in selecting the system's components (Mahesh & Sandhu, 2015). For this study, wind, solar PV, and diesel fuel resources were considered. The solar and wind resources data were taken from the National Aeronautics and Space Administration

(NASA) surface meteorology, while diesel fuel price was obtained locally. While resource data for Mavumira village specifically were not available, NASA does provide the resource data for Buzi District, where the village is located, and these data were considered in this study. The climate is characterized by the rainy season from October to April (being January and February the most critical) and the frequent droughts (Salazar-Espinoza et al., 2015).

C.2.1. Solar radiation

The Monthly Average Global Horizontal Irradiance (GHI) of the Buzi district for a period of 22 years (July 1983–June 2005) was downloaded from NASA surface meteorology using HOMER Pro software. As shown in Fig. C1, the site presents great solar energy potential, with the scaled average solar radiation of 5.31 kWh/m^2/day, owing to its geographic location. Solar radiation is expected to be high every month, except in June and July. The maximum solar radiance is approximately 6.15 kWh/m^2/day in December, and the minimum is 4.00 kWh/m^2/day in June. The clearness index can also be used to define the solar resource. Under clear sunny conditions, the clearness index has a high value and low value under cloudy conditions. The average temperature is about 26 °C.

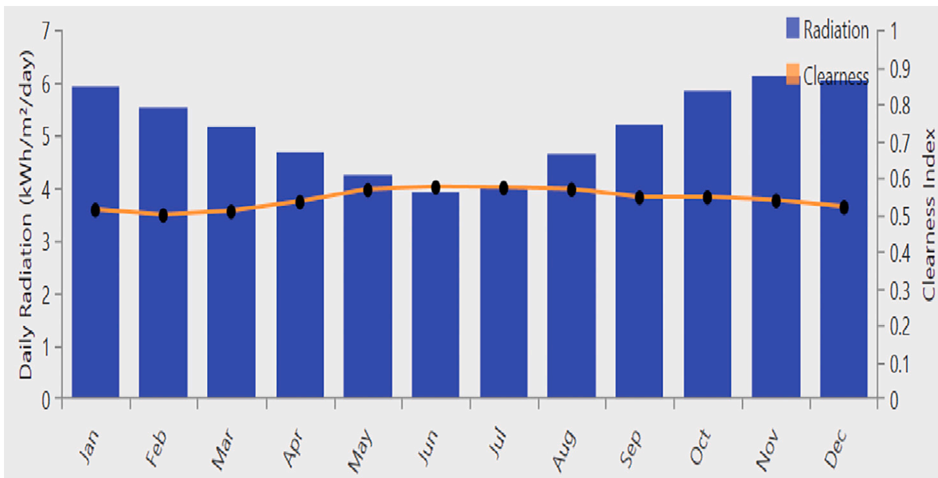

Fig. C1. Global solar irradiance and clearness index (Monthly average).

C.2.2. Wind resources

Wind energy is another component of the hybrid system. An annual average wind speed of 5.8 m/s is needed for large-scale wind turbines while for small-scale wind turbines it is necessary at least 4 m/s (Farret & Simões, 2006). For this study, the wind potential for the Buzi district was downloaded from NASA provided by HOMER Pro software for a period of ten years (July 1983 to June 1993). The monthly average wind speed is presented in both tabular and graphic forms in Fig. C2. The annual average is 4.74 m/s, varying between 4.09 m/s (the lower) in May and June to 5.84 m/s (the higher) in October.

