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The Integration of Economic, Environmental, and Social Aspects by Developing and Demonstrating an Analytical Framework That Combines Methods and Indicators Using Mavumira Village as a Case Study

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Abstract: Access to electricity is a crucial factor in boosting the economic, environmental, and social development of developing nations. This study presents a framework that combines and integrates indicators and methods to determine the most sustainable solution for off-grid electrification, focusing on the Mavumira village in Mozambique. The framework covers various methods including input–output, life cycle assessment based on SimaPro, and HOMER. Data for the analysis were obtained from the literature, the HOMER database, and the ecoinvent database. Our results show that renewables are the most sustainable solutions compared to diesel-only options as they can lower the cost of electricity by 20%, create approximately 26 more local jobs, reduce about 77% of greenhouse gas emissions caused by burning fossil fuels, and have higher values of HDI than diesel-only options. Using the MCDA (TOPSIS method), we found that the future renewable scenario ranked highest with a closeness value of one, while the diesel-only option ranked third and fourth on a ranking scale from 1 to 4. This study concludes with future research directions for applying the framework to other case studies using different renewable technologies like wind, hydropower, and biomass in villages with similar characteristics to Mavumira. The novelty of this study lies in applying various methods and indicators to analyze the sustainability of an implemented project for the current and future scenarios. Additionally, the framework presented in this study would assist policymakers in selecting the best energy alternatives for rural electrification.

Keywords: framework; sustainability; indicators; economic; environmental; social; integrated assessment; multi-criteria decision-making

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1. Introduction

The electricity sector plays a significant role in contributing to the environmentally, socially, and economically sustainable development of many nations. However, the unaffordability and unreliability of electricity sources and supply constitute some of the major hindrances to rural communities' development, especially those located remotely from the existing main electricity grid. These challenges are directly applicable to developing countries like Mozambique, where electricity generation in rural areas is highly dependent on conventional alternatives like diesel generators (DGs). The increasing global oil prices and greenhouse gas (GHG) emissions, particularly CO_2 and other air pollutants from burning diesel, render these systems socially, economically, and environmentally unattractive [1,2]. This has led to advancements in renewable energy technologies, including hybrid renewable energy systems (HRESs) that have proven to be a reliable, sustainable, and economical source of electricity as they can significantly reduce the GHG impact and high costs of using diesel alone. In the literature, the sustainability of renewable energy (RE) off-grid services has been commonly evaluated using the following three dimensions: social, economic, and environmental. Some studies also include technical and institutional dimensions to determine the local impact of the projects, as they help to assess the operation and management issues of projects [3–6].

Economic and social aspects include ensuring the human well-being of communities by providing reliable, safe, and fair living conditions, the economic viability/profitability of the project, and environmental aspects, including the impact of the project on human health and ecosystems.

In our previous study [7], which focused on a review of HRESs for off-grid electrification, we analyzed the main factors contributing to the success and failure of these systems in various developing regions. From this analysis, we developed a framework indicating the key prerequisites that need to be considered for the success of these systems, including social, economic, and technical aspects. More specifically, our framework outlines the importance of involving the local communities from the initial stage of project development, revenue collection to ensure the social and economic viability of the project at the local level, and the application of different methods for sizing the system. In a subsequent study [6], we applied this framework to evaluate a concrete mini-grid project in Mavumira village, Mozambique, by looking into the techno-economic performance of the mini-grid based on the application of HOMER pro software. The software was used to model the HRES lifetime cost per kWh with component and installation site-specific parameters. Additionally, we evaluated the project's social, economic, institutional, and technical sustainability based on the application of qualitative indicators to address future improvements to the system's performance. We found that in the future, the optimized system will be cost-effective and bring social and economic benefits regarding the future sustainability of the project, like a potential reduction in the tariff applied, which implies fewer government subsidies than today's case, increased economic activities, and improvements in education and health services. An overview of the positive (+) and negative (−) sustainability impacts of the mini-grid projects implemented in different developing countries [7], particularly in the Mavumira project [6], is given in Table 1.

Table 1. Summary of the sustainability impact of different projects *.

Impact	Remarks
Social sustainability	
Involvement of community members in the project development, including in the decision-making process	(−) Lack of community involvement is among the indicators that negatively influence the sustainability of the mini-grids in developing regions, including Mozambique, making it difficult to ensure the project's viability [6,7].
Improvements in education and health services	(+) According to [6,7], access to electricity positively affects education and health indicators as a result of the improvements in education (e.g., increased study hours) and health (e.g., safe childbirth) services.
Improvements in safety during the night because of electricity	(+) This indicator had a positive impact on the sustainability of the mini-grid projects as a result of the access to streetlights and safety in the villages [6,7].
Economic sustainability	
Increase in economic activities, income-generating activities, and increase in productive use linked to electricity	(+) Access to electricity brought new village economic activities, thus increasing the income of the local communities [6,7].
Satisfaction with tariff adopted	(−) In particular, our study [5] revealed dissatisfaction with the tariffs applied to the mini-grid as the rural communities pay the same tariff applied to the national grid for domestic consumers (there is no tariff differentiation).

Table 1. *Cont.*

Impact	**Remarks**
Willingness to pay for electricity services	(+) This indicator positively affected the sustainability of the Mavumira project despite the high tariffs applied by the government because the communities are willing to pay, owing to the desire to have electricity [6].
Management of the revenue collected	(+) A study [6] found that in some villages, the revenue collected is used for rapid response to the mini-grid issues. (−) The Mavumira case study [6] showed a negative sustainability impact as the collected revenue was not kept in the village, making it difficult in case of failures/outages in the system.
Money savings because of a reduction in diesel fuel consumption	(+) Rural communities are highly dependent on diesel. With the arrival of the mini-grid, they save money used on diesel fuel acquisition [6,7]
Technical sustainability	
Reliability of power supply by ensuring continuous operation of the system	(−) The Mavumira case study [6] illustrated that the reliability indicator scored low because the system registered a breakdown for a long period (two months).
Availability of local skills for rapid response to failures and outages	(−) In general, the lack of local skills to manage the systems is one of the aspects hindering the sustainability of the mini-grids in developing countries [6,7]
Institutional sustainability	
Effective local governance or their ability to respond to the technical and financial aspects	(−) The Mavumira case study [6] addressed the negative sustainability impact of this indicator as the local governance is not in a position to respond to technical and financial issues related to the mini-grid.

* A (+) indicates that the indicator had a positive impact while (−) indicates a negative impact.

In the previous studies [6,7], however, we did not take into account a quantitative assessment of the economic, environmental, and social indicators in an integrated way.

Experiences in integrating different indicators and methods to assess the economic, environmental, and social impact of energy projects have accumulated in recent years, particularly using multi-criteria decision analysis (MCDA) [8–12]. For example, the study by [13] applied MCDA to rank different energy alternatives and select the best electrification option of the Greek interconnected electricity system based on fifteen indicators. Under the equal weight approach, the findings of the study indicated that wind energy is the first most sustainable option followed by small hydro from the environmental and economic dimensions. Solar PV is ranked as the best option in terms of the social dimension. Finally, conventional lignite power plants are ranked the worst option due to their negative environmental impact. Additionally, the authors in [12] assessed the sustainability of the electricity sector in Turkey using twenty environmental, economic, and social indicators. The results found that hydropower is the best option as it presents fewer GHG emissions, the lowest cost of electricity, and high employment opportunities, followed by geothermal power, which is the second-best option in terms of the environmental impact despite its high capital cost and wind power. However, the use of indicators and methods in an integrated way has not been tested for a specific project in Mozambique.

In the present study, we applied a combination of different methods and indicators (detailed in Section 2.2) to quantitatively assess the sustainability of an implemented project in Mavumira village (Mozambique). Each selected method was assessed based on data from different sources like the literature, HOMER database, and Ecoinvent database V.3.7. Next, a multi-criteria decision-making (MCDM) method was used to rank the energy alternatives and select the most feasible solution for electricity supply based on the economic, environmental, and social indicators. Among the MCDA methods, the Analytic Hierarchy Process, Weighted Product Method, Elimination and Choice Translating Reality, Preference Ranking Organization Method for Enrichment of Evaluations, Multi-Criteria Optimization and Compromise Solution, Compromise Programming, Elimination et Choix Tradusiant la Realité, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) came out as the most used methods to rank the best energy solutions [14–16]. TOPSIS is a multi-criteria decision method applied to compare different alternatives to rank and identify the best option based on pre-specified criteria and attributes. The

TOPSIS method was selected for this study because it assesses the relative performance of each energy alternative in a simple mathematical form; is comprehensible; has good computational efficiency, rationality, and simplicity; and can handle an unlimited number of criteria and HRES alternatives compared to other aforementioned MCDM methods [17–19]. To determine attribute weights used in the TOPSIS method and to provide more robust results, we applied two different approaches: (i) the equal weight approach, and (ii) the weight attributed based on our opinion on the criteria's importance (allocated randomly).

Aim and Novelty of the Study

The main goal of the present study is to conduct an integrated economic, environmental, and social analysis by developing and demonstrating an analytical framework based on a combination of indicators and methods. We use Mavumira village as a case study to quantitatively determine the sustainability impact of a mini-grid. This study focuses on a comparison between the renewable options (solar PV/diesel/battery) and the diesel option (diesel-only), selected among different system configurations that have been analyzed through the HOMER tool to identify the more sustainable solutions to supply electricity to Mavumira village, considering the current scenario (today's load) and future scenario (increase in future load demand scenario of 60%, assuming that the existing system would boost the future load demand in the village). We focus again on Mavumira, a remote village located in the district of Buzi in Sofala Province, located in central Mozambique. From our previous study [6] we already know the situation of the village and the main challenges that may hinder the long-term functionality of the system. More detailed information on the study area, load profile, and resource availability, among others, are presented and described in our previous study [6].

This study seeks to address the following questions:

(1) What are the particular restrictions to evaluate the economic, environmental, and social indicators?
(2) Which economic, environmental, and social indicators and methods can be used to quantitatively measure the sustainability of the Mavumira project?
(3) How can the economic, environmental, and social aspects be integrated with each other to determine a sustainable solution for the future performance of a mini-grid, using Mavumira village as a case study?

In this study, we make valuable additions to the existing body of knowledge in the following manners: firstly, to assess the economic, environmental, and social impact of a concrete project using identified criteria and indicators; secondly, to use, for the first time, the HDI as a social indicator to establish a link with other variables such as the cost of power, project expenditures, employment, and local environmental consequences; and thirdly, to assess the use of different methods to monitor the economic, environmental, and social impacts of a rural electrification project for future system performance. Finally, this study aims to aid decision-makers and project developers in evaluating and choosing sustainable technology for off-grid rural electrification in specific locations, such as Mavumira village. This study recognizes the significant influence of economic, environmental, and social factors in shaping investment strategies in the energy sector. The article is structured as follows: Section 2 outlines the procedures employed to choose the indicators, including the methodologies used for each indicator and the sources of data. Section 3 presents the results and discussion. Section 4 presents the main conclusions and recommendations for further studies.

2. Materials and Methods

In this study, two scenarios (current and future) were analyzed and compared, considering a system that relies on renewable energy and a diesel-only option. The ***current scenario (today's case)*** corresponds to the optimized system based on the current village load demand of 571.5 kWh/day (peak load of 52.95 kW). In this scenario, we assessed the best techno-economic system that can meet the village's current load demand, based on parameters like the village load profile. These parameters were assessed through the load survey conducted in 2019 on the existing mini-grid system in the study area. The ***future scenario (future case)*** corresponds to the best future-optimized system based on an expected increase in future load demand of 914.4 kWh/day (mini-grid future peak load of 84.72 kW). In this scenario, we assessed the best system configuration that can meet the load demand in the future at the lowest cost of electricity. We assumed that the existing system would boost economic and social development, such as an influx of people from neighboring villages seeking better living conditions and an increase in income-generating activities, resulting in a growth of 60% in the village load demand. Sensitivity parameters like a future decrease of 15% on battery cost multipliers and 60% on solar PV capital cost multipliers were considered for the analysis (see our previous study [6] for more details).

The methodology used for this study is depicted in Figure 1. More specifically, the methodology employed to achieve the objective of this study encompassed the following steps:

Step 1: We conducted an extensive literature review [20–23] to select a set of indicators previously used to evaluate project sustainability in different regions, covering the economic, environmental, and social sustainability dimensions (more details in Section 2.1.1). Based on the results from the literature review, we compiled a list of indicators selected to assess their impact on the Mavumira project. The refined list of indicators (e.g., cost of electricity, project expenditures, employment, and global warming) was based on different criteria/principles including the availability of data and the quantification methods for the indicators (more details in Section 2.1.2). These indicators were used to evaluate the sustainability impact of the project at the local level.

Step 2: After selecting the indicators, we applied different methods (input–output [IO], HOMER, and LCA) to quantitatively assess the economic, environmental, and social impact of the Mavumira project for a deeper understanding of the aspects that affect the sustainability of the project to address further improvements of the mini-grid system. Under the economic dimension, we selected indicators that allow the evaluation of the project's profitability from the investors' viewpoint and the impact of the project on the national economy. To evaluate the contribution of the mini-grid to the social well-being of the local communities, we selected the human development index (HDI) as it incorporates education, health, and standard of living. We selected the indicator of profitability to be the cost of electricity (LCOE) as it is an important metric that allows a financial comparison between the cost of different components of the system and helps analyze the attractiveness of the project investment [24–27]. The LCOE indicator was estimated based on the HOMER pro and considered a discount rate of 8% and an inflation rate of 2% over the lifetime period of 25 years [6]. Various methods such as the Computable General Equilibrium (CGE), IO, and employment factor approach can be used for the project's economic evaluation linked to the local, national, and regional levels [28]. For this study, we employed both the employment factor approach to estimate the local, direct impact on employment for the Mavumira project and the IO method to assess the project's impact on the national economy. These methods allowed the quantification of direct and indirect economic impact, using indicators such as the effect on employment. To quantitatively evaluate the environmental indicators and compare which technology is a better choice in terms of sustainability impact throughout the life cycle of the system, we applied life cycle assessment (LCA), with the ecoinvent database. Life cycle assessment implies the evaluation of the environmental impact of products, processes, or services throughout all life stages of the technology and has become key for decision-makers and policymakers.

Step 3: A correlation analysis was performed to evaluate the extent to which the level of HDI, cost of electricity, project expenditures (inside and outside the village), direct and indirect jobs, and environmental impacts (CO_2 emissions and other emissions to air like particulate matter and photochemical ozone formation) can be achieved simultaneously. These elements were selected to provide a general approach to the village's social development after the mini-grid arrival.

Step 4: Finally, we applied the TOPSIS method to integrate and select the best sustainability option for the electrification of the Mavumira village based on selected economic, environmental, and social indicators (e.g., LCOE, jobs, CO_2 emissions, and HDI) for different scenarios (diesel-only and renewables).

