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Optimal Sizing and Assessment of Standalone Photovoltaic Systems for Community Health Centers in Mali

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Abstract: Despite abundant solar resources, Mali has remained one of the least electrified countries in the world. Besides daily life activities and the economy, the shortage of electricity has severely affected the quality of healthcare services in the country. In the absence of electrical grids, standalone photovoltaic (PV) systems could be an alternative option in Mali for the electrification of isolated community health centers. However, because standalone PV systems are highly weather-dependent, they must be properly sized according to the local weather conditions. This paper presents the optimal sizing of standalone PV systems for the electrification of community health centers in Mali. The optimization for PV systems was performed for five different locations through simulation and modeling using PVsyst, considering the autonomy of 1 to 3 days and the probability of loss of load for 1 to 5%. Furthermore, for the economic analysis, the levelized cost of electricity (LCOE), payback period and return on investment for the standalone PV systems were calculated. Through the optimization, it was found that the standalone PV systems with PV array sizes ranging from 1650 to 2400 watts, along with 606 Ah battery storage, would be suitable to supply the daily energy demand for community health centers anywhere in the country. Moreover, by only replacing the 606 Ah battery storage with 1212 Ah and 1818 Ah sizes, the PV systems would be able to help and keep the energy reserves for 2 and 3 autonomous days, respectively. Furthermore, the results show that in comparison to a LCOE of 0.94–0.98 USD/kWh for a diesel generator, the LCOE for the standalone PV system would range from 0.23 to 0.46 USD/kWh without discounted rates and from 0.33 to 0.60 USD/kWh if discounted at 6%. In addition to a lower LCOE, the saving of 46–76 tons of CO_2 during the project's lifespan, the short payback periods and high return of investment (ROI) values make standalone PV systems a suitable electrification option for Mali. Considering the total expenses, LCOE, payback period, and ROI, standalone PV systems for community health centers were found to be economically viable in all cases for Mali.

Keywords: standalone photovoltaic systems; optimal sizing; PVsyst; loss of load probability; levelized cost of energy; community health centers; Mali

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Citation: Ali, A.; Volatier, M.; Darnon, M. Optimal Sizing and Assessment of Standalone Photovoltaic Systems for Community Health Centers in Mali. *Solar* **2023**, *3*, 522–543. https://doi.org/10.3390/solar3030029

Academic Editors: Luis Hernández-Callejo and Miguel-Ángel Muñoz-García

Received: 30 July 2023
Revised: 16 August 2023
Accepted: 12 September 2023
Published: 15 September 2023

1. Introduction

Electricity has become one of the essential needs of a modern society. Besides the industrial, commercial and domestic applications, access to reliable electricity has become equally important for healthcare services [1]. It is true that the quality and style of living in most developed countries have improved; however, there are many countries, particularly in Africa, where access to electricity is still a dream for a large proportion of the population [2]. Among these countries, Mali has remained one of the least electrified, where more than 61% of its population is living without electricity [3]. Besides daily life activities, the lack of electricity has severely affected the quality of health services in the country [4]. As healthcare centers are equipped with medical electronics devices and critical temperature-controlled medicines, the access to a reliable supply of electricity is essential [1].

Solar photovoltaic (PV) technology, among the other alternative sources of energy, has become a better choice to use for producing electricity due to its reduced costs and improved efficiency [5]. PV systems are environmentally friendly and can produce electricity without the use of fossil fuels [6]. As PV modules are manufactured to last for more than 20 years, their utilization could save a large amount of CO_2 and other gases during their operational lifespan compared to producing electricity from fossil fuels. The only emissions come from their manufacturing, transportation, installation, and decommissioning, which are offset by the emissions they avoid during their operation. In the past, the cost of PV modules was comparatively high. However, the dramatic reductions in the costs and improvements in the efficiencies of solar cells during the last 10–15 years have made PV technology a suitable option to produce electricity at a lower price [7].

Traditional PV technologies encompass crystalline, silicon-based solar cells, including monocrystalline and polycrystalline variants, which dominate the market, with proven efficiency and reliability. Additionally, thin-film solar cells, like amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), offer flexibility and cost advantages, catering to specific installation needs [8]. However, cutting-edge research in PV efficiencies in recent years centers on novel materials, advanced cell architectures, and precision engineering techniques to achieve record-breaking conversion efficiencies. Tandem solar cells, multi-junction configurations, and innovative light management strategies are being explored to maximize energy extraction from sunlight and revolutionize the solar energy landscape [9]. Excellent light absorption, charge-carrier mobilities, and use lifetimes provided by perovskite materials lead to high device efficiencies and potentially, low-costs, which would contribute to making PV a dominant source of electricity in the coming years [10].

PV modules can directly convert sunlight into electricity; however, electricity produced from PV modules cannot be stored by the PV modules themselves. For grid-connected PV systems, the electricity produced by them can be directly injected into the grids. Therefore, for standalone PV systems, some energy storage devices such as batteries can be used to store the electricity from the PV modules during the daytime [11]. The electricity stored in the batteries can be used at any time, i.e., nighttime or during cloudy weather. The main components of a standalone PV system are provided in Figure 1, where PV panels, batteries, and the usage load (a health center for example here), are connected with a power inverter with a built-in charge controller.

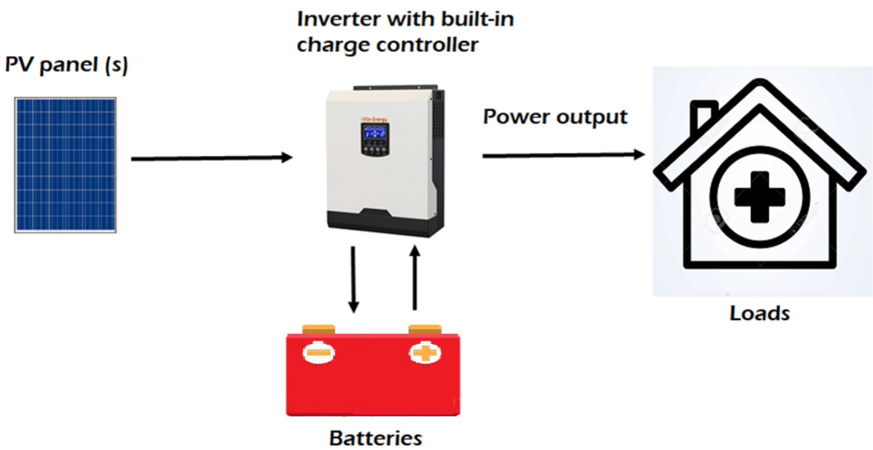

Figure 1. Main components of a standalone PV system.