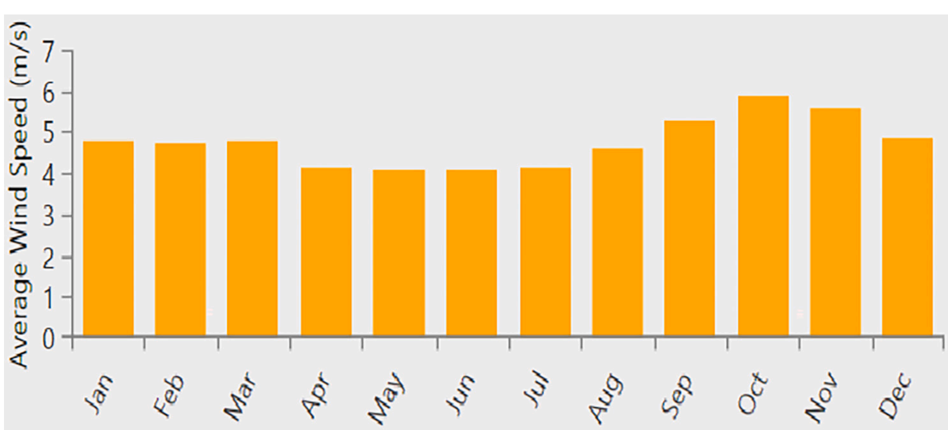

Fig. C2. Wind speed (monthly average).

Appendix D. Data and assumptions for HOMER pro calculations

D.1. System's components

D.1.1. Solar PV panels

In this study, a generic flat-plate PV was selected from the HOMER Pro software components library. For the analysis, the solar PV power output was considered ranging from 0 to 400 kW at 100 kW intervals (zero is included in case the system is simulated without solar PV). A derating factor of 80 % was considered for each panel, and 25 years of project lifetime, which corresponds to the lifetime of the PV module. HOMER calculates the power output of the solar PV array using Eq. (D.1.1).

$$P_{PV} = Y_{PV} f_{pv} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_C - T_{C,STC} \right) \right] \tag{D.1.1}$$

where: Y_{PV} is the rated capacity of the PV array in [kW], $\overline{G}_T$ is the solar radiation incident in [kW/m^2], f_{PV} is the PV derating factor [%], $\overline{G}_{T,STC}$ is the incident radiation [1 kW/m^2], α_P is the temperature coefficient [%/°C], $T_{C,\ STC}$ is the PV cell temperature [25 °C], and T_C is the PV cell temperature [°C]. If the effect of temperature is neglected, HOMER assumes the temperature coefficient of power equal to zero, resulting in a simplified Eq. (D.1.2) (Suite & Co, 2016).

$$P_{PV} = Y_{PV} f_{pv} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \tag{D.1.2}$$

D.1.2. Wind resources

From the HOMER Pro database, a generic 10 kW (G10) wind turbine system, with 24 m and a lifetime of 20 years, was selected and added to the hybrid system. The wind turbine is connected to the AC bus, as presented in Fig. 3.

D.1.3. Diesel generators

The dispatchable diesel generator is incorporated into the system as a backup to ensure a continuous power supply during the intermittent RE resources period. However, diesel generators consumes fuel to produce electricity. It is important to ensure a continued supply because diesel generators can balance the intermittent and variability of the power output of solar PV alone. In hybrid systems, diesel generators' capacity depends on the load demand and varies from 5 kW to 100 kW. Capacities up to 5 kW rely on gasoline, while larger sizes use diesel (Asian Development Bank, 2017) and are more efficient than the ones that use gasoline. Its lifetime is more prolonged (usually 6–10 years). In this study, generators that use diesel were considered. However, diesel price highly influences the operation of diesel generators, and it has slight variations according to the locations, transportation costs, market price, and subsidies applicable in each country (Givler & Lilienthal, 2005). The diesel price is relatively high in remote areas than urban areas due to fuel transportation costs. For example, the cost of diesel varies from 62.5 MZN/L in Beira, Sofala Capital City, located 285 km from Mavumira village, to 65.28 MZN/L at the nearest petrol station located 55 km from Mavumira village. There is no petrol station in Mavumira village. These values, when converted into US dollars per liter, would be approximately 1.00 $/L and 1.05 $/L (1USD = 62.20 MZN as of August 2019), respectively. In this study, the generic 59 kW diesel generator was considered for the optimal configuration of the system.