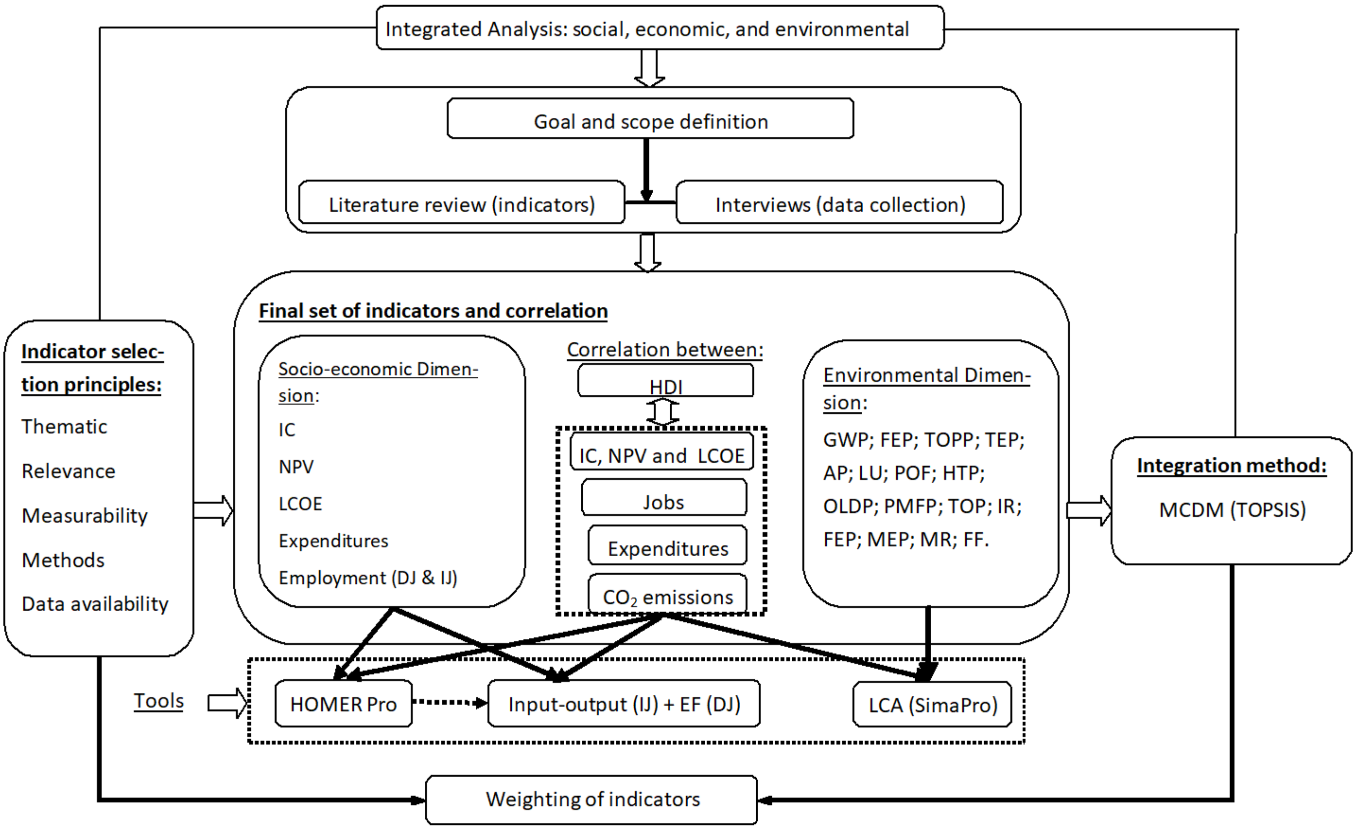


Figure 1. Flowchart depicting the methodology used in the present study. Note: Human development index (HDI); Employment factor (EF); Direct jobs (DJ); Indirect Jobs (IJ); Investment cost (IC); Net present value (NPV); Levelized cost of electricity (LCOE); Internal rate of return (IRR); Global warming potential (GWP); Freshwater eutrophication potential (FEP); Tropospheric Ozone Precursor Potential (TOPP); Terrestrial ecotoxicity potential (TEP); Acidification potential (AP); Land use (LU); Photochemical Ozone Formation (POF); Human toxicity potential (HTP); Ozone layer depletion potential (OLDP); Particulate matter formation potential (PMFP); Tropospheric ozone formation (TOF); Ionizing radiation (IR); Freshwater ecotoxicity potential (FEP); Marine ecotoxicity potential (MEP); Mineral Resources (MR); and Fossil fuels (FF); Multi-criteria decision-making (MCDM); Life cycle assessment (LCA).

2.1. Selection Criteria for Indicators

2.1.1. Literature Review

To guarantee a thorough compilation of pertinent material and find relevant articles for our literature review, we searched several academic databases, including Google Scholar, Scopus, and Web of Science. Search terms comprised a mix of phrases like sustainability, social, economic environmental impact assessment, and indicators. The indicators were collected from scientific articles and reports from various organizations particularly the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA). As shown in Appendix A, a total of 17 themes within the main dimensions were identified: 11 related to social, 3 to economic, and 3 to environmental. The social dimensions represented a larger number of themes compared to economic and environmental. However, most of the social themes were qualitatively analyzed. As a result, from the 17 themes, we identified 105 indicators considered important to measure the sustainability of rural electrification projects at the national or local level, including the unit of measurement for each indicator (see Appendix A). The indicators were selected from 36 different studies using different energy technologies, including solar PV, biomass, and nuclear energy. The identified indicators served as a starting point for further refinement to apply to the local context of the Mavumira project.

2.1.2. Refinement and Selection Criteria for Indicators

After our literature review, we refined a set of indicators within the economic, environmental, and social dimensions to provide a quantitative assessment of the Mavumira project. To facilitate the refinement of the indicators, the literature addressed guiding criteria/principles [20,29,30], which include the following:

(i) Thematic—The indicators are grouped into themes based on their sustainability approach. These themes are frequently mentioned in the literature (e.g., [21,31]) for the sustainability impact assessment of electricity projects grouped in different criteria.
(ii) Relevance—Relevant to evaluating the energy sustainability of the project.
(iii) Measurable—Measurability in quantitative terms.
(iv) Method—Application of a method for the indicator, if available.
(v) Impact level—National or local level.
(vi) Data availability—Availability of local data about the indicator or data sources from the literature.

It is worth noting that Appendix A presents a comprehensive list of indicators for measuring a project's sustainability (e.g., social conflicts and accident fatalities). However, not all indicators listed in Appendix A were considered in this study due to factors like the unavailability of data for quantitively evaluating their impact. Out of the 105 indicators collected, 22 indicators were selected for this study. Three economic indicators (cost of electricity, expenditures, and employment), and 18 environmental indicators, which include global warming potential (GWP), terrestrial ecotoxicity potential (TEP), terrestrial acidification potential (AP), marine ecotoxicity potential (MEP), eutrophication potential (EP), land use (LU), water use, marine eutrophication, freshwater ecotoxicity, terrestrial ecotoxicity, mineral resources, fossil resources including the indicators with local impact on human health, ozone layer depletion potential (OLDP), particularly human toxicity potential (HTP), particulate matter formation potential (PMFP), tropospheric ozone formation potential (TOFP), and ionizing radiation potentials (IRP), and one social (HDI) were considered to analyze the sustainability of the project.

The selected indicators have been previously used to analyze the impact of energy projects [32–35]. In general, the indicators were selected for the following reasons:

(i) Their ability to perform a quantitative assessment, which will help measure and understand the aspects influencing the sustainability performance of the Mavumira project and give recommendations for sustainability improvements in rural electrification projects.
(ii) There is quantitative data available to measure the indicators.
(iii) Their implications or concerns for the economic, environmental, and social sustainability of the project can be analyzed.

The set of indicators applied to measure the sustainability of the Mavumira project is presented in Table 2, along with their description. Similar to other studies [14,22], the set of indicators selected within the economic dimension is easier to quantify compared to the chosen indicators within the social dimension. The increased number of sicknesses due to the emission of hazardous substances resulting from the electricity project deployment has raised concerns in society [36]. Human health indicators, particularly human toxicity and ionizing radiation potentials, can be considered under environmental or social dimensions. However, in our study, we considered these indicators within the environmental dimension as the calculation results and characterization factors are linked to that dimension.

Table 2. Refined list of indicators and the assessment method.

Sustainability Dimension	**Indicator Code**	**Indicator**	**Unit**	**Description of the Indicator**	**Input Data**	**Data Availability/Data Collection: Available (++); Difficult to Acquire (+); Not Available (−).**
Economic	ECO1	Cost of electricity (LCOE)	USD/kWh	LCOE is an economic metric that assesses the project's economic viability and helps to compare the costs of different energy system configurations [6,7].	Investment costs; operation and maintenance (O&M) cost, discount rate, incentives, project lifetime, and fuel costs.	Data available (++); Data acquired through load survey in the study area and processed through HOMER.
	ECO2	Project expenditures (GDP and Imports)	USD	Project expenditures investigate the project's contribution to GDP (value added) and imports in the economy.	National statistics and different sources	Data available (++); literature; National statistics; SAMs report for Mozambique [37];
	ECO3	Direct and indirect effects on employment	Jobs/kW	Direct employment estimates the number of jobs directly related to the project, particularly during the construction and operation stages. It may include jobs involved in the production and transport of the equipment [38], while indirect employment is linked to the production stage and services in the supply chain [39,40].	National statistics and different sources	Data available (++); literature; National statistics; SAMs report for Mozambique [37]
Environmental	ENV1	Global warming potential (GWP)	kg CO_2 equivalents (eq.)/kWh	Greenhouse Gas (GHG) emissions that cause global warming represent the most frequently used indicator under environmental sustainability and are expressed in terms of CO_2-equivalents (for a 100-year time horizon) [6,41,42]. This indicator estimates the radiative forcing of various substances and their remaining times in the atmosphere and attributes relative values referent to those for the reference gas CO_2 [43].	Through the ecoinvent database and Google searches (e.g., transportation distance from a manufacturing country to Mozambique)	Data available (++) through the ecoinvent database (adapted to the local conditions as much as possible). Data were acquired through a load survey in the study area and processed through HOMER. All environmental impacts were calculated using LCA (SimaPro 9.4) software based on the ReCiPe method.
	ENV2	Terrestrial acidification potential (TAP)	kg SO_2 eq./kWh	The power generation process causes the emission of acid gases like sulfur dioxide (SO_2), hydrogen chloride (HCl), nitrogen oxides (NOx), and ammonia (NH3) that contribute to acid rain and relative impacts. This can cause mortality of aquatic organisms in rivers and lakes and also erosion [44]. This indicator measures how the sulfates, nitrates, and phosphates deposited from the atmosphere alter soil acidity [45].		
	ENV3	Terrestrial ecotoxicity potential (TEP)	kg DCB[a] eq./kWh	TEP measures the impacts on ecosystems. This indicator is based on the utmost endurable concentrations of toxic substances by diverse organisms in the terrestrial environment [44].		
	ENV4	Marine ecotoxicity potential (MEP)	kg DCB[a] eq./kWh kg	MEP measures the impacts on ecosystems. This is an important indicator to consider as the electricity generation project may result in the utmost endurable concentrations of toxic substances and an increase in temperatures by diverse organisms in marine environments [44].		
	ENV5	Eutrophication potential (EP)	kg PO_4 eq./kWh	EP is defined as the potential of nutrients like N and NOx contributing to the over-fertilization of water and soil [44]. This indicator is important to consider when assessing the local and/or regional environmental impact of the project [46].		
	ENV6	Land use/transformation (LU)	m^2/kWh	LU measures the land occupation throughout the life cycle of the project, which becomes unavailable for other uses, like agricultural purposes. The land is essential for the implementation of renewable technologies. For example, solar PV requires a large area for the installation of solar panels, which directly affects the environment and landscape. Similar to other environmental indicators, the land use impact can be estimated using the ReCiPe method [5].		

Table 2. *Cont.*

Sustainability Dimension	Indicator Code	Indicator	Unit	Description of the Indicator	Input Data	Data Availability/Data Collection: Available (++); Difficult to Acquire (+); Not Available (−).
	ENV7	Human toxicity potential (HTP)	kg 1,4-dichlorobenzene (DB) eq	During the life cycle of an electricity generation project, toxic substances are emitted that cause harm to humans. It is an important indicator as it measures the impacts of the released chemicals on human health. It can be measured by the years of Life lost/kWh [45].	Through the ecoinvent database and Google searches (e.g., transportation distance from a manufacturing country to Mozambique)	Data available (++) through the ecoinvent database (adapted to the local conditions as much as possible). Data were acquired through a load survey in the study area and processed through HOMER. All environmental impacts were calculated using LCA (SimaPro 9.4) software based on the ReCiPe method.
	ENV8	Ozone layer depletion potential (OLDP)	kg CFC-11 eq./kWh	OLDP is one of the important indicators to consider under human health issues. It is associated with the erosion of the stratospheric ozone layer caused by anthropogenic emissions. During the production and installation phase of renewable energy projects, some gases may be released into the atmosphere [5]. This results in the transmission of UVB radiation to the earth's surface, which contributes to skin diseases (skin burning) [44,45].		
	ENV9	Particulate matter formation potential (PMFP)	kg PM_{10} eq	PMFP is a mixture of very small particles, a widespread air pollutant, is injurious to human health, and causes environmental degradation [46]. It is a commonly used indicator to estimate the effects of carbon combustion emissions on human health. PMFP are categorized by micro-size pollutants with a diameter of less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) [46,47]. These emissions are related to the electricity production by fossil fuels (e.g., diesel) that result in the emissions of primary and secondary particle precursors [48].		
	ENV10	Tropospheric Ozone formation Potential (TOFP)/Photochemical ozone formation	kg NMVOC eq	TOFP is related to the impacts of ozone and other reactive oxygen compounds formed as secondary pollutants in the troposphere by the oxidation of the primary contaminants carbon monoxide or volatile organic compounds (VOC) in the existence of nitrogen oxides (NOx) in the effect of light [5]. This indicator can cause smog episodes on a local level, which may affect the surrounding areas, combined with large emissions and good climate conditions. Additionally, it may cause immediate damage to human health due to the ozone concentrations and other photooxidants [5].		
	ENV11	Ionizing radiation potentials (IRP)	kg U^{235} eq	IRP assesses the damage to human health and the ecosystem taking into account the radiation types α-, β-, γ-rays, and neutrons. It is an important indicator as it expresses human disability due to the effects of exposure to radiation that causes severe diseases like cancer [44,49].		
Social	SOC 1	Human Development Index (HDI)	-	HDI expresses the level of development as a result of introducing a new technology in developing countries.	Annual electricity consumption per capita	Data availability (−); Data not available; however, we used the correlation with other indicators (e.g., LCOE, expenditures, and jobs)

2.2. Assessment Methods for the Sets of Indicators

2.2.1. Economic Sustainability

Cost of Electricity

To assess the profitability of the project, we used the LCOE. The LCOE has been used to estimate the costs of different technologies (solar PV, diesel, battery, and converters), considering the investment cost, O&M costs, fuel, and discount rate. The LCOE is an important metric to guide the investors and project developers in the selection of the best solution among various alternatives. It is calculated by considering input parameters particularly the O&M costs, capital costs, and fuel cost [50–52], using Equation (1).

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{served}} \tag{1}$$

where E_{served} and $C_{\mathrm{ann,tot}}$, are the primary load served in kWh/year and the total annualized cost in USD/year, respectively.

The total annualized cost is the annual cost of the project in (USD/year). It is expressed, using Equation (2):

$$C_{ann,tot} = C_{capann} + C_{repann} + C_{O\&Mann} \tag{2}$$

where C_{repann} represents the replacement cost, C_{capann} represents the capital cost, and $C_{\mathrm{O\&Mann}}$ represents the O&M.