The added cost from the batteries increases the total cost of the standalone PV system [12]. Therefore, designing standalone PV systems with optimal numbers of PV modules and batteries could significantly reduce the total cost of the system. Photovoltaic technology is considered a reliable renewable source, providing PV projects are sized considering weather and performance variations, since real-world weather conditions are not perfect and static [13]. Several studies have focused on standalone PV system sizing for several countries. However, there are fewer PV studies for Mali. For example, the study of [14] presented the sizing of standalone PV systems for Nigerian household loads using an online tool, "global solar atlas". Moreover, a generalized economic model in [15] was developed to assess the cost–benefit of standalone PV systems for rural areas in Nigeria. The results of these studies indicate that the feasibility of standalone PV systems is highly location-dependent. Moreover, solar irradiation and other weather data for these articles were predicted using the diffuse component of solar radiation. The research in [16] used mathematical modeling for the design and analysis of standalone PV systems. The solar irradiation and other weather data for this study were also taken from the existing published works. The study in [17] presented a numerical approach for a standalone photovoltaic system for the electrification of a household located in a rural area in the western region of Cameroon. Monthly solar irradiation for a period of one year was taken from Photovoltaic Geographical Information System (PVGIS). The work of [18] presented the design of a PV system through a numerical approach for two communities in Gambia. The average monthly solar radiation and temperature were obtained from various sources including the Photovoltaic Geographical Information System (PVGIS). While PV systems have been taken into consideration for rural areas in Africa, there is no evidence in the literature that provides a multi-site analysis in Mali using commercially available software for designing hybrid remote PV systems.

Some studies have also been conducted for the potential use of standalone PV systems for healthcare services. For example, the study in [19] proposed technical and economic evaluation to identify the optimal sizing for an off-grid hybrid energy system made up of PV modules, wind turbines, a diesel generator and batteries for a typical rural healthcare center in Nigeria. The weather data for this study were taken from the NASA website, whereas for the simulations, HOMER software was used. Furthermore, a study in [20] proposed the techno-economic optimization of microgrid systems and its application for a hospital in Uganda. In [21], the feasibility analysis of a hybrid energy system for the electrification of households, schools, health centers, churches, and retail shops in a rural community in South Sudan was presented. The weather data in their study were also taken from NASA. The significance of investigating hybrid PV systems for health centers is underscored by these studies; however, none of them have acknowledged the inherent environmental benefits of utilizing a PV system compared to a diesel generator.

In the present study, we have examined different approaches that have been used for the sizing of standalone PV systems in general and focused more on studying PV application for health-related applications in Mali. On one hand, accuracy and reliability of weather data are very important for the planning and designing of standalone PV systems [22]. On the other hand, the review of the literature for the current study has revealed some critical issues with the reliability and methods of using weather data for the sizing of standalone PV systems. The reliability of standalone PV systems in most existing studies, over their 20-year operational lifespan, has not been taken into account. As a result, the performance of standalone PV systems would start to decrease with the passage of time and PV array and battery storage calculated based on the first year would not be able to fulfill the energy needs at the end of the system's life. Moreover, several studies have followed step-by-step numerical approaches, which require a significant amount of time to calculate and summarize many parameters for a 20-year PV project.

In contrast to analytical approaches, simulation software offers easier and more accurate PV system sizing by considering complex variables and real-world conditions. The details of widely used simulation tools can be found in [23,24], and we have reported a comparison of the main simulation tools in Table 1 that have been used in the literature for the sizing of PV systems. We can see that each tool has its own advantages and limitations. Considering the importance of reliable weather data and the need for quick calculations for 20-year PV projects, PVsyst seems the best choice for modeling long-term projects at multiple sites.

Table 1. Comparison of simulation tools used for the sizing of PV systems.

Software/Tool	Advantages	Disadvantages
SAM	User-friendly; easy to understand	Limited weather analysis
PVsyst	Extensive meteorological and PV system component databases; has ability to identify the weaknesses of the system design through loss diagram; results include several dozens of simulation variables	Inability to handle shadow analysis
HOMER	Determines the possible combinations of a list of different technologies; has optimization algorithms used for feasibility and economic analysis	Inability to guess missing values or sizes; complex and time-consuming; detailed input data are needed
PV*SOL	Vast meteorological database; strong component database	Complexity in building and site modeling; advanced scientific calculation is not supported
RETScreen	Strong meteorological and product database; high strength in financial analysis	No option for time series data; does not support advanced calculations
Analytical/ numerical	User-defined	Extensive time and complexity in calculating large number of variables and summarizing results

The use of a professional tool such as PVsyst software, with built-in formulations and reliable sources of weather data, could help in designing standalone PV systems quickly and with more accuracy. PVsyst is a well-known modeling and simulation program used to design and optimize different types of PV systems such as standalone, grid-connected, DC grid, and water pumping systems [25]. It has been used in many studies related to the sizing of PV systems [26–28]. PVsyst adapts and makes the use of the extended knowledge pool and database of PV technology and contains meteorological irradiation data for many countries, including Mali. Considering these features, we have used PVsyst for the optimal sizing and assessment of standalone PV systems for community health centers in Mali. The novelty in sizing a standalone PV system using PVsyst lies in the comprehensive capabilities to accurately model and simulate several operational lifespan parameters of a PV installation, leading to more informed decision making, optimal design, and better predictions of system performance. In addition to using PVsyst, the sizing of standalone PV systems through their technical, economic, and environmental assessment would lead to a cost-effective and a reliable supply of electricity that would be able to fulfill the demand at the end of the project's life. This can ultimately result in the implementation of more efficient, reliable, and cost-effective PV systems for community health centers.