D.1.4. Battery

The battery is an important component of the system. It is used as a storage device to store the excess electricity generated in the solar PV. It can be used to satisfy the load demand during periods when solar or wind energy is not supplying enough power. In this study, a generic 12 V lead-acid battery with 1 kWh of energy storage was chosen. The lead-acid battery was selected for this study due to its reliability and cost effectiveness (Das & Zaman, 2019; IRENA, 2012). Each battery's lifetime is considered to be 10 years, 800 kWh of throughput, and a roundtrip efficiency of 80 %. For the analysis, different numbers of batteries were found, and the sizes vary from 0 to 1200 units (in 200 intervals). HOMER assumes that the battery properties remain constant over its lifetime without being affected by external factors like temperature (Farret & Simões, 2006).

D.1.5. Converter

A generic system converter was considered in this study that contains both AC and DC elements. Its efficiency is considered to be 95 %, and its lifetime is up to 15 years. As the converter converts DC produced by the solar panels into AC, the efficiency of the converter should drive the efficiency of solar panels. The size of the converter was calculated using the HOMER optimizer.

D.2. Cost of the system's components

To date, the literature has shown that the costs of the system's component assumed for different countries are varied. For example, the capital cost of a generic wind turbine of 10 kW was taken as $20,000 for a study realized in Kenya (Ghaem et al., 2015), 45,000 for a study conducted in Ethiopia (Bekele & Palm, 2010), and 25,000 for a study realized in Sri Lanka (Kolhe et al., 2020), while HOMER Pro software considers the capital cost of a generic wind turbine (10 kW) as $50,000. For the present study, the costs were estimated based on the costs of the components and services available in the HOMER Pro cost library, except for the wind turbine, which we applied the costs proposed in (Ghaem et al., 2015) in Kenya. We found these costs more realistic for Mozambique based on comparing costs used in (Bekele & Palm, 2010; Kolhe et al., 2020) for Ethiopia and Sri Lanka, respectively. A summary of the estimated capital cost ($), O&M cost ($/year), and the system components' replacement cost ($), inserted into HOMER Pro software, are presented in Table 1. It does not matter what value is entered for the replacement cost since the solar PV lifetime is the same as the project lifetime. For the diesel generator, HOMER calculates the fuel costs separately from other costs.

Table D2
Cost of the system's components used as input for HOMER simulations. Taken from (Ghaem et al., 2015) and HOMER cost library.

Components	Capital ($/kW)	Replacement ($/kW)	O&M ($/kW)/yr.	Lifetime (yr.)
Solar PV	2500	0	10	25
Wind	20,000	15,000	200	20
Diesel	500	500	0.03	15,000 h

(*continued on next page*)

Table D2 (*continued*)

Components	Capital ($/kW)	Replacement ($/kW)	O&M ($/kW)/yr.	Lifetime (yr.)
Battery	300	300	10	10
Converter	300	300	0.0	15

D.3. Economic evaluation for hybrid systems

Homer Pro was used to perform the economic evaluation of the optimized system, considering today's load and the increased future load demand (60 %). The costs from the optimized system were compared to the current tariff applied to the existing mini-grid (Mavumira village) to analyze the economic viability of the project. HOMER uses the total NPC as the main economic output to assess the feasibility of different system options within the same load profile. However, as mentioned early, the LCOE were used for the economic appraisal of the Mavumira project. The LCOE is affected by various factors like the economies of scale contributing to the decrease in the cost owing to the high automation in the production of technology. However, it does not consider important aspects affecting the viability of the project, like local subsidies and variation in demand (Zebra et al., 2021).

D.4. Parameters used for economic evaluation of hybrid system

D.4.1. Net present cost

The NPC is calculated considering the capital costs, O&M costs, replacement costs, fuel costs, including the cost of any penalties on emissions, for each system component, using Eq. (D.4.1) (Bahramara et al., 2016a; Lambert et al., 2006; Krish, 2018; Salisu et al., 2019).

$$NPC = \frac{C_{ann,tot}}{CFR\left(i, R_{proj}\right)} \tag{D.4.1}$$

where C_{NPC} represent the total NPC ($); $C_{ann,tot}$ is the total annualized cost in $/year; I represents the Interest rate (%); R_{proj} is the project lifetime (years), and CRF is the capital recovery factor, given by Eq. (D.4.1).

$$CRF_{i,N} = \frac{i\,(1+i)^N}{(1+i)^N - 1} \tag{D.4.2}$$

where *i* represents the annual real interest rate, and N represents the number of years.