(i) *Data source and assumptions for the calculation of the project's profitability*

To analyze the impact of the cost of electricity and the capital cost, we used the results from our previous study [6], estimated based on HOMER software. A summary of the main values/parameters considered for the estimation of the LCOE of the project, like the total primary energy demand and the annual energy output, are presented in Table 3.

Table 3. Overview of the parameters and assumptions used for the calculation of economic, environmental, and social indicators [a].

		Current Scenario: Optimized Today's Case (Current Load Demand)		**Future Scenario: Optimized Future Case (Increased Load Demand)**	
Parameter	**Unit**	**PV/DG/B**	**DG**	**PV/DG/B**	**DG**
Solar PV	kW	100	-	300	-
DG	kW	59	59	94	94
Battery	kW	200	-	800	-
Converter	kW	40.6	-	72.9	-
PV production	kWh/year	118.954	-	355.737	-
DG production	kWh/year	116.573	209.827	104.192	335.664
Renewable fraction	%	44.1	0	68.8	0
Diesel consumption	l/year	42.276	74.201	33.530	110.472
Capacity factor	%	26	40.6	12.7	40.8
Total electrical production	kWh/year	235.526	209.827	459.929	335.667
Total load, E_{load}	kWh /year	208.598	208.598	333.756	333.756
Unmet load	kW/year	0	0	0	0
Number of persons	Nr	277 × 6 = 1662	277 × 6 = 1662	443 × 6 = 2658	443 × 6 = 2658
Excess electricity	kW/year	15.504 (6.58%)	1.230 (0.586%)	90.180 (19.6%)	1.911 (0.569%)
LCOE	USD/kWh	0.52	0.59	0.47	0.63

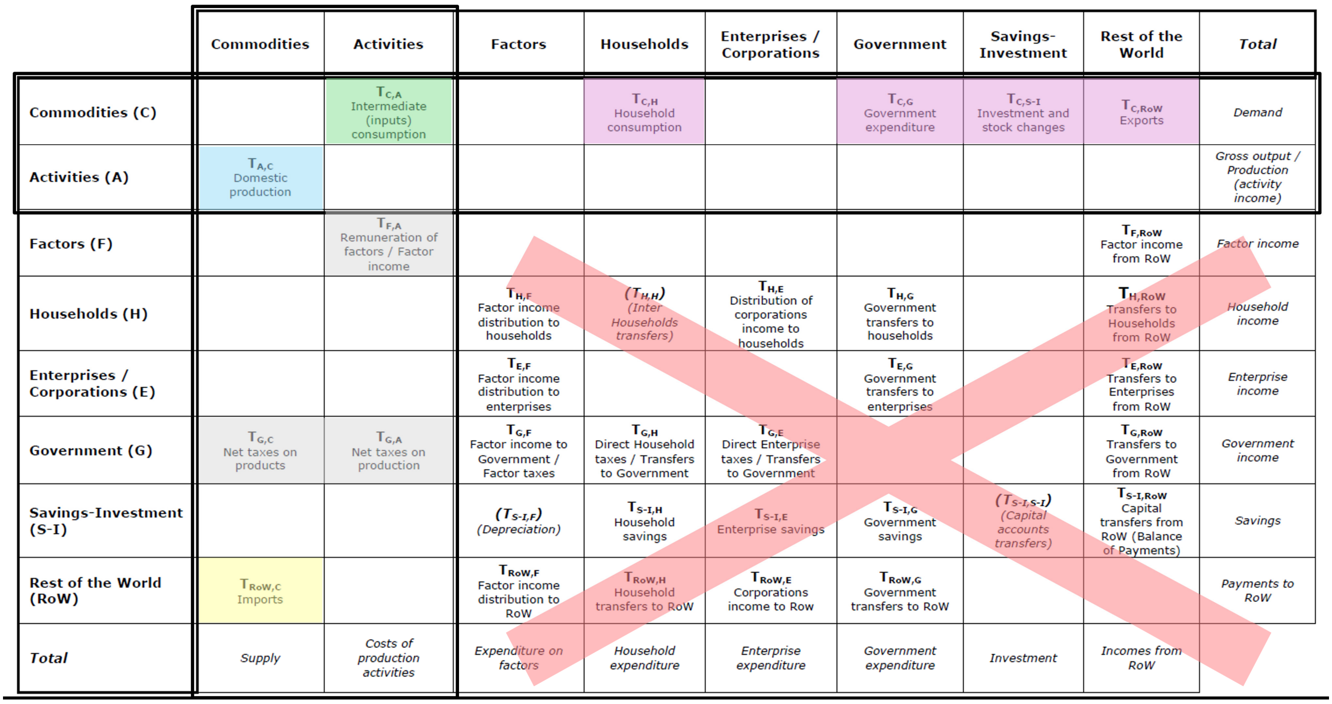
[a] Parameters presented in this table were estimated based on data from the study area (existing mini-grid) and processed through HOMER. HOMER provided the optimum energy system configuration for Mavumira village. Of the total electricity production, 50.5% comes from solar PV and 49.5% from DGs. Of the total electricity production, 77.3% comes from solar PV and 22.7% from DGs. The number of persons was estimated based on the scaled annual average for the current load demand (571.5 kWh/day) and an expected increase in the future load demand of 60% (914.40 kWh/day, taking into account the that each household consumes on average 2.063 kWh/day/household (refer to our previous study [5]). Discount rate: The discount rate is used to convert annualized costs and one-time costs. In our study, we considered a discount rate of 8% for all technologies to allow the financial comparison, along with an inflation rate of 2%. Lifetime for the components of the system: For solar PV, we assume a project duration (lifetime) of 25 years. A lifetime of 8 years is assumed for batteries (approximately three replacements over the project lifetime), which means that it requires three replacements over the project lifetime and 15,000 h for the diesel generator (to be replaced once after 21 years). The 1 kWh lead–acid battery weight is 25 kg [53]. The weight of a single diesel genset is estimated at 1250 kg [54]. Diesel fuel cost is estimated based on the current cost of 1.0 S/L with an expected increase of 1.4 USD/L.

Impact on Project Expenditures and Employment

Consumer expenditures and employment are two parameters that strongly influence economic growth [55]. The literature has discussed different methods that help to quantify project expenditure and employment effects in a specific project, particularly through economic-wide models that are generally framed between input–output (IO) and Computable General Equilibrium (CGE) models. These methods are frequently used for the evaluation of the macro-impact of projects on a regional and national economy (they can differentiate between indirect, direct, and induced effects), and the employment factors, which are methodologically easier and can help in assessing the impact at the local level [56–59]. The indirect jobs are likely to be temporary jobs as opposed to the direct jobs that are usually permanent and beneficial for the local communities. However, the employment factor methods do not determine the indirect and induced effects. The IO method can evaluate the responses of the economic system to different scenarios and policies without considering consumption. At the same time, the CGE describes the relationship between the main factors (capital, labor, and natural resources) by using elasticities of substitution. The CGE models have been widely used to study the effects of economic policies on various economic variables like output, prices, and employment. However, CGE models are more complex and rely on a large number of parameters, particularly the elasticities of substitution, to capture the complexity of economic agents' decision-making processes. In the absence of sufficient data and expertise to construct a CGE model, IO models based on the Supply and Use Framework can provide a useful alternative for policy analysis. These models rely on a simpler set of assumptions and data, making them more accessible and transparent. More specifically, IO models can estimate the direct and indirect effects of a policy shock on the economy, particularly changes in output, income, and employment, by using a matrix of intersectoral transactions and value added. The method has previously been applied by [60–63] in the context of developing economies to analyze the economic and social impact of projects or activities on, for example, the coffee sector in Kenya [61]. In this study, we used the IO method to assess the effect of expenditures and jobs created inside and outside Mavumira village, using the Social Accounting Matrices (SAMs) of Mozambique as published by the Nexus Project [37]. The total expenditures were assessed using the results from the IO analysis in terms of the project's expenditure outside the country (referring to the imports of equipment, including fuel, etc.) and expenditures inside the country (direct value added), considering that not all the expenditures are local. For example, Mozambique does not manufacture solar PV and relies on diesel fuel imports. The country has only one solar PV assembly factory located outside Mavumira village.

A Supply and Use Table (SUT) provides the link between components of industry inputs, gross value added, and industry outputs. Although typically shown only by the industry dimensions, SUTs can also be formulated to show the role of different institutional sectors. Consequently, SUTs do not only provide a framework to ensure the best quality estimates of the economy but they are also an important resource for different analyses like CGE models and IO models. This concept finds a more consistent representation in the SAM. SAM links the micro-statistics of labor market together with the macro-statistics of national accounts, consumption, household income, and other social statistics [58]. SUTs are an integral part of the SAMs, which provide a macroscopic representation of a circular flow, where everything remains within the economy. However, they do not include social notations that are important to correctly describe the income flow. It is an underlying assumption in the SUT framework that every commodity that has been produced by all the activities needs to be consumed by other activities or by final demanders.

A specific SAM, representing the economic intersectoral flows of Mozambique in 2015, was chosen for the presented assessment, allowing for the construction of a suited SUT to perform the IO analysis. The methodology consisted of assessing the impact of project expenditures and employment, taking advantage of the level of detail offered by the database to perform a shock analysis of the SUT of Mozambique. The SUT offers a rich description of Mozambique's economy and interconnection having 54 commodities, including electricity, gas, and steam (e.g., celec), and 54 activities table (e.g., aelec). There were 11 factor inputs, of which 8 were labor (unskilled, semi-skilled, and skilled) accounts. In this way, it was possible to evaluate the impact of the Mavumira mini-grid, estimating employment both on the geographic (rural or urban area) and education levels (from non-scholarized to holder of a tertiary degree). The model also accounted for the degree of dependence on foreign commodities necessary to meet the demand for goods and services required to invest in and operate the mini-grid. Figure 2 presents the SAM adopted for the application of the SUT model for the present study. As can be seen from Figure 2, we did not use all SAM elements as input because the SUT model adopted in this study did not require information like factors and enterprises.



	Commodities	**Activities**	**Factors**	**Households**	**Enterprises / Corporations**	**Government**	**Savings-Investment**	**Rest of the World**	***Total***
Commodities (C)		$T_{C,A}$ Intermediate (inputs) consumption		$T_{C,H}$ Household consumption		$T_{C,G}$ Government expenditure	$T_{C,S\text{-}I}$ Investment and stock changes	$T_{C,RoW}$ Exports	*Demand*
Activities (A)	$T_{A,C}$ Domestic production								*Gross output / Production (activity income)*
Factors (F)		$T_{F,A}$ Remuneration of factors / Factor income						$T_{F,RoW}$ Factor income from RoW	*Factor income*
Households (H)			$T_{H,F}$ Factor income distribution to households	$(T_{H,H})$ *(Inter Households transfers)*	$T_{H,E}$ Distribution of corporations income to households	$T_{H,G}$ Government transfers to households		$T_{H,RoW}$ Transfers to Households from RoW	*Household income*
Enterprises / Corporations (E)			$T_{E,F}$ Factor income distribution to enterprises			$T_{E,G}$ Government transfers to enterprises		$T_{E,RoW}$ Transfers to Enterprises from RoW	*Enterprise income*
Government (G)	$T_{G,C}$ Net taxes on products	$T_{G,A}$ Net taxes on production	$T_{G,F}$ Factor income to Government / Factor taxes	$T_{G,H}$ Direct Household taxes / Transfers to Government	$T_{G,E}$ Direct Enterprise taxes / Transfers to Government			$T_{G,RoW}$ Transfers to Government from RoW	*Government income*
Savings-Investment (S-I)			$(T_{S\text{-}I,F})$ *(Depreciation)*	$T_{S\text{-}I,H}$ Household savings	$T_{S\text{-}I,E}$ Enterprise savings	$T_{S\text{-}I,G}$ Government savings	$(T_{S\text{-}I,S\text{-}I})$ *(Capital accounts transfers)*	$T_{S\text{-}I,RoW}$ Capital transfers from RoW (Balance of Payments)	*Savings*
Rest of the World (RoW)	$T_{RoW,C}$ Imports		$T_{RoW,F}$ Factor income distribution to RoW	$T_{RoW,H}$ Household transfers to RoW	$T_{RoW,E}$ Corporations income to Row	$T_{RoW,G}$ Government transfers to RoW			*Payments to RoW*
Total	*Supply*	*Costs of production activities*	*Expenditure on factors*	*Household expenditure*	*Enterprise expenditure*	*Government expenditure*	*Investment*	*Incomes from RoW*	

Figure 2. Social Accounting Matrix adopted for the application of the SUT framework based on [61,64].

To estimate the impacts associated with the mini-grid, information on the time, magnitude, and sector of consumption is needed. This requires integration between the HOMER energy model and the adopted IO model. The optimal solutions of HOMER are characterized by different choices of technologies and activities, which can be translated into final sectoral consumption within the IO model. This can then be translated into the values of investments in these sectors.

As previously mentioned, the objective of using the IO model in this study was to assess the economic factors F (linked to f, which is the production over the matrix of monetary exogenous coefficients), considering the implementation and use phases. In both the investment and operation assessments, the commodities needed for the production, installation, and maintenance of the technologies are characterized based on the information provided by HOMER using cash flows [6]. In Equations (3) and (4) the linear algebra behind the estimation is provided.

$$\Delta \underline{\underline{F_i}} = \underline{\underline{f}}[\overbrace{(\underline{\underline{I}} - \underline{\underline{z}})^{-1}\underline{Y_i}}^{X_i}] - \underline{\underline{f}}[\overbrace{(\underline{\underline{I}} - \underline{\underline{z}})^{-1}\underline{Y}}^{X}] \tag{3}$$

$$\Delta \underline{\underline{F_o}} = \underline{\underline{f_o}}[\overbrace{\left(\underline{\underline{I}} - \underline{\underline{z_o}}\right)^{-1}\underline{Y}}^{X_o}] - \underline{\underline{f}}[\overbrace{(\underline{\underline{I}} - \underline{\underline{z}})^{-1}\underline{Y}}^{X}] \tag{4}$$

* A variable with double underline identifies a matrix, while a variable with one underline identifies a vector. Absolute units are identified in capital letters (e.g., Gg or M USD), while output-specific units are in small letters (e.g., Gg/M USD or M USD/M USD).

Here, Y and X are the total production of commodities and industrial activities and the final demand of commodities, respectively; z is the supply and uses representing the technological structure of the economy; and I represent the identity matrix of the same dimensions of z. In Equations (3) and (4), subscript o denotes data after the intervention, while subscript i indicates investment data.

Within the current open-modeling community, tools for convenient and efficient handling that can comprehensively process all the different types of IO tables and provide a framework to easily and automatically reproduce shock analysis and implement transparency are not available. In our study, the SUTs were powered by Multi-Regional Analysis of Regions through input–output (MARIO). MARIO is a Python module developed and published openly on *GitHub* [65,66]—the tool functions as a general framework for performing input–output analysis without needing in-depth knowledge of programming. MARIO supports automatic parsing of structured tables like EXIOBASE [67], EORA [68], EUROSTAT [69], and ad hoc built tables in different formats like SRIO and MRIO tables in monetary or hybrid units. Supply and Use tables are also supported and can be translated into IO tables using a built-in function that implements the transformation models described and adopted in different studies [70–72].