2. Materials and Methods

2.1. Locations and Meteorological Data

This study was conducted in order to find the optimal sizes for standalone PV systems for community health centers located in Bamako, Kayes, Kolokani, Sikasso, and Barouéli. Bamako is the capital and largest city of Mali. Geographically, Bamako is located at latitude 12°37′ North and longitude 8°1′ West. The location of Bamako and the rest of the sites are mapped through a global solar atlas [29] and are shown in Figure 2. While this distribution of solar resources shows increased solar potential toward the northern areas, the choice of five locations in the southern areas is mainly due to their higher populations and the related development plans for the country.

The meteorological data for the five sites under current study were extracted from the meteorological database available in PVsyst. According to the meteorological data, the monthly horizontal global irradiance (GHI) received at Bamako ranges between 150 and

193 kWh/m^2, with lowest solar irradiance in the months of December and the highest solar irradiance in the month of July. The daily average GHI received at Bamako is 5.65 kWh/m^2/day and cumulatively, Bamako receives 2060 kWh/m^2 of GHI per year. Moreover, the ambient temperature at Bamako ranges between 24.5 °C and 32.4 °C, with the average annual temperature of 27.8 °C. The lowest and highest temperatures are observed in the months of January and April, respectively. In addition, wind speed at Bamako ranges from 1.8 to 3.5 m/s. The annual GHI for other sites ranges between 1980–2080 kWh/m^2. The summary of the annual GHI in kWh/m^2 and average ambient temperatures of the five locations are provided in Figure 3. The meteorological statistics provided in Figure 3 evidence the great potential and encourage the use of solar energy in Mali and the weather conditions at the five sites are very competitive compared to many countries, such as Australia, China, and India. Note that for the Kayes site, the average temperature is slightly higher and the annual GHI is slightly lower than for other sites. However, even with lower irradiance, this site is well suited to solar projects.

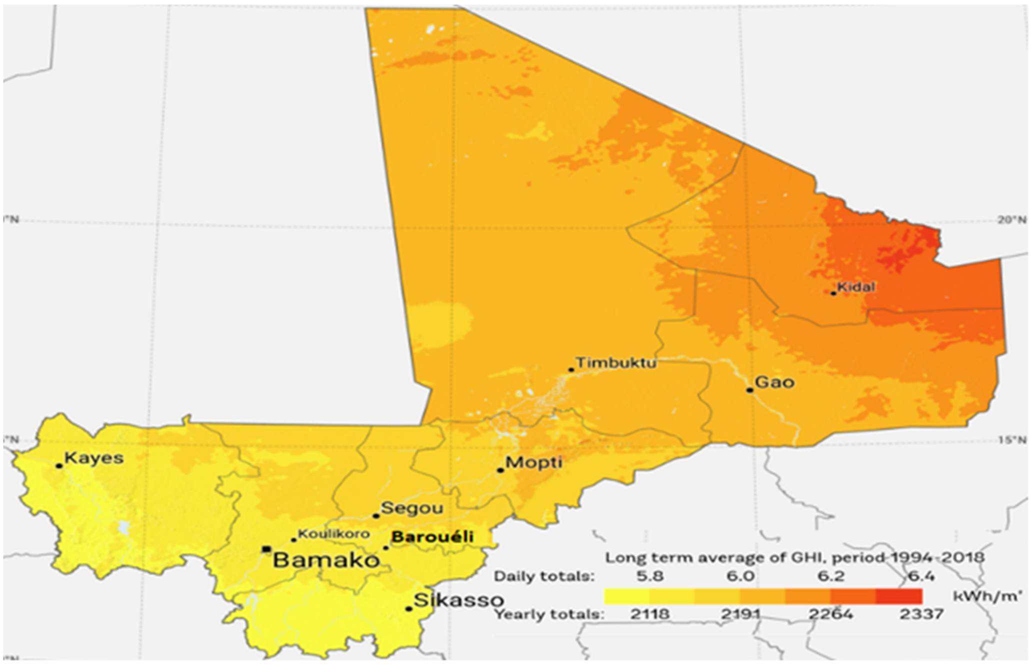

Figure 2. Locations and distribution of solar resources at potential sites.

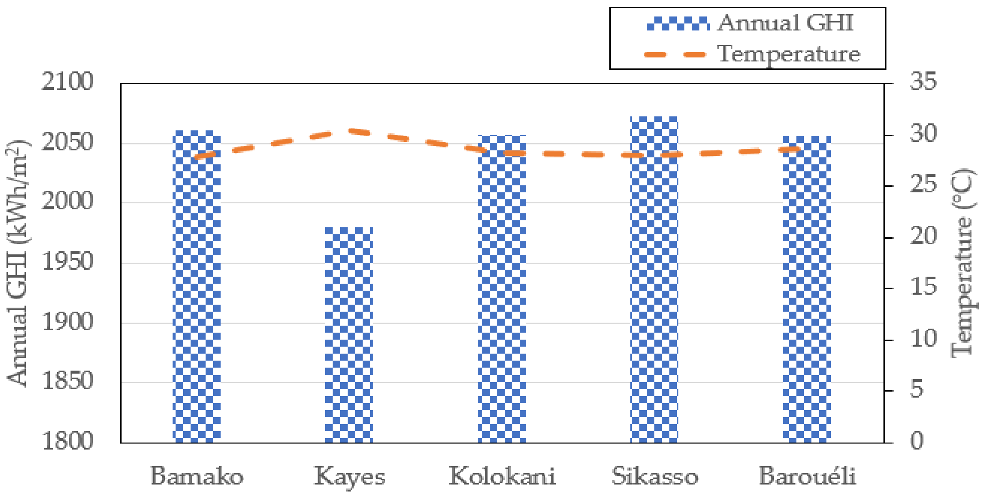

Figure 3. Annual GHI and ambient temperature at the potential studied sites.