D.4.2. Levelized cost of electricity

The cost of energy, or LCOE is important to guide investors for the projects (Agyekum & Nutakor, 2020b). HOMER defines the LCOE as the average cost per kWh of useful energy produced by the system. The LCOE is calculated by dividing the annualized cost of electricity by the total load (electric load) served, considering input parameters like capital costs, O&M cost, incentives, fuel costs, discount rate, and project lifetime. It is calculated using Eq. (D.4.3) (Rad et al., 2020). For our analysis, a discount rate of 8 % and a project lifetime of 25 years were considered.

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{D.4.3}$$

where $C_{ann,tot}$ represents the total annualized cost in $/year and $E_{served,}$ is the primary load served in kWh/year.

The total annualized cost represents the annual cost of the project in ($/year), and is expressed as:

$$C_{ann,tot} = C_{capann} + C_{repann} + C_{O\&Mann} \tag{D.4.4}$$

where:

C_{capann} represents the capital cost, C_{repann} represents the replacement cost, and $C_{O\&Mann}$ represents the O&M (Micangeli et al., 2017).

D.5. Sensitivity parameters

In this study, the sensitivity analysis was performed by varying the solar radiation (solar scaled average), wind speed (wind scaled average), solar PV capital cost multiplier, battery capital cost multiplier, the scaled annual average (expected demand growth), and the diesel fuel price as the sensitivity parameters to examine their effects on the costs. For wind speed, solar radiation, and diesel fuel price, three different values were selected for the analysis, including the maximum and minimum values for solar radiation (4 kWh/m^2/day and 6.15 kWh/m^2/day) and wind speed (4.09 m/s and 5.84 m/s) provided by NASA in the HOMER software database. The diesel fuel price applied in Sofala Province during the period in which we conducted the study was approximately 1.00 $/L. Even though diesel price highly influences the costs of the system, we did not consider high variations for diesel fuel price (1.00 $/L to 1.4 $/L) as it decreases or increases depending on parameters such as fuel price fluctuations, government subsidies, and also exchange rates in force.[1] For example, in Mozambique, the government subsidizes the diesel fuel price, making it more affordable for the communities. However, the subsidies are gradually being removed (Mokveld & von Eije, 2018). Additionally, after the arrival of the mini-grid, the Mavumira village experienced a significant influx of people from neighboring villages looking for better living conditions, which resulted in increased demand. Thus, we investigated the future implications of the demand growth for the system performance, by scaling up the load demand up to 60 % (914.4 kWh/day) over the actual load. Contrary to the load demand increases with the arrival of electricity in the village, solar PV and battery capital costs have fallen due to technological advancements. Based on the IRENA reports (IRENA, 2016a; IRENA, 2016b), the costs of renewable technologies, especially solar and wind, are declining and will continue to decrease up to 2035 and beyond, making renewables more attractive. For example, the solar PV capital cost will continue to fall by up to 57 % by 2025 over the year 2015. Moreover, a study by (Mongird et al., 2020) indicated that the lead-acid battery capital cost is expected to fall by 15 % by 2025. Therefore, we assumed a decrease in solar PV capital cost by up to 60 % and battery capital cost by 15 % over the baseline cost and investigated the cost effect on the system performance.

D.6. Operation strategy

Dispatch strategy was considered for the assessment as it significantly influences the results of the hybrid system configuration. It is a group of rules applied to control the storage and generator whenever RE is insufficient to feed the corresponding load. HOMER Pro can model several dispatch strategies, like cycle charging (CC), load following (LF), and combined dispatch, to control the generator and energy storage operation. The LF strategy is the most recommended in the literature as it helps to reduce the total NPC of the system, followed by the CC strategy (Halabi & Mekhilef, 2018; Ngan & Tan, 2012; Halabi et al., 2017; Das et al., 2021). In the CC dispatch strategy, the generator produces excess power that can be used to feed the load and charge the batteries. Thus, the cost associated with charging the battery bank is not zero. Alternatively, in the LF dispatch strategy, the excess electricity from renewable power sources is used to charge the batteries. This way, the generators are used to produce power to meet the primary load only. Hence, the cost related with the battery bank charging is always zero (Das & Zaman, 2019; Farret & Simões, 2006; Aziz et al., 2019).