Since the IO method is limited to the macro-impact, we applied the employment factors approach to calculate the direct jobs (local jobs required for daily O&M of the mini-grid). We considered direct jobs that were contracted or undertaken, during the O&M of the project, at the local level that could contribute to the functioning of the mini-grid and to the village's economic development (e.g., O&M technicians and cleaners). The O&M jobs last the duration of the project lifecycle (25 years) due to ongoing equipment maintenance (solar PV panels, batteries, etc.). The employment factor distinguishes between jobs created in different stages over the project's life cycle (manufacturing, O&M, and construction and installation) [73–75]; they are commonly used to calculate the number of jobs created per unit of installed capacity expressed in MW for electricity-generating technologies. The total number of direct jobs was estimated by multiplying the employment factor by the renewable energy capacity (Total jobs in O&M = Cumulative Capacity in use in MW × Employment factor in jobs per MW × Regional employment multiplier for O&M × Project lifetime in years).

(i) Data source and assumptions for the employment and expenditures

Mozambique's SAM was constructed based on data from various sources, which included national statistics data provided by the National Institute of Statistics (INE) and other literature sources. More detailed information can be found in the report of the SAM for Mozambique [76]. The main assumption underlying the use of this approach is the relationship between input and output, driven by final demand. Whenever a unit of a good consumed within the country is demanded, the activities described by the supply side of the table are activated. Sometimes, import dependence can supply part of the demand. These proportions are assumed based on what is described in the table and may therefore not be representative of the specific product to be modeled by the 54 sectors offered by the SUT. For example, as shown in Figure 3, if a unit of the commodity "machinery and equipment" is demanded, the system expects an economic flow distribution with imports as the main demand-side factor. However, other activities, including domestic ones, are involved in the distribution of this economic flow, like the manufacturing sector, albeit to a small extent. This sector employs workers with varying levels of education. The data used to estimate the employment factor is derived from different studies. For example, the installed capacity (for solar and DGs) is obtained from our previous study [5]. Each technology considered in a hybrid combination has a specific employment factor. As developing countries, like Mozambique, lack data on employment factors, we applied data from Organization for Economic Co-operation and Development (OECD) country studies for each technology; for example, for solar PV, the employment factor for the O&M is 0.7 jobs/MW, while for diesel, as no employment factors are available, the factor for gas of 0.14 jobs/MW was applied for this technology [77–79]. For the regional employment multiplier, we applied data for the sub-Saharan region of 6.42 for the year 2020 (current scenario) and 5.0 for the year 2030 (future scenario), adjusted for labor productivity in each region [80,81].

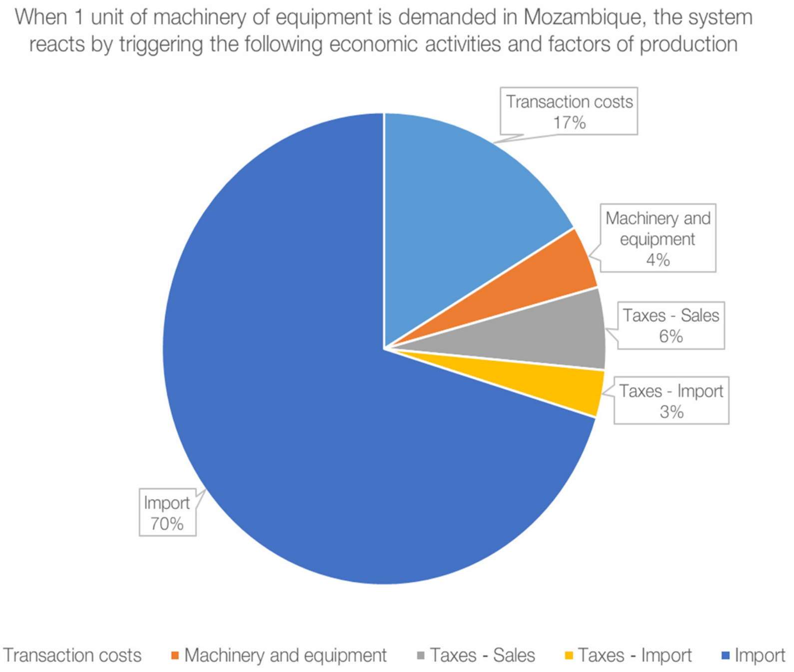


Figure 3. The demand for machinery and equipment in Mozambique triggers economic activities and factors of production.

2.2.2. Environmental Sustainability

In this study, an environmental analysis of different scenarios of the energy supply mix in Mavumira village (Mozambique) was conducted. To this aim, the LCA methodology was used, following the latest ISO 14040-44 standards [80] and the guidelines from the European Commission [2,82,83]. The literature indicated four software programs (SimaPro, Gabi, Umberto, and OpenLCA) as the most applied tools for the environmental LCA of a product or service, following the “cradle-to-grave” or “cradle-to-gate” approach from the extraction of raw material until the final disposal [84]. The choice of software for the analysis depends on the objectives of the study. In our study, we employed the software SimaPro 9.4, developed by PRé Sustainability [85], and the database ecoinvent 3.7 for modeling the analyzed scenarios. The SimaPro tool was used as it employs multiple methods to determine the impact assessment and presents an extensive and detailed database, and the results of the analysis are presented in a user-friendly manner [86–88]. The environmental (midpoint and endpoint) indicators were used for quantifying the relative magnitude of the environmental impacts. For the estimation of the emission damage, the literature suggested the ReCiPe method, which calculated both midpoint and endpoint indicators [88,89]. The endpoints are associated with damages to human health, ecosystems, and resource availability areas of protection. In this study, the potential impacts were calculated using the following midpoint impact categories (see Table 2): climate change, photochemical ozone formation, particulate matter, human toxicity (non-cancer and cancer), eutrophication (freshwater, marine and terrestrial), ozone depletion, ecotoxicity (freshwater), acidification, ionizing radiation, water use, land use, and resource use (fossils and minerals and metals). These parameters have been applied in different LCA studies [54,89,90] for environmental impact assessment.

Functional Unit, System Boundaries, and Data Sources

In this section, the functional unit (FU) and systems boundaries are defined based on the recommendations of ISO 14040 referent to LCA [76], including data sources for the selected indicators. It should be noted that FU has to be chosen carefully, concerning the product function, and is usually time-bound [85]. Many studies consider 1 kWh as the FU of energy provided to the system [54,90]. This FU enables an easy comparison of energy system configurations. Therefore, in accordance with these studies, a functional unit of 1 kWh of electricity was chosen for this study. In this study, 85 kW is the corresponding peak load to meet the future electricity demand in the village (914.4 kWh/day) while the actual current peak load is 52.95 kW (corresponding to a load of 571.5 kWh/day). A project lifetime of 25 years was considered in the analysis. Regarding the system boundaries, we used the methodology guidelines for the life cycle of solar PV [88], which include the raw material, transportation (from the factory to the installation site), use phase (installation of the project and O&M), and end-of-life management (transport, waste processing, recycling, and disposal), as presented in Figure 4. The definition of specific data requirements and calculation steps are also carried out.

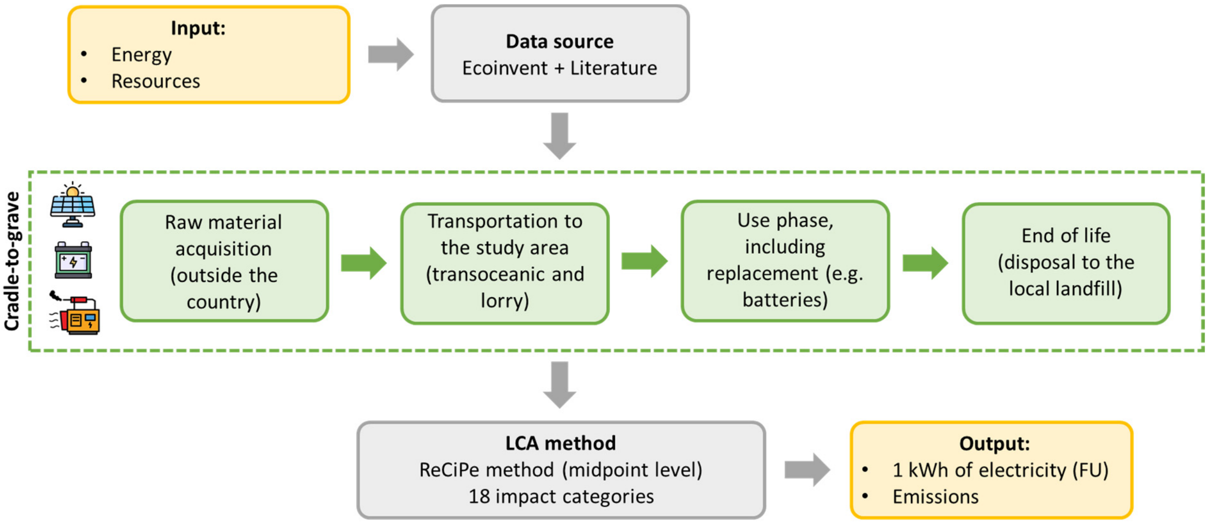


Figure 4. System boundary.

One of the greatest challenges in LCA studies is the availability of good-quality inventory data. For the analysis of each indicator, a combination of data sources was used (see Table 2), which consisted of data collected from the interviews conducted in the study area (Mavumira village), data from literature focused on electricity generation, and data from ecoinvent database. The technologies used in the renewable-based scenarios (solar PV, lead–acid batteries, and DGs) are not produced in Mozambique. Therefore, the background LCA database, ecoinvent (the ecoinvent database was developed and implemented by the Swiss Centre for Life Cycle Inventories [89]), was used for the main components of the system, based on data from China and adapted, whenever necessary and possible, to the local conditions of this study. Our understanding is that these values will be useful in providing an overview of the environmental aspects of Mavumira village. More details on the assessment methods, data source, and assumptions for the selected indicators are provided in the following sections.

(i) *Life cycle inventory data and assumptions for the estimation of the local environmental impact*

This section presents the life cycle inventory data for a functional unit of 1 kW, including production of the raw material, transportation of equipment (by ship and track) from the factory to the project's location, use, and end-of-life (final disposal of the equipment) phase. As previously mentioned, the data used in the present study were obtained from different sources (ecoinvent database, literature studies on LCA, and available local/country-specific data). Environmental indicators were assessed based on background life as life cycle inventory data available in the SimaPro (ecoinvent 3.7 database) for the main components of hybrid system configurations (solar PV, diesel generator, and Li-ion battery). These data were adjusted as much as possible to the conditions in Mozambique and to match the size of the system components optimized with the HOMER software. Similar to other developing countries, Mozambique does not yet produce the components and therefore relies on imported system equipment, like solar PV and batteries. We assumed that equipment would be manufactured and assembled outside the country (e.g., in China), except for the other material that can be purchased locally (e.g., for the solar PV mounting system). The chosen transport modes were transoceanic ship and lorry (16–32 t), followed by road transportation after the arrival of the equipment in Mozambique (from Beira Porto to the final destination). The life cycle inventory data for transport was estimated based on the distance between the manufacturing of the components (China) and the project site (Mozambique): 15,186 km by ship from China to the port of Beira and 200 km by lorry from the port of Beira to the project site (Mavumira village) [90]. During the use phase, the PV system and the batteries do not consume any energy and do not emit any emissions [91,92]. Diesel fuel is imported from outside the country because there is no active fuel refinery in Mozambique. For the use of diesel generators, the diesel production, transport, and emissions resulting from the combustion of diesel were considered [92], assuming the diesel fuel consumption in liters, and the components of diesel generators are presented in Appendix B. These emissions are usually the air emissions caused by fuel and energy use in the system. According to international standards, all the materials are recycled or disposed of in the landfill at the end of the project [93]. However, in developing countries like Mozambique, there is a lack of recycling facilities for equipment like PV modules and batteries. It was therefore assumed that all materials would be sent to the landfill. Summaries of the inventory data used for current and future scenarios and for the two configurations, DG-only and HRES (hybrid, with RES and DG), to produce 1 kWh of electricity are presented in Tables 4 and 5.

Table 4. Inventory data used for the current scenario (DGs and hybrid solar PV/DG/B).

Flow	**Quantity**		**Proxy Dataset in Ecoinvent 3.7**
	Current Scenario: DG	**Current Scenario: HRES (PV/DG/B)**	
Generators [p]	2.78×10^{-6}	1.48×10^{-6}	Adapted from "Diesel-electric generating set, 18.5 kW {GLO}∣ market for ∣ Cut-off, S", to represent a genset of 59 kW with a weight of 738 kg
Diesel [kWh]	3.53	1.79	Modified from diesel, burned in diesel-electric generating set, 18.5 kW {GLO}∣ diesel, burned in diesel-electric generating set, 18.5 kW ∣ Cut-off, U
Transport by lorry [kg·km]	9.27	5.16	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}∣ market for transport, freight, lorry 16–32 metric ton, EURO5 ∣ Cut-off, S
Transport by ship [kg·km]	31.9	33	Transport, freight, sea, container ship {GLO}∣ market for transport, freight, sea, container ship ∣ Cut-off, S
Photovoltaic panel [m^2]	0	1.25×10^{-6}	Photovoltaic panel, single-Si wafer {GLO}∣ market for ∣ Cut-off, S
Photovoltaic plant [p]	0	1.32×10^{-8}	Photovoltaic plant, electric installation for 570 kWp open ground module {GLO}∣ market for photovoltaics, electric installation for 570 kWp module, open ground ∣ Cut-off, S
Photovoltaic mounting system [m^2]	0	1.25×10^{-6}	Photovoltaic mounting system, for 570 kWp open ground module {GLO}∣ market for ∣ Cut-off, S
Battery [kg]	0	8.67×10^{-5}	Battery, Li-ion, rechargeable, prismatic {GLO}∣ market for ∣ Cut-off, S
Landfill [kg]	2.1×10^{-3}	2.3×10^{-3}	Municipal solid waste {RoW}∣ treatment of, sanitary landfill ∣ Cut-off, S

Table 5. Inventory data used for future scenarios (DGs and hybrid solar PV/DG/B).