2.2. Orientations for Installation of PV Modules

PV panels produce maximum energy when they are positioned directly facing the sun and receive the solar irradiation at a normal angle (90 degrees). However, the position of the sun with respect to the Earth keeps changing throughout the day and seasons. Therefore, it is very important to install the PV panels in an alignment that PV panels should receive maximum sunlight throughout the day and seasons. One way of doing this is through the use of motorized trackers, which ensure that the PV panels are facing toward the sun all times with the help of a programmed tracker controller [30]. However, such motorized trackers are costly and require regular maintenance [31]. They are therefore not suitable for small-scale standalone PV systems. Another way to maximize energy production is to install PV panels at proper tilt and azimuth angles that optimize the annual sunlight collection. Considering this, we chose a PV installation with a fixed tilt angle. The optimum tilt and azimuth angles for the potential sites were calculated using PVsyst, based on transposition factor, and it was found that with a tilt fixed at 15° from the ground and an azimuth angle of 0°, i.e., facing south, the maximum annual global irradiation on the collector plane at the potential sites can be achieved. The transposition factor (FT) is the ratio of the incident irradiation on the plane to the horizontal irradiation. The FT shows yield gains for each tilt and azimuth angle used. It was found that with 15° tilt angle, annual global irradiation on the collector plane could reach up to 2117 kWh/m^2 at Bamako, 2030 kWh/m^2 at Kayes, 2121 kWh/m^2 at Kolokani, 2117 kWh/m^2 at Sikasso, 2110 kWh/m^2 at Barouéli. Overall, the tilting of PV modules at 15° helped to increase the annual global irradiances on the collector plane by 2.7%, 2.5%, 2.9%, 1.8%, and 3.2%, respectively, compared to the annual global irradiation on horizontal plane.

Electrical Loads for Community Health Centers

Details of electrical loads and their daily operational durations are very important in estimating the daily energy demands and peak loads for a standalone PV system. We have used a generic load for community health centers in African countries provided by the World Health Organization (WHO) [1]. The details of electrical loads for community health centers and their daily operational durations are provided in Table 2; the total daily energy demand for each community health center is estimated to be ~6000 Wh. Using the daily operational timings provided by WHO for each appliance at the community health centers, a 24 h daily electrical demand curve has been generated and is shown in Figure 4. This load profile has been considered for each day of the modeling, regardless of the season.

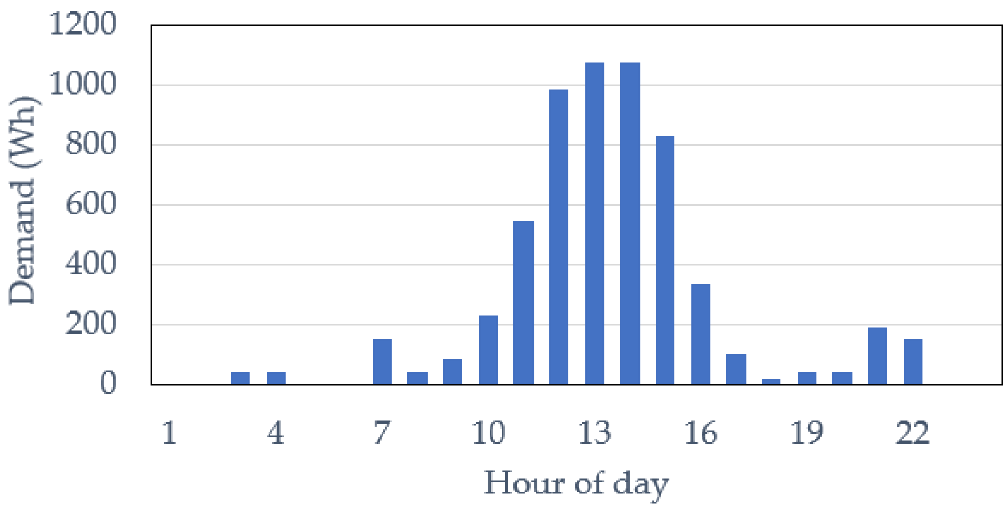

Figure 4. Generic hourly electrical demand of a community health center in Africa.

Table 2. Generic electrical loads and daily energy needs for community health centers in African regions [1].

Description	Quantity	Power (Watts)	Total Power (Watts)	Operation Duration (Hours/Day)	Energy (Wh)
Refrigerator-vaccines	1	40	40	10	400
Refrigerator-non-medical	1	150	150	5	750
Centrifuge	2	242	484	4	1936
Microscope	2	20	40	6	240
Blood chemical analyzer	1	45	45	4	180
Hematology analyzer	1	230	230	4	920
CD4 machine	1	200	200	4	800
Radio	1	15	15	2	30
Tubular LED lights	4	18	72	8	576
Desktop computer	1	30	30	4	120
Total			1306 watts		5952 Wh

2.3. Sizing Methodology for Standalone PV Systems in PVsyst

The modeling and simulations of standalone PV systems have been performed using PVsyst software [32]. PVsyst helps to determine the number of PV modules and sizes for the balance of system (BOS) and evaluates the performance of PV systems through calculating several important parameters. Setting up PVsyst software using the primary data is the first step for the modeling and simulation for standalone PV systems for Mali. For the modeling and simulations, following information has to be provided by the user as input to PVsyst:

I. Meteorological data, as provided in Section 2.1.
II. PV module orientation, as provided in Section 2.2.
III. Project energy needs, as provided in Section 2.3.
IV. Probability of loss of load (PLOL). This generic term refers to the percentage of the energy demand that cannot be supplied by electrical generators [33]. In PVsyst, PLOL is the percentage of time during which PV installation cannot meet the project's needs. For example, with 1% of PLOL, there is a probability that 3.65 days may suffer from a shortage of energy. The value of PLOL is very important to consider in PVsyst for standalone PV systems. The sizing of PV arrays and battery storage is significantly influenced by the PLOL value used. In literature, PLOL is seen to vary between 2 and 10% for renewable energy systems [34,35]. For sensitivity analysis and impact of varying PLOL on the sizing of PV arrays, a PLOL with values ranging from 1 to 5% is considered.
V. Autonomy days. For standalone PV systems, calculation for batteries is the first step in the design process. The number of batteries required is mainly dependent on the daily energy consumption by the loads and the number of autonomy days. Autonomy days refer to the number of days that battery will be capable of providing the required daily needs without the support of the PV modules. Autonomy days are very important to consider for cases such as monsoon seasons or similar weather conditions, when there is a possibility that Sun may not shine for one or more days. Generally, choice of autonomy days for standalone PV systems depends on the weather conditions or the user preference. Because prices of batteries are very high at the moment, the choice of autonomy days has to be made very carefully. Any increase in autonomy days will increase the number of batteries, and ultimately, this will increase the total cost and make the PV system more expensive. In the literature, autonomy is seen to vary from 1 to 3 days [36–38]. For sensitivity analysis and impact of autonomy days on the sizing and overall performance of the PV system, during the modeling and simulation for this study, 1, 2, and 3 autonomy days were considered.

The modeling framework based on deterministic approach using PVsyst with the user inputs provided for optimization and the output parameters calculated by the PVsyst software is provided in Figure 5.

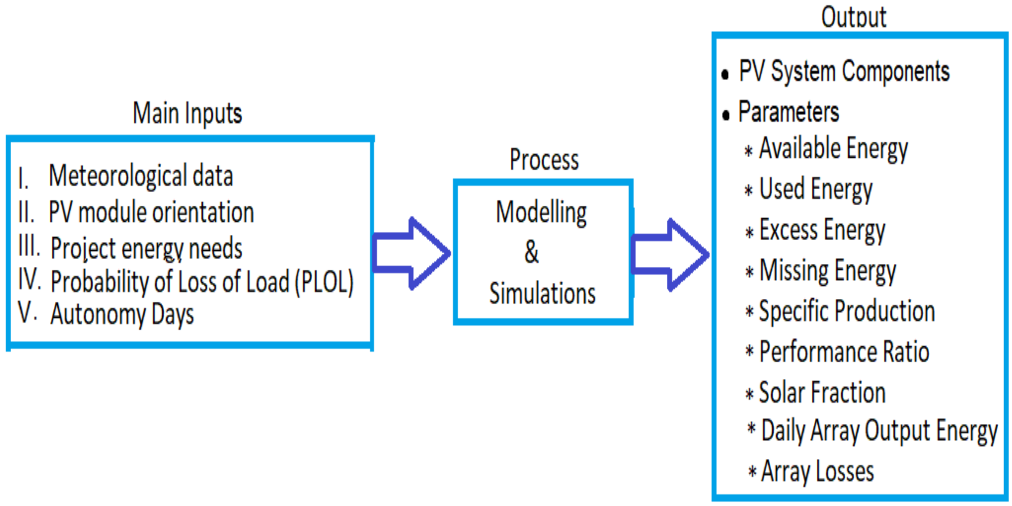

Figure 5. Modeling and simulation framework used for PVsyst.

The technical and economical evaluation of this study was performed using the following parameters.

2.3.1. Solar Fraction

The solar fraction is defined as the percentage of the entire electrical demand of the load supplied by the standalone PV system over a period of time [39]. Mathematically, it can be calculated using the following equation.

$$\text{Solar Fraction} = \frac{\text{Electricity supplied to the load by standalone PV System}}{\text{Total electrical demand}} \tag{1}$$

2.3.2. Performance Ratio (PR)

The performance ratio (PR) for standalone PV systems is the ratio of the energy effectively supplied to the load (kWh) with respect to the theoretical reference yields that would be produced by the system under standard test conditions (STC) [40,41]. Mathematically, this can be represented as follows.

$$\text{PR} = \frac{\text{Electricity supplied to the load by standalone PV system (kWh)}}{\text{Annual GHI}\left(\frac{\text{kWh}}{\text{m}^2}\right) * \text{PV surface area } (\text{m}^2) * \text{PV module efficiency}} \tag{2}$$

2.3.3. Levelized Cost of Electricity (LCOE)

The levelized cost of electricity (LCOE), also referred as levelized cost of energy (LCOE), is used for electrical systems to calculate the cost of producing one unit of electricity (USD/kWh). LCOE for standalone energy systems is calculated by dividing the operational lifespan cost of system with total electricity supplied to the loads [42,43]. Mathematically, LCOE for standalone PV systems can be represented as follows [44].

$$\text{LCOE} = \frac{\text{Lifecycle cost of PV project (\$)}}{\text{Total electricity supplied to the loads by standalone PV system (kWh)}} \tag{3}$$

The operational lifespan cost includes the initial cost of capital, operations, and maintenance and the cost of replacement (i.e., batteries and electronic equipment). Despite the fact that the cost of purchases and maintenance for this project comes from subventions

(United Nations Development Program), to evaluate the financial viability for standalone PV systems in Mali, LCOE has been calculated using two assumptions. Based on the first assumption, LCOE is calculated using Equation (3) by just breaking down the cost of standalone PV project into cost per kWh supplied to the loads (USD/kWh). In this case, we do not consider inflation nor price evolution (e.g., diesel price) and time value of money. With regard to the second assumption, time value of money is considered and LCOE is calculated using a discount rate. The LCOE at discount rate is calculated as follows [44,45].

$$\mathrm{LCOE} = \frac{\text{Initial costs} + \sum_{n=1}^{N} \frac{\text{O\&M (\$)}}{(1+\mathrm{DR})^{n}} + \sum_{n=1}^{N} \frac{\text{Replacements costs(\$)}}{(1+\mathrm{DR})^{n}}}{\sum_{n=1}^{N} \frac{\text{Annual electricity supplied to the load by standalone PV system (kWh)}}{(1+\mathrm{DR})^{n}}} \quad (4)$$

where, N is the project lifetime and DR is the discount rate. Considering economic aspects, the per unit cost of electricity for PV systems significantly depends on several factors including the geographical locations and discount rates [46]. For PV projects in African countries, this value is seen to range between 4 and 8% [45,47,48]. As an average, discount rate of 6% is used for Mali.