The hybrid solar PV/diesel/battery system is presented in Fig. 3. It is assumed that only RE sources will charge the batteries owing to the high penetration of solar sources in the village (see Appendix C). In this case, the simulations were performed under the LF dispatch strategy. This strategy considers the power generated from RE (solar PV and wind turbines) sufficient to meet the load demand. Therefore, the diesel generators will only serve the required load in the absence of RE sources and battery power. The purpose of selecting the LF is to maximize the use of renewable resources and reduce the diesel generators' operating hours, which will result in the use of a minimal amount of diesel fuel in the system (Maatallah et al., 2016b). As previously mentioned, we expect Mavumira village load demand to increase by up to 60 %. Simultaneously, there are clear indications that the capital cost of solar PV and batteries will decrease. This will allow the system to increase the number of batteries and integrate more renewables, thus reducing diesel fuel consumption and making it more sustainable.

Appendix E. Map of solar and wind potential for Sofala Province

These maps are extracted from the RE Atlas of Mozambique (Gesto Energy, 2014). As visible on the maps, specifically in the study area location (Sofala province), wind potential is limited, especially for wind speeds below 4 m/s compared to solar PV potential.

Appendix F. Results from the interviews

The results of the sustainability impact assessment, based on data collected during the interviews in the study area (Mavumira), are presented in this Appendix. They are clustered in the following four main themes: social, economic, technical, and institutional sustainability dimensions, with their corresponding indicators.

F.1. Social dimension

Community involvement

The respondents were asked to express their opinion concerning their level of organization and involvement in the project, including the decision-making process, as presented in the questionnaire (Appendix A). Additionally, the questionnaire included questions about the community's ability to operate and maintain the system. According to the respondents (a representative from the local government and community members), community organization to oversee the project was not observed, and no meetings were scheduled. As a result, the community members did not influence the project's development, making it difficult to achieve the sense of community ownership and challenging to ensure the project's viability at the local level. However, the community members were informed of the project before the system's arrival. According to the respondent from FUNAE, the government of Mozambique has not yet established a clear ownership model for the mini-grids installed. However, he mentioned that community-based management would be less efficient, associated with their experience with the stand-alone systems previously implemented in many rural villages, where two local technicians were trained to maintain stand-alone systems. After some time, the technicians migrated to neighboring countries such as South Africa or large cities, looking for better living conditions.

[1] The price of diesel has increased considerably worldwide. According to the recent data (April 2022), the average global diesel fuel price is 1.29 $/L. However, there is a considerable difference in the prices between countries due to the local taxes and subsidies. For example, the lowest fuel price is observed in Iran (0.01 $/L), while the highest is observed in Sweden (2.638 $/L) (Global petrol prices, 2022). In Mozambique, from the period we visited the village, the diesel price registered a slight increase from 1.0 $/L (2019) to 1.1 $/L (2022). Additionally, the diesel price fluctuations will continue to be a challenge for the economy of many nations. Projections from (US Energy Information Administration, 2017) indicated that the retail price would range from 2.56 $/gallon (low case) to 7.02 $/gallon (high case) in 2050.

Education services

We assessed the social impact of the mini-grid by investigating how electricity has impacted the education services in the village, especially when looking into the increase in study hours and the possibility of night classes. Although the installed system had only six months of operation when we visited Mavumira village, we found some indications of the impact on students' performance. According to the respondents (teachers and students), the arrival of electricity has positively impacted education. It replaced the pollutant and non-efficient kerosene used by students for their activities after sunset and improved academic performance. In addition, the students have more hours to perform their school tasks during the night and hence more chances to improve their educational attainment. According to one of the teachers interviewed, the electricity will encourage night lectures, allowing more people to attend the schools, thus reducing the illiteracy rate in the village. Furthermore, access to electricity brought the need for other electrical appliances, for example computers, printers, and photocopiers, to be used by teachers, students, and administrative staff to improve administrative processes and securely archive information.