Flow	Quantity		Proxy Dataset in Ecoinvent 3.7
	Future Scenario DG	Future Scenario: HRES (PV/DG/B)	
Generators [p]	1.74×10^{-6}	3.62×10^{-7}	Adapted from "Diesel-electric generating set, 18.5 kW {GLO}∣ market for ∣ Cut-off, S", to represent a genset of 94 kW with a weight of 1175 kg
Diesel [kWh]	3.29	0.725	Modified from diesel, burned in diesel-electric generating set, 18.5 kW {GLO}∣ diesel, burned in diesel-electric generating set, 18.5 kW ∣ Cut-off, U
Transport by lorry [kg·km]	8.67	2.29	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}∣ market for transport, freight, lorry 16–32 metric ton, EURO5 ∣ Cut-off, S
Transport by ship [kg·km]	31.9	34.9	Transport, freight, sea, container ship {GLO}∣ market for transport, freight, sea, container ship ∣ Cut-off, S
Photovoltaic panel [m^2]	0	3.37×10^{-6}	Photovoltaic panel, single-Si wafer {GLO}∣ market for ∣ Cut-off, S
Photovoltaic plant [p]	0	3.55×10^{-8}	Photovoltaic plant, electric installation for 570 kWp open ground module {GLO}∣ market for photovoltaics, electric installation for 570 kWp module, open ground ∣ Cut-off, S
Photovoltaic mounting system [m^2]	0	3.37×10^{-6}	Photovoltaic mounting system, for 570 kWp open ground module {GLO}∣ market for ∣ Cut-off, S
Battery [kg]	0	4.2×10^{-4}	Battery, Li-ion, rechargeable, prismatic {GLO}∣ market for ∣ Cut-off, S
Landfill [kg]	2.1×10^{-3}	3.8×10^{-3}	Municipal solid waste {RoW}∣ treatment of sanitary landfill ∣ Cut-off, S

2.2.3. Social Sustainability

Human Development Index

The Human Development Index (HDI) is known as the quantitative measure of human well-being, and it is an important indicator to assess the project's impact on local community development because it measures the project's contribution to economic and social development. The HDI is represented by three base elements, which are the life expectancy at birth, gross national income per capita, and expected years of schooling; these are indices that are often considered in the literature [94], as presented in Appendix A. Access to electricity directly affects the economic and social development of many nations, especially at the local level by improving living conditions through the provision of access to education and health services, which contributes to high HDI. Therefore, developing countries with low HDI consume less electricity than countries with high HDI. For example, an aggregated score varying from 0 and 1 was considered by the United Nations Development Program (UNDP), which is above an HDI of 0.8 for high-development countries and below an HDI of 0.5 for low-development countries [95]. In the case of Mozambique, the HDI of 0.418 was provided by the UNDP in 2015, which is considered low due to factors like the lack of access to electricity that limits the economic opportunity for income-generating activities, especially in rural areas [96]. In this study, we addressed the link between HDI, cost of electricity, project expenditures (inside and outside the village), direct and indirect jobs, and local environmental impacts like CO_2 and other emissions to air (particulate matter and photochemical ozone formation) to understand how these factors can be achieved simultaneously to improve the well-being of the local communities.

Correlation Between HDI, Cost of Electricity, Project Expenditures (Inside and Outside the Village), Direct and Indirect Jobs, and Local Environmental Impact Like CO_2 and Other Emissions to Air (Particulate Matter and Photochemical Ozone Formation)

The literature has explored the relationship between the HDI, cost of electricity, and CO_2 emissions separately and in different manners [97–99]. However, no study has addressed the correlation between HDI, cost of electricity, project expenditures (inside and outside the village), direct and indirect jobs, and local environmental impact like CO_2 and other emissions to air (particulate matter and photochemical ozone formation) simultaneously. In this study, we examined the relationship between HDI, cost of electricity, jobs, project expenditures, and environmental (CO_2 emissions), considering the renewable and diesel-only options for scenarios, as described in Section 2. We used a mix of approaches (quantitative and qualitative) to evaluate the indicators and employed different methods to analyze their effect on the sustainability of the Mavumira project. For example, for the cost of electricity, we resorted to the results from our previous study [5] obtained through HOMER pro. For the direct and indirect jobs, project expenditures (inside and outside the country), and the environmental analysis, we employed the results from the IO and LCA models, respectively. We found no study in the literature discussing the indices of the HDI (education, health, and income) in full for HRESs. However, some studies have addressed different aspects like the correlation between HDI and electricity consumption [35,36,94]. They applied a method consisting of the maximization of HDI as a part of optimization results estimated based on different optimization techniques like genetic algorithm and HOMER pro software. This method considered that the HDI can be improved through the excess electricity produced by the HRES that can be used for extra loads. Such excess electricity cannot be used to supply the load. Additionally, it cannot be stored in batteries as the alternating current loads are already covered by the electricity produced in the system. In this study, since we lacked data for the quantitative evaluation, we did not analyze the HDI separately for each scenario (diesel-only and renewable). However, for the correlation, we analyzed how some elements of HDI (prosperity, health, and economic activities) influence or are linked to the cost of electricity, project expenditures (inside and outside the village), direct and indirect jobs, and local environmental impacts like CO_2 and other emissions to air (particulate matter and photochemical ozone formation); for example, how local prosperity is linked to the cost of electricity, how health is linked to CO_2 emissions and other emissions to air, and how income is linked to employment and expenditures. For the correlation, we used a ranking scale to make our estimations quantitative. We ranked it from (−2) to (+2) based on nine sub-criteria (CR1 to CR9): (−2) represents a strong negative relationship, (−1) a moderate negative relationship, (0) a neutral relationship, (+1) a moderate positive relationship, and (+2) a strong positive relationship. The criteria were selected within the economic and environmental dimensions (Table 6). We considered the hybrid PV/DG and DG-only options for the current and future scenarios, and the rank for each energy alternative was attributed based on the values from our analysis of the selected sub-criteria (CR1 ... CR8) and our own opinion.

Table 6. Criteria used for the selection of the best energy alternative for Mavumira village.

Criteria	**Sub-Criteria and Unit**	**Sub-Criteria Code**	**Unit**
Trade	Expenditures inside the country (GDP/Value added)	CR1	M USD
	Expenditures outside the country (Imports)	CR2	M USD
Jobs	Local direct jobs	CR3	Nr. Of jobs
	Indirect jobs	CR4	Nr. Of jobs
Prices	Cost of electricity	CR5	USD/kWh
Environmental	CO_2 emissions	CR6	kg CO_2 eq
	Particulate matter	CR7	kg PM_{10} eq
	Photochemical ozone	CR8	kg NMVOC eq
Well-being	HDI	CR9	-

2.3. Integration Method

2.3.1. TOPSIS Method

To integrate the economic, environmental and social aspects and identify the best sustainable option for the Mavumira project, we used MCDA based on the TOPSIS method. TOPSIS is a multi-criteria decision-making approach that is used to compare and rank a set of alternatives based on a set of defined criteria. The method is used particularly in cases where decision-makers are faced with making analytical decisions based on conflicting metrics when ranking alternatives [18]. TOPSIS works on the basic principle that the best solution is the energy alternative with the relative value closest to 1 while the worst energy alternative is the one that presents the relative value furthest away from 1 [17,100]. The TOPSIS method is typically implemented using 7 steps [17] as follows:

1. Set up an "evolution matrix" comprising M alternatives and N criteria. This usually takes the form described by the following expression in Equation (5).

$$\left(X_{ij}\right)_{M\times N} \tag{5}$$

2. The next step is the normalization of the evolution matrix that is developed in the previous step using the expression in Equation (6). Each sub-criteria j for each energy option i is normalized to range between 0 and 1. Metrics with higher values are desirable.

$$X_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{M}\left(X_{ij}\right)^2}} \tag{6}$$

3. In Step 3, the weighted normalized decision matrix is calculated, using the following equations. Typically, each criterion is allocated its own weight, and the sum of their weights is summed up to 1. These weights can either be based on expert knowledge or allocated randomly (see Equations (7)–(9)).

$$V_{ij} = X_{ij}W_j \tag{7}$$

$$W_j = \frac{W_j}{\sum_{j=1}^{N} W_j} \tag{8}$$

$$\sum_{j=1}^{N} W_j = 1 \tag{9}$$

4. The next thing is to calculate the maximum and minimum value of each energy for the energy alternatives. In this step, the best and the worst alternatives for each criterion are determined using Equations (10) and (11).

$$V_j^+ = \max_{i=1} V_{ij} \tag{10}$$

$$V_j^- = \min_{i=1} V_{ij} \tag{11}$$

5. The next step calculates the Euclidean distance between the target choice and the best/worst choice, as shown in Equations (12) and (13).

$$S_i^+ = \sqrt{\sum_{j=1}^{m}\left(V_{ij} - V_j^+\right)^2} \tag{12}$$

$$S_i^- = \sqrt{\sum_{j=1}^{N}\left(V_{ij} - V_j^+\right)^2} \tag{13}$$

6. In Step 6, the similarity to the worst alternative is estimated for the individual alternatives. The result obtained from here is the TOPSIS score (relative closeness), as shown in Equation (14).

$$P_i = \frac{S_i^-}{S_i^- + S_i^+} \tag{14}$$

In the last step, the alternatives are ranked in descending order based on the TOPSIS score obtained in the previous step. The alternative with the score closest to the best will obtain the highest score and, therefore, will be the most preferred alternative.

2.3.2. Criteria and Weight Attribution

The literature presented different methods for assessing the weight of different criteria, including the Criteria Importance Through Intercriteria Correlation (CRITIC), entropy weight method (EWM), and weight attributed based on our opinion and the results from our analysis on the criteria's importance [17,101]. However, the application of methods like the CRITIC and EWM can be challenging for many real cases because the methods assign more weight to criteria with greater dispersion of data. To attribute weights used in the TOPSIS method and have more robust and more accurate comparison of the results, we applied two approaches: (i) equal weight approach, in which we assumed that the nine sub-criteria had an equal weight of 11.1% each, and (ii) weight attributed based on our opinion on the criteria's importance, which consisted of attributed weight (from 5% to 100%) for each criterion according to their importance compared to others, allocated randomly (Figure 5). This meant that the higher the importance of the indicator, the more points it received [102]. For example, the expenditures inside the country and the local direct jobs required for the on-site O&M of the system received a high importance of 25% each because they are positive factors contributing to the local economic development. Mozambique does not produce equipment, like solar PV equipment and batteries. The equipment is imported from outside the country (e.g., China). Therefore, we attributed low importance to the sub-criteria like expenditures outside the country (7.5%) and indirect jobs (7.5%) because they are negative factors, considering that they occur outside the village and therefore do not contribute directly to the local economic development. We attributed fewer points of 7.5% each to the CO_2 emissions and other emissions to air (particulate matter and photochemical ozone) because these factors represent the emissions caused by the combustion of diesel and should be reduced as much as possible. Despite being a positive factor for local development, the HDI was attributed a relatively low weight of 5% because we found that, overall, the correlation between HDI and other sub-criteria (from CR1 to CR8) was not very strong (there was no direct correlation).

We distinguish between positive (beneficial) and negative (non-beneficial) criteria. For the positive criteria, we attributed maximum values (between 0.2 and 0.4) because we assumed that they are beneficial to the local context. The negative criteria are those with the minimum values and are non-beneficial to the local context, as presented in Table 7. For example, CR1, CR3 and CR9 are non-beneficial criteria, while CR2, CR4, CR5, CR6, CR7 and CR8 are beneficial criteria.

Table 7. Weight attributed for each sub-criteria.

Attributes	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Equal weights method	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
Weight attributed based on the criteria's importance method	0.250	0.075	0.250	0.075	0.075	0.075	0.075	0.075	0.050
Beneficial criteria	0.400		0.400						0.200
Non-beneficial criteria		0.150		0.200	0.200	0.150	0.150	0.150	

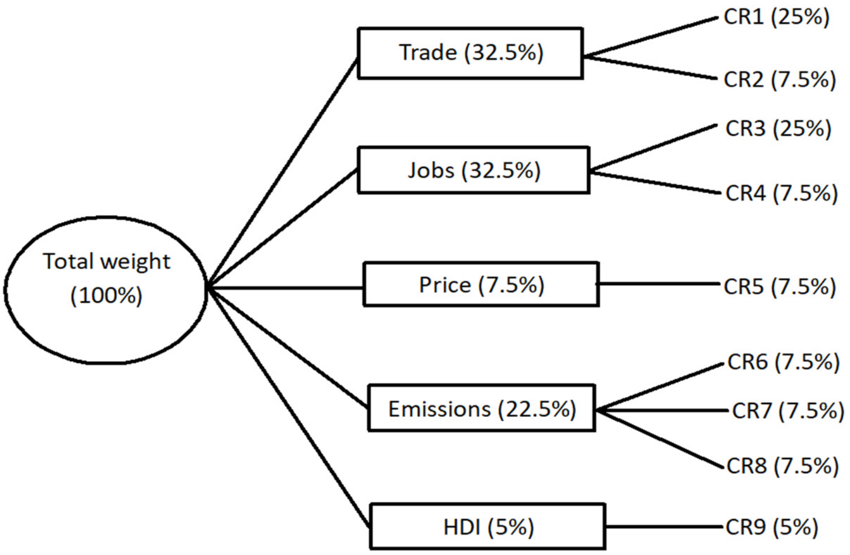


Figure 5. Criteria used for the selection of the best energy alternative for Mavumira village.

3. Results and Discussion

3.1. Economic Impact

3.1.1. Cost of Electricity

The results of our study indicated that in both current and future scenarios, the system powered by diesel only had relatively high LCOE values of 0.63 USD/kWh and 0.59 USD/kWh, compared to the renewable option (solar PV/DG/Battery) of 0.52 USD/kWh and 0.47 USD/kWh, respectively. This suggests that the LCOE of the renewable option will decrease by approximately 20.3% in the future compared to the diesel option (see Figure 6), which means that the renewable option is likely to ensure greater sustainability than the diesel option.

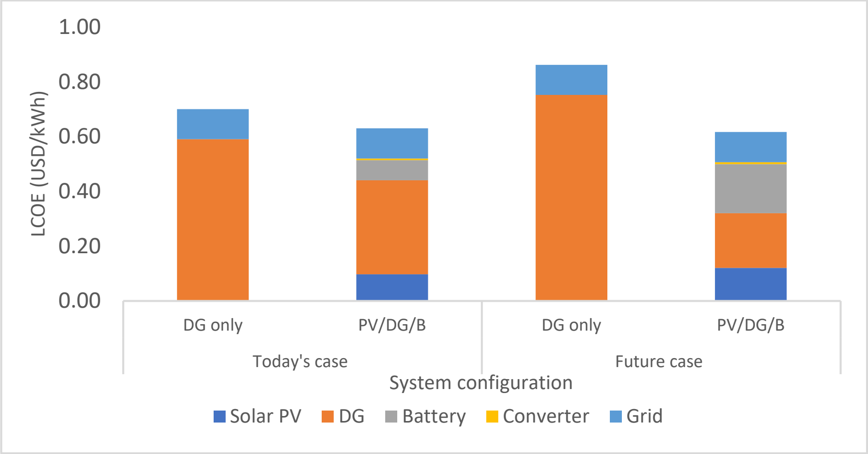
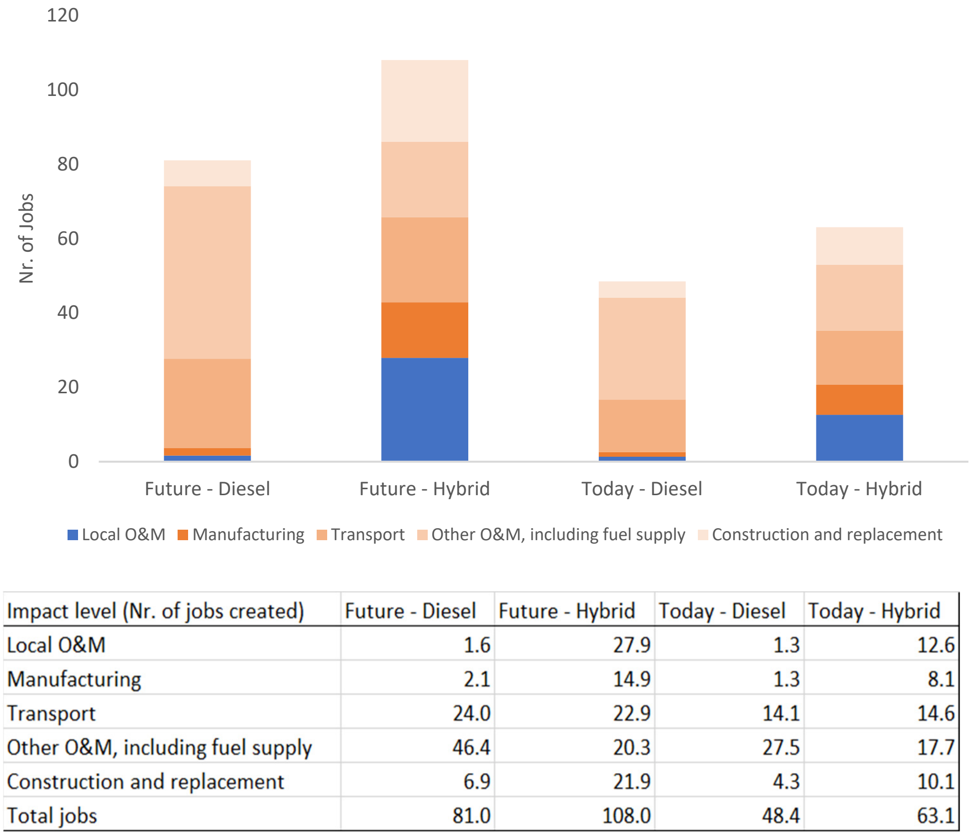


Figure 6. Cost of electricity for current and future scenarios based on our previous study [6].