2.3.4. Payback Period

The payback period is the period required to recoup the funds expended in an investment, starting from the investment year. The payback period for standalone PV systems can be calculated by following [49]:

$$\text{Payback period} = \frac{\text{Lifecycle cost of standalone PV project (\$)}}{\text{Total revenues (\$)/Project lifetime (years)}} \quad (5)$$

2.3.5. Return on Investment (ROI)

Return on investment (ROI) is a popular profitability metric used to evaluate how well an investment has performed. ROI for standalone PV systems is expressed as a percentage and is calculated by dividing project's net profit by operational lifespan cost of standalone PV project. Mathematically, it can be expressed as follows [50]:

$$\mathrm{ROI} = \frac{\text{Total revenues (\$)} - \text{Lifecycle cost of standalone PV project (\$)}}{\text{Lifecycle cost of standalone PV project (\$)}} * 100 \quad (6)$$

Similar to the LCOE, payback period and return on investment (ROI) for the two cases shall be calculated separately with and without the use of the discount rate.

2.4. Optimization Flowchart

The optimal sizing for standalone PV systems for Mali was performed based on the technical, economic, and environmental assessments for all the PV arrays calculated based on PLOL and autonomy days used. The step-by-step process for optimal sizing for standalone PV systems used for each location is explained through the flowchart, as shown in Figure 6.

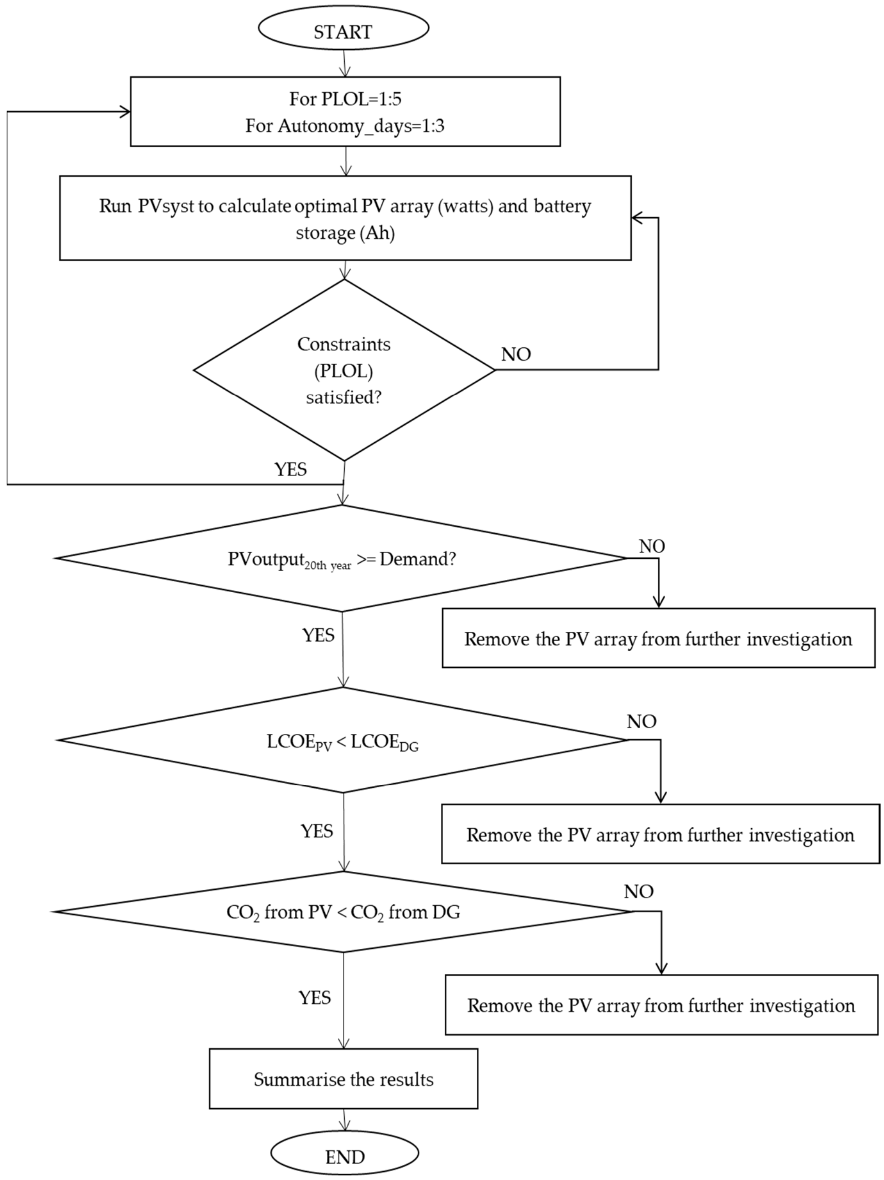

Figure 6. The flowchart showing the step-by-step process for sizing and optimization for standalone PV systems.

3. Results and Discussion

The sizing of standalone PV systems for community health centers in Mali was carried out through modeling and simulation using the daily energy demands and meteorological data provided in the Materials and Methods section of this paper; using the input values for PVsyst provided in Table 3; and using the PV modules, battery storage, and inverter provided in Table 4. Moreover, detailed technical specifications and the V-I curve for the PV module used in this study are provided in Table 5 and Figure 7, respectively.