Health services

To investigate the impact of health on the local communities, the respondents were asked to explain how electricity impacts the health services in the village, looking at the following two main strands: reduction in kerosene use (in general) and better access to health services. According to the respondents from the health center, before the arrival of electricity, they used kerosene lamps and candles for childbirths, making this procedure difficult and risky. The mini-grid system has positively impacted the health services in the community. The deliveries have become safer, and the vaccine refrigeration system is appropriate to store the vaccines. Additionally, as reported by the respondents (owners of small shops and households), electricity replaced kerosene and candles, reducing the negative impact of these fuels on health. The benefits also included shortening the distance traveled by pregnant women in search of safe hospitals for their childbirths.

Job opportunities

This indicator was analyzed considering the direct job opportunities linked to the project during the operation stage, based on the information obtained during the interviews in the study area (Mavumira village). Unfortunately, it was impossible to get information about the number of people employed during the construction phase project. According to the results from the interview with FUNAE's provincial delegate and the representative from local governance, within the local community, only four local members were assigned to work during the operational stage of the project, of whom one person had to clean the system components (solar panels, batteries, inverters, and other accessories) and two local young people were appointed to collect the monthly revenue in collaboration with the representative of the local governance.

Safety and communication

The respondents were asked to explain how the arrival of the mini-grid in the village had improved the living conditions in terms of enhanced security and safety, including access to information. According to the community members, the streetlights have improved safety in the village, allowing people, especially women, to walk in the streets during the evenings. The system also brought benefits concerning facilitating communication. It has improved access to information by providing electricity to power radios, televisions, and mobile phones, enabling communication with people inside and outside the village. However, the community members indicated that the mobile phones were already used before the mini-grid, powered by individual small solar PV systems. Some community members reported paying each time they charged their cell phone in the neighborhoods or shops.

F.2. Economic dimension

Economic activities

One of the questions addressed to the respondents was to express their impression of the village's productive activities to get an overview of the economic development before and after the mini-grid implementation. According to the representative from local governance, the majority of the village population is low-income and relies on agriculture, trade, and breeding of goats, cattle, and birds as their main source of income. However, according to the local authorities and owners of small shops, the arrival of the PV mini-grid had a significant impact on the village's economic development as it has increased income generation activities. This is noticeable from the increased number of small shops spread throughout the village, a rise in the number of trade activities in agriculture, commercialization of basic products bought from nearby cities (Beira, Muchungue, and Chimoio), as well as carpentry. Additionally, the owners of small shops reported that the access to electricity had improved the business due to the presence of customers at night, extending their working hours into the evening.

Satisfaction with tariff applied

According to respondents (revenue collectors and FUNAE's representative), despite the village being far from the national grid, the existing mini-grid applies the same domestic tariff that has been set by the vertically integrated, government-owned electricity utility company (Electricity of Mozambique) since the mini-grids consumers pay the same tariff as the grid-connected domestic consumers of 0.12 $/kWh for pre-paid services. The community members considered the tariff high, taking into account their economic activities and development compared to the large cities. However, consumers pay according to their consumption. There is no tariff differentiation between the residential, commercial, and public infrastructures, which means that low-income consumers (residential) pay the same tariff as the high-income users (commercial). As previously mentioned, there is a high disparity in the amount paid, as commercial properties consume more electricity than residential ones. For example, according to the information collected during the interview with the revenue collector, in April 2019, an owner of a small shop paid the highest tariff of 1709 MZN ($27.48) compared to the lowest amount of 6 MZN ($0.10) paid by the owners of some small residences.