3.1.2. Input–Output Analysis

This section presents the effect of expenditures and employment on economic growth. The results, as outlined in Appendix C, demonstrate that diesel-only scenarios lead to higher expenditures (total expenditures and imports) than renewable scenarios. For example, the absence of refineries in the country suggested more diesel expenditures outside the village. This impacted our results for the short and long term, in which diesel expenditures will be 26.6% and 47.5% higher than the renewables, respectively. Additionally, the diesel expenditures outside the country (imports) increased by approximately 244% over the expenditure inside (GDP/value added) in future diesel scenarios. This is because the future diesel system will require more diesel that relies on fuel imports, making it less viable compared to the renewable option.

Figure 7 compares the local employment generated by the investment and operation of the mini-grid for different scenarios over a 25-year project lifetime. The values are reported in annual contracts equivalent to the 25 years of the project. Indirect employment was estimated using cash flows derived from the HOMER model and fed into a supply and use input–output model, with results presented in orange. The results from the SUT model are provided in local currency that is estimated to be earned by Mozambican workers, which are present for both investment and operational shocks. The values in money were then converted into annual contracts using four different levels of annual salaries matched with the education level, based on the current salaries recently approved by the government of Mozambique in 2023 [103]. The lowest salary range was chosen to convert cash flows into employment contracts as it represents the majority of employees in the mini-grid. From the IO analysis, we observe significant differences in the indirect employment impacts of mini-grid electrification under different scenarios. Specifically, the assumption of higher demand in the future case leads to a higher peak load and therefore higher investment, resulting in more workers being employed, particularly in manufacturing and other sectors related to the construction and replacement of machinery, which is particularly relevant if a hybrid system is adopted. In contrast, relying on diesel generators requires less initial investment but creates a greater dependence on the diesel supply chain, resulting in the equivalent of 10–26 additional indirect contract jobs associated with maintenance and fuel supply. These workers are mainly employed in the transport and trade sectors and have a higher level of education than primary school.



Impact level (Nr. of jobs created)	Future - Diesel	Future - Hybrid	Today - Diesel	Today - Hybrid
Local O&M	1.6	27.9	1.3	12.6
Manufacturing	2.1	14.9	1.3	8.1
Transport	24.0	22.9	14.1	14.6
Other O&M, including fuel supply	46.4	20.3	27.5	17.7
Construction and replacement	6.9	21.9	4.3	10.1
Total jobs	81.0	108.0	48.4	63.1

Figure 7. Direct and indirect impact on employment.

The reduced reliance on diesel generators in the scenario where solar and batteries are also used leads to a decrease in the number of jobs created by the operation of the mini-grid. However, the initial investment in this scenario generates an estimated 7–12 jobs in the manufacturing sector, depending on whether the current or future demand scenarios are considered. In addition, the replacement of equipment, like the inverter every 6 years, induces about 6–15 additional annual contracts required to manage the supply chains involved in grid renewal. The workers involved in these cases are mainly located in the manufacturing (around 36%), transport (around 30%), and trade (18%) sectors, with a prevalence of primary or lower education over secondary education. Furthermore, the study analyzed the impact on jobs derived from the replacement of diesel generators with renewable energy technologies. As shown in Figure 7, there are differences in the total employment effects between the diesel-only and RE options for the current and future scenarios. Moreover, indirect employment represents the majority of jobs (e.g., acquisition of equipment, including diesel fuel imports) and is therefore likely to be only temporary, as opposed to direct jobs (O&M) that are usually more permanent. The estimated local direct employment (in blue), calculated using the employment factor, indicated that in the future the renewable mini-grid will require more jobs (approximately 27.9 jobs) compared to the current renewable scenario (12.6 jobs). The diesel-only option involves fewer direct workers overall over the 25 years analyzed compared to the renewable options for the current and future scenarios. For example, the total number of employees for the local O&M of the system in the current scenario is 11.3 higher in the renewable option than the diesel-only option, while for the future scenario, the number of renewable employees is 26.3 higher than the diesel-only option, which means that replacing diesel generators with renewables will have positive benefits not only on local communities but also on different industrial sectors. Our results also suggested that the fuel supply has a higher probability of generating indirect employment (outside the village) for the 100% diesel system because of the diesel imports and the number of diesel operating hours in the diesel-only system.

3.2. Environmental Impact Assessment

The life cycle environmental impacts were calculated for both current and future scenarios related to the energy demand of Mavumira village; the results are summarized in Table 8. For each scenario, DG and HRES configurations were assessed using the EF 3.0 method in accordance with the latest guidelines of the European Commission [104]. All 18 indicators available within this method were considered to facilitate future environmental comparisons in a similar context. In addition, a contribution analysis was conducted to identify processes with the greatest impact.

Table 8. Overall impact categories for the production of 1 kWh of electricity in the four analyzed scenarios.

		Current Scenario		**Future Scenario**	
Impact Category	**Unit**	**DG**	**HRES (DG + PV + B)**	**DG**	**HRES (DG + PV + B)**
Climate change	kg CO_2 eq	1.14	5.81×10^{-1}	1.06	2.41×10^{-1}
Ozone depletion	kg CFC11 eq	2.45×10^{-7}	1.25×10^{-7}	2.28×10^{-7}	5.08×10^{-8}
Ionizing radiation	kBq U−235 eq	6.87×10^{-2}	3.51×10^{-2}	6.41×10^{-2}	1.46×10^{-2}
Photochemical ozone formation	kg NMVOC eq	2.03×10^{-2}	1.03×10^{-2}	1.89×10^{-2}	4.20×10^{-3}
Particulate matter	disease inc.	2.14×10^{-8}	1.10×10^{-8}	2.00×10^{-8}	4.78×10^{-9}
Human toxicity, non-cancer	CTUh	1.25×10^{-8}	6.48×10^{-9}	1.17×10^{-8}	3.06×10^{-9}
Human toxicity, cancer	CTUh	1.48E^{-10}	8.16E^{-11}	1.42×10^{-10}	5.02×10^{-11}
Acidification	mol H+ eq	1.59×10^{-2}	8.09×10^{-3}	1.48×10^{-2}	3.32×10^{-3}
Eutrophication, freshwater	kg P eq	2.24×10^{-5}	1.35×10^{-5}	2.15×10^{-5}	1.17×10^{-5}
Eutrophication, marine	kg N eq	7.08×10^{-3}	3.60×10^{-3}	6.60×10^{-3}	1.47×10^{-3}
Eutrophication, terrestrial	mol N eq	7.75×10^{-2}	3.94×10^{-2}	7.22×10^{-2}	1.60×10^{-2}
Ecotoxicity, freshwater	CTUe	8.82	4.67	8.27	2.46
Land use	Pt	1.96	1.06	1.83	5.93×10^{-1}
Water use	m3 depriv.	1.11×10^{-2}	6.58×10^{-3}	1.06×10^{-2}	5.23×10^{-3}
Resource use, fossils	MJ	1.53×10^{1}	7.78	1.42×10^{1}	3.21
Resource use, minerals, and metals	kg Sb eq	1.44×10^{-6}	1.21×10^{-6}	1.40×10^{-6}	2.07×10^{-6}

The results illustrate that the options implementing HRES have significantly lower environmental impacts than the DG-only option for almost all impact categories and in both current and future scenarios. The only exception is for the indicator resource use (minerals and metals), which in the future scenario was lower for the DG-only option than for the HRES option. This is also underlined in Figure 8, where the percentage change between the impacts of the HRES and the DG configuration is indicated for both scenarios (current and future). In particular, for the current scenario, the results of the renewable options (HRES) are between 16% and 49.2% lower than the DG option. For future scenarios, the decrease in impact ranges from 45.6% to 77.8%, except for resource use (minerals and metals) resulting in 32% lower in the DG-only scenario. Clearly, in the future scenario, the total impact of satisfying the energy demand of the Mamuvira village will increase because of the population increase. However, the higher efficiency of renewable technologies in the future scenario leads to a decrease in the impacts related to 1 kWh of provided energy. For example, climate change in the future scenario is estimated at 0.24 $kgCO_2/kWh$ compared to 0.58 $kgCO_2/kWh$ in the current HRES scenario. This means that in the analyzed case, the use of renewable energy is more environmentally efficient if it has to meet a higher load demand (future scenario). The only exception is for the indicator of resource use (minerals and metals) whose impact results are lower in the current scenario than in the future. This is mainly due to the higher percentual use of the battery in future scenarios. The results of the DG option have very similar impacts for all indicators in the current and future scenarios (1.14 and 1.06 $kgCO_2/kWh$).

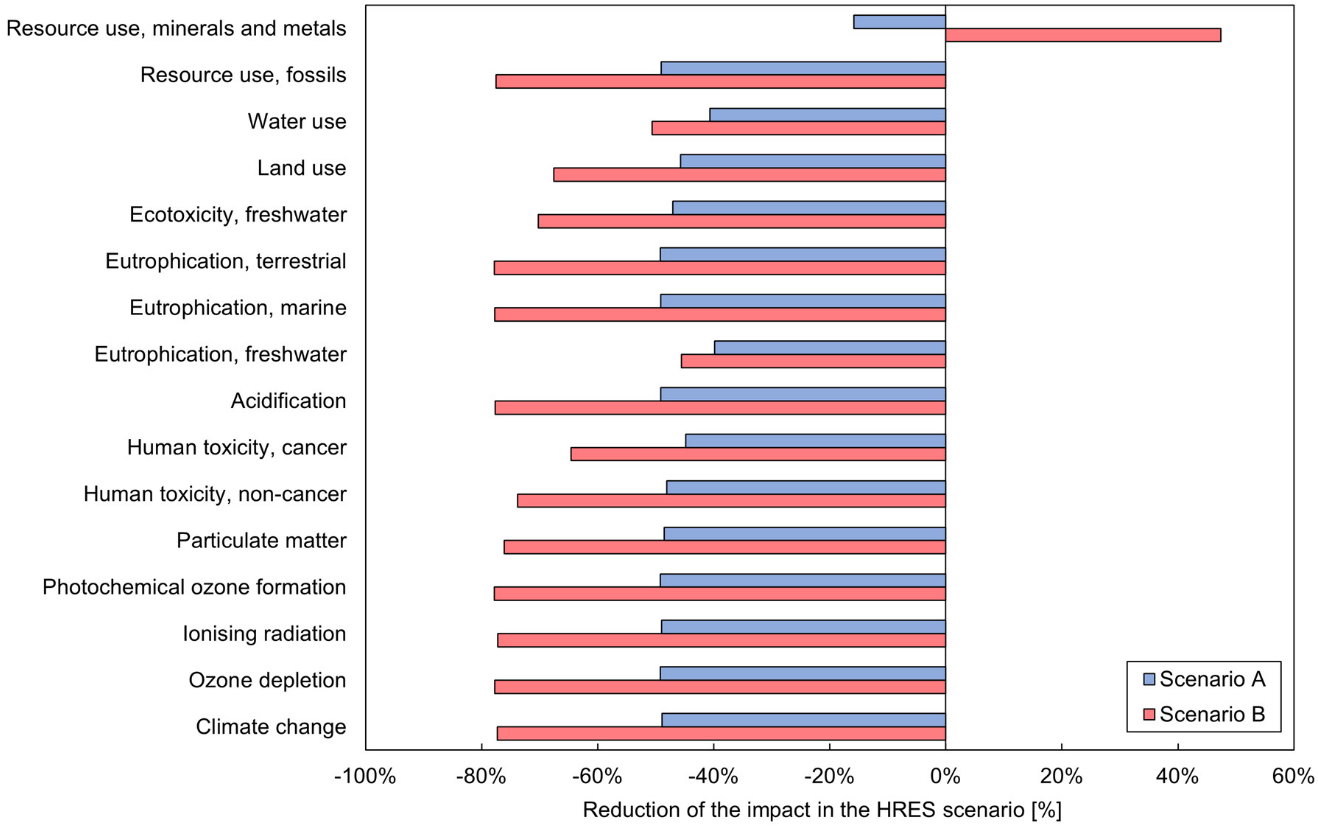


Figure 8. Reduction in the impact in the Mavumira mini-grid, evaluated concerning the DG configuration for current (blue bars) and future (red bars) scenarios.

The flow charts in Figure 9 graphically show the carbon footprint along the production chain of the four analyzed scenarios for the provision of 1 kWh of electricity. In all scenarios, including the HRES ones, the combustion of diesel from the genset plays a key role, accounting for a large percentage of the impacts (ranging from 94.7% to 97.9% of the total carbon footprint depending on the scenario).