The sizes of PV arrays and batteries calculated using PVsyst for Bamako are provided in Table 6. During the simulation, PVsyst, with its built-in global system optimization process, will choose the minimum PV size and battery storage which just meets the required PLOL. It was found that the sizes of PV arrays calculated for 1-day autonomy are 2400, 1800, and 1650 watts when the value of the PLOL is 1%, 2% and 3%, respectively. The size of the battery for 1-day autonomy was calculated as 606 Ah. There is no further change when the PLOL is increased from 3% to 4 and 5%.

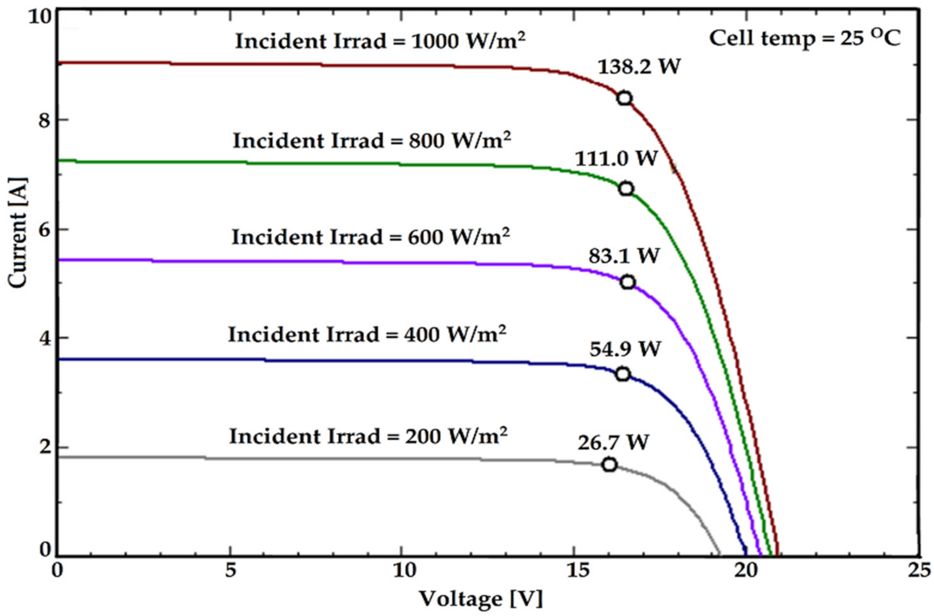

Figure 7. V-I curve for PV module used in our study.

Table 3. Inputs for modeling and simulations used for PVsyst.

Location	Bamako, Kayes, Kolokani, Sikasso, and Barouéli
Source of meteorological data	Metenorm within PVsyst
Daily energy demand	5.95 kWh
Peak load	1306 watts
System voltage	12 Volts
Number of autonomy days	1, 2 and 3 days
Value of PLOL	1%, 2%, 3%, 4% and 5%

Table 4. General specifications for PV system components.

Component	Technology	Manufacturer	Model	Availability in PVsyst Databse
PV Module	Poly-silicon	Generic	Poly 150 Wp 36 cells	Available
Battery	Lithium ion LFP	Victron Energy	LFP-CB 12.8/200	Available
Inverter	Hybrid solar inverter	Primax	Venus 2000	Manually added

Table 5. Technical specifications for PV module used.

Description	Unit	Value
Maximum power rating (Pmax)	Wp	150
Maximum power voltage (Vmp)	V	17.80
Maximum power current (Imp)	A	8.43
Open circuit voltage (Voc)	V	22.40
Short circuit current (Isc)	A	8.93
Module efficiency	%	16.99
Normal operating cell temperature (STC)	[°C]	25
Short circuit temperature coefficient Isc	[%/°C]	0.6
Open circuit voltage temperature coefficient Voc	[mV/°C]	−0.73
Maximum power point temperature coefficient Pmp	[%/°C]	−0.40

The increase in autonomy from 1 to 2 days doubled the sizes of batteries, i.e., a 1212 Ah; however, at the same time, the size of the PV was reduced. The size of PV arrays for 2 autonomy days is 1800 watts for PLOL = 1%, 1650 watts for PLOL = 2 and 3%, and 1500 watts when PLOL = 4 and 5%.

Table 6. Sizes of PV-batteries calculated using PVsyst for Bamako.

Autonomy Days	System Size	PLOL (%)				
		1	2	3	4	5
1	PV array (watts)	2400	1800	1650	1650	1650
	Battery (Ah)	606	606	606	606	606
2	PV array (watts)	1800	1650	1650	1500	1500
	Battery (Ah)	1212	1212	1212	1212	1212
3	PV array (watts)	1650	1650	1500	1500	1500
	Battery (Ah)	1818	1818	1818	1818	1818

Similarly, the increase in autonomy from 2 to 3 days resulted in a similar increase in the sizes of batteries, reaching 1818 Ah. The sizes of PV arrays for 3 autonomy day are 1650 watts for PLOL = 1% and 2%, whereas it is 1500 watts for PLOL = 3, 4 and 5%.

Therefore, we can say that the size of the battery is dictated by the number of autonomy days required, while the size of the PV array depends on the acceptable PLOL. Irrespective of PLOL, the minimum PV array size required for each location was found to be 1500 watts, whereas the maximum size of PV array was found to vary and depended on weather conditions. The summary of minimum and maximum PV array sizes for each location is provided in Table 7.

Table 7. Minimum and maximum PV arrays sizes calculated for Kayes, Kolokani, Sikasso, and Barouéli.

Location	PV Array Size (Watt)	
	Min	Max
Bamako	1500	2400
Kayes	1500	2550
Kolokani	1500	2550
Sikasso	1500	2550
Barouéli	1500	2250

3.1. Technical Evaluation

Since the sizes of PV arrays and batteries have been determined, the next step is to evaluate the technical performance of each PV battery system, i.e., of each autonomy-day/PLOL configuration. Table 4 summarizes the study in Bamako. It presents the annual PV energy production, the unused PV energy (when batteries are full), the missing energy and the energy supplied to the community health center during the first year. In addition, Table 8 presents the solar fraction and the performance ratio of each configuration. As a reminder, in Table 1, the daily energy needs of a generic community health center is estimated to be ~6000 Wh a day; thus, the yearly demand reaches 2281 kWh, including the inverter losses.