Willingness to pay and expenditure

The respondents were asked questions about their capability to pay for electricity services considering their income and electricity usage for different purposes. According to the respondents (owners of small shops), the access to electricity boosted the village's economic development and allowed the communities to increase their business activities; consequently, their income and capacity to pay for electricity also improved. However, the revenue collector explained that the tariff is paid based on the user's consumption in a pre-paid metering system by purchasing a code based on the amount paid according to their purchasing capacity and consumer needs. This method is efficient as it allows the users to control their consumption, facilitates the collection, and avoids difficulties with regular payments compared to a monthly post-paid way. As previously mentioned, the customers complained about the high tariff applied by FUNAE. However, despite the high cost of electricity, they are willing to pay, considering the economic activities developed in the village, combined with the desire to have electricity at home. Apart from its positive impact on income generation activities, the existing mini-grid also affects people's expenditures. The respondents reported spending part of the money allocated for food to pay for electricity.

Revenue

During the interview with the revenue collectors and the representative from local governance, we asked how the revenue is collected, specifically the frequency and purpose of the revenue collected. As mentioned previously, the revenue is collected by two appointed people in collaboration with a representative from the local governance through a pre-paid metering method. The respondents explained that from the revenue collected, 25 % is used to pay the three employees as an incentive, and the other 75 % is sent to FUNAE's bank account, which is used for O&M and replacement purposes. The local government representative is responsible for depositing the collections at FUNAE's bank account, since he has to travel long distances to the bank. Therefore, no funds are left in the village for maintenance purposes, making it difficult for rapid response to the issues.

Money savings

Respondents were asked to express if they had saved money after the arrival of the mini-grid. As previously mentioned, Mavumira village is highly dependent on diesel generators and kerosene as its primary source of electricity. However, with the arrival of mini-grids, the community members have become less dependent on these pollutant sources. In particular, the owners of the small shops stated that they were more dependent on diesel generators to run their businesses, which was very expensive because they had to travel long distances to the nearby petrol station (located 55 km from Mavumira) to buy fuel. As a consequence, they save money and time spent on diesel transportation. Additionally, the money paid for traveling long distances in search of better health conditions has reduced as a result of electricity in the village.

F.3. Technical dimension

Reliability of power supply

The reliability of the power supply was assessed based on the information collected during the interviews conducted with FUNAE's provincial delegate, the revenue collectors, and a representative from local governance. According to the respondent from FUNAE's provincial delegation, the system registered two months of breakdown for the following two possible reasons: the cyclone Idai that affected the Sofala Province in March 2019 (Herreras Martínez et al., 2013) and system overload. He pointed out that the beneficiaries connected more and inadequate electrical appliances than expected, which caused the system's overload. He also mentioned that there were milling machines initially connected to the mini-grid, but they were disconnected because the system did not respond positively, which resulted in frequent failures. As stated by the revenue collectors and the local authorities, the breakdown in the system took approximately two months to be solved because there were no local people technically skilled in repairing the system. Therefore, they have to wait until FUNAE sends someone to the village to repair the system.

Local skills

To assess the availability of local skills, the respondents were asked about the community's ability to operate and maintain the system, which is important for rapid response to the issues to avoid failures and long periods of breakdown in the system's operation. As previously mentioned, four community members with a low level of education and no technical skills for system management have been appointed to collect the revenue and clean the equipment. The system is currently managed by FUNAE's staff located a long distance from the village. According to the respondents (revenue collector and the representative from local governance), none of the community members benefited from training to operate and maintain the system. Further, there is no skilled technical person within a reasonable distance, which hinders the rapid response in case of breakdowns in the system.

F.4. Institutional dimension

Effective local governance

An interviews was conducted with the representative from local governance to understand how the local government is involved are organized to manage the project and if there is external support for that purpose. According to the respondent, the local government is not in a position to take over the management of the system or respond to technical and financial related to the system's operation. FUNAE, as the owner and manager of the system, addresses operational issues to keep the project going. Additionally, there were no regular meetings, and the local community did not benefit from training to operate and maintain the system. However, the local governance was contacted about the project's arrival and worked together with FUNAE to identify the beneficiaries of electricity. They also assisted FUNAE to appoint the community members assigned for the revenue collection and cleaning of the equipment.

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