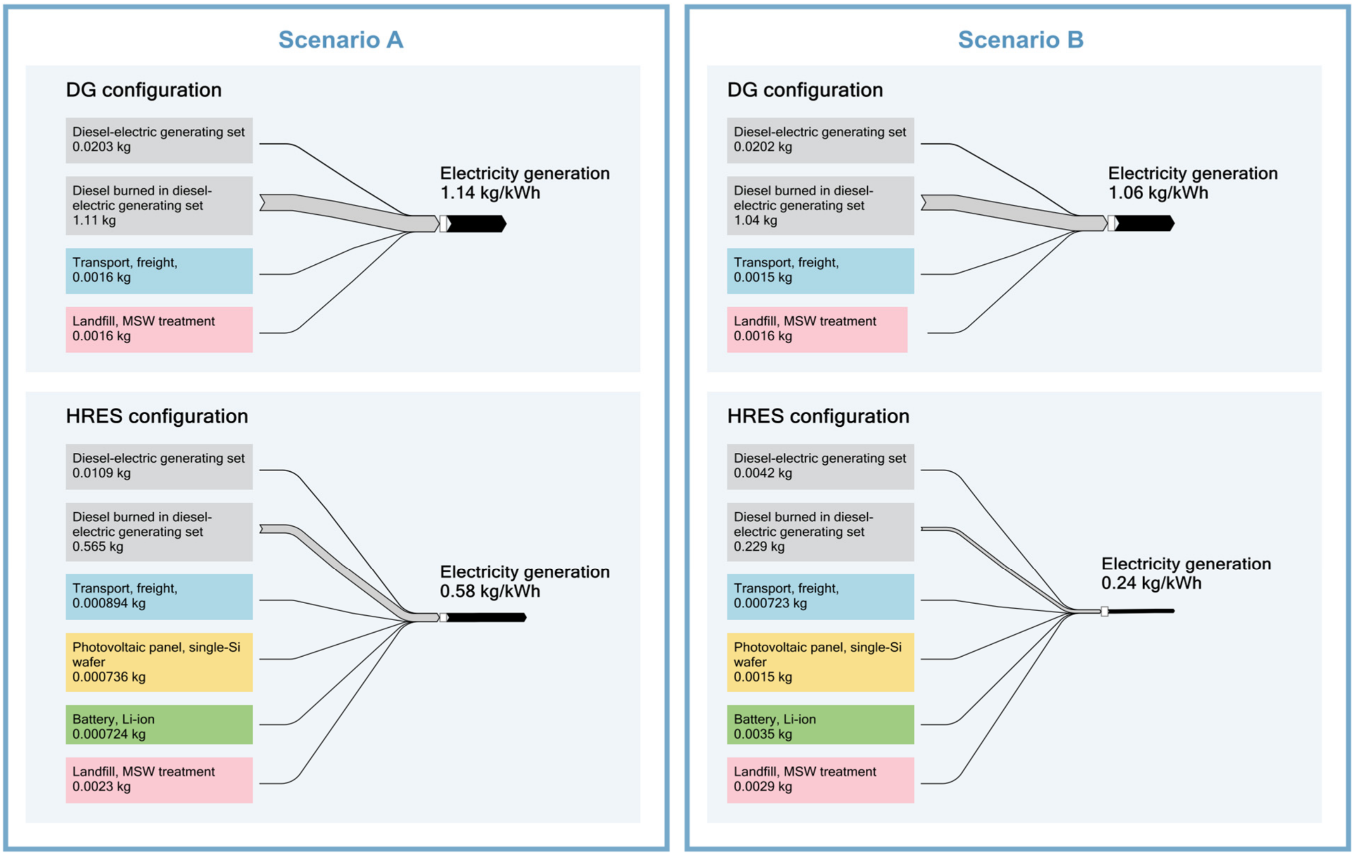


Figure 9. Potential impact on climate change for the production of 1 kWh of electricity for the current (**A**) and future (**B**) scenarios, HRES and DG configuration.

3.3. Social Impact

Correlation Analysis

Table 9 presents the correlation analysis between the HDI, cost of electricity, project expenditures (inside and outside the village), direct and indirect jobs, and local environmental impact performed using the ranking scale of −2 to +2 based on our expert judgment and the values from our analysis on each criterion. We added the elements CR1 to CR8 and used the result (CR9) as the input for the TOPSIS model in Section 3.4 to analyze how the HDI criteria influence the other criteria (CR1. . . CR9).

Table 9. Correlation analysis.

	Energy Alternatives	**CR1**	**CR2**	**CR3**	**CR4**	**CR5**	**CR6**	**CR7**	**CR8**	**CR9**
Today	PV/DG	1	2	1	1	1	1	1	1	9
	DG only	2	2	0	1	1	−1	−1	−1	3
Future	PV/DG	2	2	2	2	2	1	2	2	15
	DG only	2	1	0	2	1	−1	−1	−1	3

Note: CR1—Expenditures Inside the country (GDP/Value added); CR2—Expenditures outside the country (Imports); CR3—Local direct jobs; CR4—Indirect jobs; CR5—Cost of electricity; CR6—CO_2 emissions; CR7—Particulate matter; CR8—Photochemical ozone; CR9—HDI.

We found that the expenditures and jobs that occurred inside the village were more beneficial for local development than those outside the village. Therefore, we attributed the rank of (+2) for the highest value of expenditures and jobs inside the village and (+1) for the lowest value. In contrast, the expenditures and jobs outside the village were attributed (+1) for the highest value and (+2) for the lowest value as they are non-beneficial for local development. For the direct jobs, we attributed zero for the DG-only jobs (current and future scenario) because the number of jobs was very insignificant compared to the jobs from the renewable option. This result is associated with the complexity of the hybrid system compared to the diesel-only system. In general, replacing diesel with renewables strongly stimulates the HDI by providing more local job opportunities and therefore increasing the income-generating activities in the village. We considered local prosperity as an element of HDI and linked this element to the cost of electricity. We ranked (+2) for the future hybrid PV/DG system as it presented the lowest price of electricity, which was beneficial for the local communities compared to the cost of the DG-only system. For the CO_2 and other emissions to air (CR6 to CR8), we ranked (+1) for the hybrid PV/DG in the current scenario because the system contained emissions from diesel fuel despite its lower effect compared to the DG-only system, which was ranked (−1). The CO_2 emissions for the future renewable option ranked high (+2) because it reduced the emissions compared to the current renewable option, which was ranked (+1). Overall, our findings suggested that the HDI is strongly and positively correlated to hybrid configurations for current and future scenarios with values of 15 and 9, respectively, compared to diesel-only systems with values of 3, respectively.

3.4. Analysis of the Multicriteria Decision Method

The MCDM was used to rank different energy alternatives and select the most appropriate system to provide electricity to Mavumira village. We analyzed two energy alternatives (DG and PV/DG) for the current and future village load demand, considering nine sub-criteria as presented in the initial decision matrix (Table 10). The values attached to the indicators were obtained using different methods (i.e., HOMER and IO), as described in Section 2. The analysis was performed using the TOPSIS for the nine sub-criteria (see Section 2.3), with an equal weight of 0.11 attributed to each criterion (CR1 to CR9), and the weight attributed based on the criteria's importance, for which we attributed a higher weight to the criteria that are important for local development and a lower weight for the criteria with a low impact on local development. For the calculations, we used MS Excel, following Equations (5)–(12). Solving multicriteria problems is more complex compared to those with a single criterion due to challenges in comparing different units attributed to each criterion. However, the weighted normalized matrix presented in Appendix D.1 facilitates a comparison of different criteria. Appendices D.2 and D.3 show the rank of energy alternatives, including the positive and negative ideal solutions for the proposed weight methods. It is evident from Appendices D.2 and D.3 that using the two weight methods (equal weight attributed and the weight attributed based on the criteria's importance), the first most promising energy option is the future hybrid energy system with renewables (PV/DG) as it presents a relative closeness of 0.825 and 0.859, respectively, compared to the DG option. This result is associated with many factors, like the higher number of direct and indirect jobs required to run the hybrid PV/DG compared to the DG option, and the lower cost of electricity of the renewable that makes the hybrid PV/DG option the best compared to the DG option for the future and current scenarios. As previously mentioned, we used different weight approaches for the comparison of the results and to allow the user to select the most suitable weight approach. It is evident that if we change the criteria's weight, the energy alternatives' rank is not affected in the sense that the best energy alternative, which presents the relative value closest to 1, is the hybrid PV/DG for the equal and different weights approach, as seen from Figure 10, and for the beneficial criteria (local) and non-beneficial criteria (outside the village/national), as presented in Figure 11 and Table 11.

Table 10. Initial decision matrix.

		Trade		Jobs		Prices	CO_2 and Other Emissions to Air			Well-Being
Scenarios	**Energy Alternatives**	**Expenditures Inside the Country (M USD)**	**Expenditures Outside the Country (M USD)**	**Direct Jobs (Nr. Jobs)**	**Indirect Jobs (Nr. of Jobs)**	**Cost of Electricity (USD/kWh)**	**CO_2 Emissions (kg CO_2 eq)**	**Particulate Matter (kg PM10 eq)**	**Photochemical Ozone (kg NMVOC eq)**	**HDI**
		CR1	**CR2**	**CR3**	**CR4**	**CR5**	**CR6**	**CR7**	**CR8**	**CR9**
Today	PV/DG	0.392	1.133	12.6	50.5	0.52	5.81×10^{-1}	1.10×10^{-8}	1.03×10^{-2}	9
	DG only	0.434	1.495	1.3	47.1	0.59	1.14	2.14×10^{-8}	2.03×10^{-2}	3
Future	PV/DG	0.588	1.633	35.8	80.1	0.47	2.41×10^{-1}	4.78×10^{-9}	4.20×10^{-3}	15
	DG only	0.738	2.537	2.1	79.4	0.63	1.06	2.00×10^{-8}	1.89×10^{-2}	3

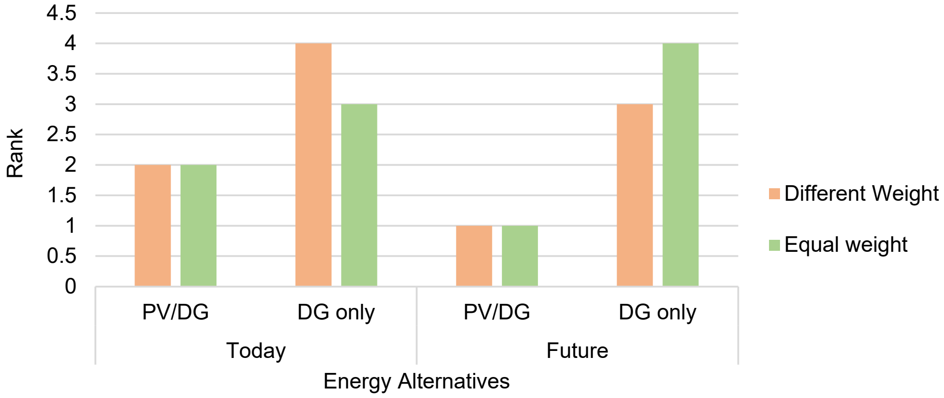


Figure 10. Rank of energy alternatives concerning equal weight and different weight.

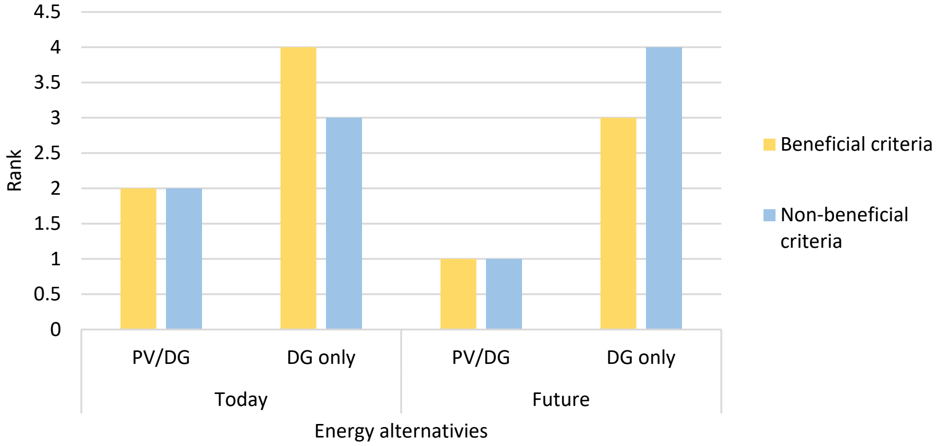


Figure 11. Rank of energy alternatives concerning beneficial and non-beneficial criteria.

Table 11. Rank of energy alternatives (beneficial and non-beneficial criteria).

Scenario	**Energy Alternatives**	**Beneficial Criteria**				**Non-Beneficial Criteria**			
		Si+	**Si−**	**Pi**	**Rank**	**Si+**	**Si−**	**Pi**	**Rank**
Today	PV/DG	0.282	0.136	0.326	2	0.053	0.123	0.699	2
	DG only	0.402	0.015	0.037	4	0.142	0.07	0.331	3
Future	PV/DG	0.054	0.393	0.879	1	0.047	0.15	0.762	1
	DG only	0.379	0.125	0.248	3	0.156	0.012	0.072	4

4. Conclusions and Recommendations

Access to electricity is a key factor in boosting the economic, environmental, and social development of many developing nations. This study presents for the first time a framework that combines and integrates indicators and methods to quantitatively determine the most sustainable solution, among the renewables and diesel-only alternatives, for the present and future. The focus is on the Mavumira mini-grid located in Mozambique, for which we compared two options (diesel-only and hybrid PV/diesel) for electricity generation both now (52.95 kW) and in the future (84.72 kW).

Based on a review of the literature, we showed that the economic and environmental indicators are well developed. The availability of data makes it possible to quantify many indicators. However, not all data are available on country and regional scales. The social indicators are less established as they are hard to quantify. The scarcity of data is more problematic here.

The framework covers various methods resulting in a set of twenty-two indicators (three economic, eighteen environmental, and one social). We applied the economic and environmental indicators (cost of electricity, project expenditures inside and outside the village, direct and indirect jobs, and local environmental impact), and the HDI as the social indicator. We used a combination of different methodologies consisting of IO and employment factors to analyze the economic impact outside the village (e.g., manufacturing of equipment, including diesel imports) and inside the village (local O&M), respectively. LCA (SimaPro) was used to determine the most pollutant gases, and HOMER was used for techno-economic analysis. Data for the analysis were obtained from interviews with local stakeholders, the literature, and the ecoinvent and HOMER database. It is important to mention that the ecoinvent and HOMER databases are subject to limitations as they partially do not reflect the local context (conditions). For example, one limitation is the lack of access to local costs for renewable energy components because Mozambique does not manufacture equipment. To integrate the selected indicators, we applied the TOPSIS method with a combination of two weighting methods (equal weighting and weight attributed based on our opinion on the criteria's importance). This method proved to be significant in the decision-making process of renewable energy systems as a framework that integrates the criteria to arrive at the most sustainable solution among various energy alternatives.

After evaluating all the parameters assessed in this study, we concluded that the renewables are overall the most sustainable and convincing alternative to supply electricity to Mavumira village compared to the diesel-only option. In addition to lowering costs by about 20%, the renewable options will create more local jobs for local O&M, with approximately 11 and 26 jobs in the short- and long-term (i.e., 2030) scenarios, respectively. This increase in employment will generate additional income for the local community and contribute to the village's economic development. Nevertheless, not all the expenditures of the project are local. For example, the absence of refineries in Mozambique suggested more diesel expenditures outside the village. This impacted our results in the short and long term, with diesel expenditures being 26.6% and 47.5% higher than the renewables, respectively. The CO_2 emissions caused by burning diesel fuel were reduced by approximately 77% in future renewable scenarios compared to the diesel-only scenario because of the use of more renewables in the system. Maximizing the renewables will allow a percentual use of solar PV panels and batteries in the system, which will decrease costs over time, contrary to the imported diesel fuel. Moreover, by reducing diesel fuel imports, the local community will save money and time spent on diesel transportation, contributing to the village's economic development. In the long and short term, the findings of our study show a positive relationship between the HDI and the renewable options (with values of 15 and 9) compared to diesel (with values of 3), indicating that replacing diesel fuel with renewables will contribute to the local economic, environmental, and social development. Based on the criteria's weight, we ranked nine indicators selected under the economic, environmental, and social dimensions, including the HDI. On a ranking scale from 1 to 4, the best option was attributed to the future renewable option, which ranked 1, with closeness values of 0.825 and 0.859, while the worst scenario was the future diesel option, which ranked 4 and 3, with closeness values of 0.180 and 0.250, when applying the equal weight approach and the weight allocated randomly based on our opinion on the criteria's importance, respectively. This study concludes with future research directions for applying the framework developed to other case studies using different renewable technologies like hydropower and biomass in villages with similar characteristics to Mavumira. Moreover, the framework developed in the present study is important because it can assist policymakers in selecting the best energy alternative for rural electrification based on parameters like cost-effectiveness, emission reductions, and the well-being of the local communities.

The following recommendations are provided in light of the main findings from the present study:

- Because one of our challenges was to find relevant and reliable data, especially when it comes to quantifying social impacts, we did not consider the exhaustive evaluation of the HDI indices. We limited our analysis to how some elements of the HDI (prosperity, health, and economic activities) are linked to economic and environmental factors, particularly the cost of electricity, project expenditures, jobs, CO_2 emissions, and other emissions to air (e.g., particulate matter). Therefore, we recommend further research to investigate the complete HDI indices for further improvements in the correlation analysis. Moreover, it is necessary to adjust the HDI by incorporating more social factors (e.g., injuries, community involvement, ownership, and security) to better understand the local impact and compare different energy alternatives.
- Our findings indicated that the renewable option would generate more jobs in the village in the future and hence require qualified individuals for local O&M. However, it is fundamental to train local community members in managing the systems to prevent failures and ensure the long-term sustainability of the mini-grids.
- The results from the MCDM tool showed no significant differences between the results obtained using equal weight attributed and the weighting attributed based on the criteria's importance weighting methods. This indicates the robustness of the results.
- Overall, the framework developed in this study primarily focused on addressing issues related to solar and diesel mini-grids. It provides a good basis to quantify and integrate different indicators to evaluate the sustainability electrification (and possibly other energy-related factors) of the projects and, in combination, can serve as a benchmark for comparing current and future scenarios of other case studies with different renewable energy alternatives (e.g., hydropower, wind, and biomass). We suggest conducting further studies to test and develop the framework further and if possible, include more indicators. This framework is also valuable for supporting designers, decision-makers, and investors in determining optimal investment priorities to contribute to economic, environmental, and social development.

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Appendix A. List of Indicators Collected from the Literature

Sustainability Dimension	Themes	Indicators	Measure Units	Analysis: Qualitative or Quantitative	Category of Principles: Relevant and Measurable	Impact Level: Global, Regional, National, and Local
Social	Working condition	Maximum number of hours of work per day	Hours/day	Qn/Ql	Relevant and measurable	Local
		% of workers with a contract	%	Qn/Ql	Relevant and measurable	Local
		Working hours	Nr. of total working hours per day	Qn/Ql	Relevant and measurable	Local
		Fair salary	-	Ql	Relevant	Local
		Skills availability	%	Qn/Ql	Relevant and measurable	Local
		Number of staff with medical insurance	Proportion of staff with medical insurance	Qn	Relevant and measurable	Local
		Child labor	% of works that are children	Qn/Ql	Relevant and measurable	Local
		Labor rights	-	Ql	Relevant	Local
		National legal minimum age	Years	Qn/Ql	Relevant	
		Breaks	Time/day	Qn/Ql	Relevant and measurable	Local
	Access to electricity	Level of rural electrification	Nr. or % of total rural households connected	Qn/Ql	Relevant and measurable	Local
		Share of the rural population without electricity	The ratio of the rural population without electricity to the total rural population (%)	Ql	Relevant and measurable	Local
	Consumer price/tariff	Consumption levels for different income groups	kWh	Qn/Ql	Relevant and measurable	Local
		Price levels for different income groups	(%)	Qn/Ql	Relevant and measurable	Local
		Satisfaction with the tariff	% respondents satisfied	Qn/Ql	Relevant and measurable	Local
		Expenditures on electricity for different income groups		Qn/Ql	Relevant	Local
	Local community impact and quality of life	Community involvement	Nr. of community members involved	Ql	Relevant	Local
		Community satisfaction	% of satisfaction with electricity services	Ql	Relevant	Local
		Contribution to education, health care, and infrastructure investments	USD	Qn	Relevant and measurable	National/Local

Sustainability Dimension	Themes	Indicators	Measure Units	Analysis: Qualitative or Quantitative	Category of Principles: Relevant and Measurable	Impact Level: Global, Regional, National, and Local
Social	Local community impact and quality of life	The proportion of staff hired from local community relative to total direct employment	%	Qn/Ql	Relevant and measurable	Local
		Spending on local suppliers relative to total annual spending	%	Qn/Ql	Relevant and measurable	Local
		Ratio permanent/temporary jobs	%	Qn	Relevant and measurable	Local
		Change in access to health care/insurance	-	Ql	Relevant	Local
		Ratio of skilled versus jobs	Nr. of skilled and unskilled jobs	Qn	Relevant and measurable	Local
		People below the national poverty line	%	Qn	Relevant and measurable	National/Local
	Human Development Index (HDI)	Access to safe water and sanitation	-	Ql	Relevant	Local
		Life expectancy at birth	Years	Qn	Relevant and measurable	National/Local
		Food and nutrition	-	Ql	Relevant	National/Local
		Health	-	Ql	Relevant	National/Local
		Mortality rates	%	Qn	Relevant	National/Local
		Expected years of schooling	Years	Qn	Relevant and measurable	National/Local
		Education	-	Qn/Ql	Relevant	National/Local
		Gross national income (GNI) per capita	-	Qn	Relevant and measurable	National/Local
		Income and poverty	-	Qn	Relevant and measurable	National/Local
		Energy use	kWh	Qn	Relevant and measurable	National/Local
	Social conflicts	Social conflicts from increased pressure on land	-	Ql	Relevant	Local
		Social conflicts with migrants	-	Ql	Relevant	Local
		Social tensions related to competition and differences between locals and migrants	-	Ql	Relevant	Local
	Safety quality	Accident fatalities/safety	No. of fatalities/kWh	Qn	Relevant and measurable	Local
	Education	Development of knowledge and skills	-	Ql	Relevant	Local

Sustainability Dimension	Themes	Indicators	Measure Units	Analysis: Qualitative or Quantitative	Category of Principles: Relevant and Measurable	Impact Level: Global, Regional, National, and Local
Social	Gender	Policy on gender discrimination	-	Ql	Relevant	National/Local
		Skills	Number of women skilled	Qn/Ql	Relevant and measurable	Local
		Labor employment gap between men and women	% of women employed	Qn/Ql	Relevant and measurable	National/Local
		Extent to which equal opportunities are extended to women and men in the workplace or other measures to improve gender equality	-	Ql	Relevant	Local
		Benefits distribution between men and women	-	Ql	Relevant	Local
	Social acceptability	Local community's opinion Public opinion (share of people with favorable opinion)	%	Qn	Relevant and measurable	Local
		Effective stakeholder participation	%	Qn	Relevant and measurable	Local
		Living conditions		Ql	Relevant	Local
	Resources availability	Use of local energy resources	Yes/No	Ql	Relevant	Local
	Land rights	Land ownership	-	Ql	Relevant	National/Local
		Land transferred in terms of ownership	Yes/No	Ql/Qn	Relevant	National/Local
		Assessment of informal use of the land	-	Ql	Relevant	National/Local
		Land conflicts	Yes/No	Ql	Relevant	National/Local
		Transparency in the process of land acquisition	-	Ql	Relevant	National/Local
		Use of documentation on the land acquisition process	Yes/No	Ql	Relevant	National/Local
		Compensation of previous users of the land	Yes/No	Ql	Relevant	National/Local
		The price paid for land	USD/m^2	Ql	Relevant	National/Local
	Infrastructures	Community infrastructures		Ql	Relevant	Local

Sustainability Dimension	Themes	Indicators	Measure Units	Analysis: Qualitative or Quantitative	Category of Principles: Relevant and Measurable	Impact Level: Global, Regional, National, and Local
Economic	Economic feasibility	Internal Rate of Return (IRR)	%	Qn	Relevant and measurable	Local
		Net present value (NPV)	USD	Qn	Relevant and measurable	Local
		Return on investment (ROI)	%	Qn	Relevant and measurable	Local
		Payback time	Years	Qn	Relevant and measurable	Local
		NPC	USD	Qn	Relevant and measurable	Local
		LCOE	USD/kWh	Qn	Relevant and measurable	Local
		Total project investment cost	USD	Qn	Relevant and measurable	Local
		O&M costs	USD/year	Qn	Relevant and measurable	Local
		Fuel costs (diesel)	USD/year	Qn	Relevant and measurable	Local
		Revenue collection and allocation	USD	Qn	Relevant and measurable	Local
		Willingness to pay	%	Qn/Ql	Relevant and measurable	Local
		Savings	%	Qn	Measurable	Local
	Macroeconomic	Contribution to GDP	USD	Qn	Relevant and measurable	National
		GDP/capita	USD	Qn	Measurable	National
	Employment	Job growth rate	%	Qn	Measurable	National
		Workforce hired locally	%	Qn	Relevant and measurable	Local
		Direct employment	Jobs/Kw	Qn	Relevant and measurable	Local
		Indirect employment	Jobs/Kw	Qn	Relevant and measurable	Local
		Household income	USD/day	Qn	Relevant and measurable	Local
		Change in income	USD/month	Qn	Relevant and measurable	Local
		Percentage of informal jobs, total jobs generated included informal	%	Qn	Relevant and measurable	Local
		Average age of employees		Qn	Measurable	National
		Household income spent on electricity	%	Qn	Relevant and measurable	Local
		Unemployment ratio	%	Qn	Relevant and measurable	Local/National
		Educational level required		Ql	Relevant	Local
		Ratio between local and migrant workers	%	Qn	Relevant and measurable	Local
		Workforce hired locally	%	Qn	Relevant and measurable	Local
	Development of productive uses	Share of electrified households using electricity for income-generating	%	Qn	Relevant and measurable	Local
		Economic activities	Nr. of economic activities	Ql/Qn	Relevant and measurable	Local

Sustainability Dimension	Themes	Indicators	Measure Units	Analysis: Qualitative or Quantitative	Category of Principles: Relevant and Measurable	Impact Level: Global, Regional, National, and Local
Environmental (local environmental indicators)	Damage to ecosystem	Global warming potential	kg $CO_{2\ eq}$./kWh	Qn	Relevant and measurable	Global/regional/ National/local
		Freshwater eutrophication potential	kg $PO_{4\ eq}$./kWh	Qn	Relevant and measurable	Local to Global
		Tropospheric Ozone Precursor Potential		Qn		Local
		Terrestrial ecotoxicity potential	kg DCB$^{a}{}_{eq}$./kWh	Qn	Relevant and measurable	Local
		Acidification potential	kg $SO_{2\ eq}$./kWh	Qn	Relevant and measurable	Local
		Land use/transformation	m^2/kWh	Qn	Relevant and measurable	Local
		Photochemical Ozone Formation		Qn	Relevant and measurable	Local
	Human health	Human toxicity potential	kg DCB$^{a}{}_{eq}$./kWh	Qn	Relevant and measurable	Local
		Ozone layer depletion potential	kg CFC-11 eq./kWh	Qn	Relevant and measurable	Local
		Particulate matter formation potential	kg PM_{10} eq	Qn	Relevant and measurable	Local
		Tropospheric ozone formation	kg NMVOC eq	Qn	Relevant and measurable	Local
		Ionizing radiation	kg U^{235} eq	Qn	Relevant and measurable	Local
		Freshwater ecotoxicity potential	kg DCB$^{a}{}_{eq}$./kWh	Qn	Relevant and measurable	Local
		Marine ecotoxicity potential	kg DCB$^{a}{}_{eq}$./kWh kg	Qn	Relevant and measurable	Local
	Damage to resource availability	Mineral resources	kg Cu_{eq}.	Qn	Relevant and measurable	Local
		Fossil fuels	kg oil_{eq}.	Qn	Relevant and measurable	Local

Appendix A presents the reference list of social, economic, and environmental indicators applied in different studies to evaluate the sustainability of energy projects, including the units, the criteria, and how each indicator could be measured. These indicators were extracted from the following reference list: [10,12,13,17,20–24,29,31,32,41,43,73,105–125].

Appendix B. Composition of the Impact Related to the Diesel-Electric Generating Set for the DG-Only Configuration for Current and Future Scenarios

Diesel-Electric Generating Set	Current Scenario—DG [kgCO_2]	Future Scenario—DG [kgCO_2]
Aluminum	10.6	10.5
Copper	0.168	0.163
Steel	1.86	1.85
Metalworking (aluminum)	3.13	3.12
Metalworking (steel)	2.25	2.24
Battery	0.609	0.601
Electronics	1.45	1.43
Use phase	0.293	0.292
Overall Impact	20.3	20.2

Appendix C. Summary of the Economic Analysis of the Mavumira Project

Indicator	A: Optimized Today's Case		B: Optimized Future Case	
	PV/DG/B	DG Only	PV/DG/B	DG Only
Total expenditures (M USD)	1.524	1.929	2.221	3.275
• Expenditures inside the country (GDP/Value added)	0.392	0.434	0.588	0.738
• Expenditures outside the country (Imports)	1.133	1.495	1.633	2.537
Total jobs	63.1	48.4	115.9	81.5
• Direct jobs	12.6	1.3	35.8	2.1
• Indirect jobs	50.5	47.1	80.1	79.4
Cost of electricity (USD/kWh)	0.52	0.59	0.47	0.63

Appendix D

Appendix D.1. Weighted Normalized Matrix

Scenarios	Energy Alternatives	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Today	PV/DG	0.353	0.319	0.331	0.382	0.468	0.346	0.348	0.345	0.387
	DG only	0.391	0.421	0.034	0.356	0.531	0.679	0.676	0.679	−0.387
Future	PV/DG	0.529	0.460	0.941	0.606	0.423	0.144	0.151	0.141	0.464
	DG only	0.665	0.714	0.055	0.600	0.567	0.631	0.632	0.632	−0.696

Appendix D.2. Rank of Energy Alternatives (Equal Weight Attributed)

Scenario	Energy Alternatives	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	Si+	Si-	Pi	Rank
Today	PV/DG	0.039	0.035	0.037	0.042	0.0520	0.038	0.039	0.038	0.056	0.093	0.096	0.507	2
	DG only	0.043	0.047	0.004	0.040	0.0590	0.075	0.075	0.075	0.019	0.165	0.043	0.207	3
Future	PV/DG	0.059	0.051	0.105	0.067	0.0470	0.016	0.017	0.016	0.093	0.035	0.166	0.825	1
	DG only	0.074	0.079	0.006	0.067	0.0629	0.070	0.070	0.070	0.019	0.164	0.036	0.180	4
	V+	0.074	0.035	0.105	0.040	0.047	0.016	0.017	0.016	0.093				
	V−	0.039	0.079	0.004	0.067	0.063	0.075	0.075	0.075	0.019				

Appendix D.3. Rank of Energy Alternatives (Weight Attributed Based on the Criteria's Importance)

Scenario	Energy Alternatives	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	Si+	Si-	Pi	Rank
Today	PV/DG	0.088	0.024	0.083	0.029	0.0351	0.026	0.026	0.026	0.025	0.174	0.094	0.351	2
	DG only	0.098	0.032	0.009	0.027	0.0398	0.051	0.051	0.051	0.008	0.249	0.031	0.109	4
Future	PV/DG	0.132	0.034	0.235	0.045	0.0317	0.011	0.011	0.011	0.042	0.040	0.244	0.859	1
	DG only	0.166	0.054	0.014	0.045	0.0425	0.047	0.047	0.047	0.008	0.236	0.078	0.250	3
	V+	0.166	0.024	0.235	0.027	0.0317	0.011	0.011	0.011	0.042				
	V−	0.088	0.054	0.009	0.045	0.0425	0.051	0.051	0.051	0.008				

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