Table 8. Technical performance of standalone PV systems during the first year.

Autonomy Days/PLOL	System Size	PV Energy Produced (kWh)	PV Energy Unused (kWh)	Energy Missing (kWh)	Energy Supplied (kWh)	Solar Fraction (%)	Performance Ratio (%)
1D/1%	2400 W 606 Ah	3784.9	1447.7	1.0	2279.8	99.90	46.10
1D/2%	1800 W 606 Ah	2814.9	492.4	2.8	2278.0	99.90	61.40
1D/3–4–5%	1650 W 606 Ah	2572.7	268.8	17.2	2263.7	99.20	66.60
2D/1%	1800 W 1212 Ah	2814.9	478.1	0.0	2280.9	100	61.50
2D/2–3%	1650 W 1212 Ah	2571.8	248.1	0.0	2280.9	100	67.00
2D/4–5%	1500 W 1212 Ah	2331.6	66.3	52.1	2228.8	97.70	72.10
3D/1–2%	1650 W 1818 Ah	2571.2	241.3	0.0	2280.9	100	67.10
3D/3–4–5%	1500 W 1818 Ah	2331.3	58.1	43.2	2237.7	98.10	72.40

From the results presented above, can be seen that the amount of energy produced by PV modules for each case is greater than the annual demand, even though for 1 autonomy day, 1, 2.8, and 17.2 kWh of energy are seen to be missing for 2400, 1800, and 1650 W arrays, respectively. The solar fraction (SF) for each case can be determined from the amount of missing energy. The SF for the 2400, 1800, and 1650 W arrays is 99.9, 99.9, and 99.2%, respectively. Besides the amount of missing energy, a significant amount of unused energy for each case can also be observed: 1447.7, 492.42, and 268.8 kWh for 2400, 1800, and 1650 W arrays, respectively. This amount of unused energy directly affects the performance ratio (PR) of the standalone PV system: 46.1%, 61.4%, and 66.6%, respectively for 2400, 1800, and 1650 W.

For 2 autonomy days, the size of the batteries required increased to 1212 Ah, and due to the increased size of the batteries, the amount of unused energy was reduced: 478.1, 248.1, and 66.3 kWh, respectively for the 1800, 1650, and 1500 W arrays. The amount of missing energy also decreased to zero for the 1800 and 1650 W arrays; however, it is 52.1 kWh for the 1500 W array. The PR for 1500 W array significantly improved: 72.1%, whereas it is 61.5% for the 1800 W array and 67% for the 1650 W array.

For the 3 autonomy days, the size of batteries required increased to 1818 Ah. The amount of missing energy for the 1650 W array is 0; however, it is 43.17 kWh for the 1500 W array. Moreover, due to the reduced amount of unused energy, the PR for 1500 W array increased to 72.4% when SF = 98.1%. For the 1650 W array, the PR is 67.1% when SF = 100%.

Overall, we can see that all combinations of batteries and PV array sizes adhere to the specifications given on the PLOL. It is worth noting that the PV fraction for each case is always larger than the PLOL. In addition to Bamako, the most efficient (in terms of performance ratio) PV arrays, considering each autonomy day, for Kayes, Kolokani, Sikasso, and Barouéli are provided in Table 9.

Table 9. PV arrays with maximum performance ratio at Kayes, Kolokani, Sikasso, and Barouéli.

Location	Autonomy Days	System Size	Solar Fraction (%)	Performance Ratio (%)
Kayes	1	1650 W 606 Ah	98.60	67.28
	2	1500 W 1212 Ah	96.60	72.50
	3	1500 W 1818 Ah	100	53.63
Kolokani	1	1500 W 606 Ah	98.26	70.68
	2	1500 W 1212 Ah	99.12	71.30
	3	1500 W 1818 Ah	99.51	71.58
Sikasso	1	1500 W 606 Ah	98.69	71.09
	2	1500 W 1212 Ah	99.55	71.71
	3	1500 W 1818 Ah	99.70	71.82
Barouéli	1	1500 W 606 Ah	98.55	71.12
	2	1500 W 1212 Ah	99.64	71.90
	3	1500 W 1818 Ah	100	72.16

PV projects are designed to last for 20–25 years, and we have considered 20 years in our case. The output from PV modules each year depends on the efficiency degradation rate specified by the PV module manufacturer. Most PV modules are designed to produce electricity with 100% efficiency during the first year and from the second year onward, PV modules continue their production with a degradation rate of 0.5% a year [51]. Considering the yearly decline in PV array energy production, the electricity produced by a PV module during the 20th year will not be same as the electricity produced during the 1st year [52]. Therefore, during the planning for the sizing of PV modules, the efficiency of PV modules at the 20th year should be considered, in order to avoid energy imbalances. The sizing of the PV array should be carried out in a proper way so that the PV array should be capable of meeting the energy demands at the end of the 20th year.

To evaluate the performance of electricity production, the annual yields for the 2400, 1800, 1650, and 1500 W PV arrays were calculated in order to determine whether the electricity produced with these arrays will meet the annual electricity demands at the 20th year of operation or not. The annual electrical production for the 2400, 1800, 1650, and 1500 W arrays, starting from the 1st to the 20th year, are plotted in Figure 8. The total annual demand for community health centers is considered constant at 2281 kWh. Except for the 1500 W array, the annual yields from the 2400, 1800 and 1650 W arrays are seen to be higher than the annual electrical demand for community health centers through the project's operational lifespan: 3441, 2559, and 2339 kWh, respectively at the 20th year. Starting from the 6th year of the project's life (highlighted with a dashed red line), the annual production from the 1500 W array would become lower than the annual electrical demand. From this, it was found that the 1500 W array would not be a suitable choice for community health centers; therefore, this option is not considered in the following part of this study.

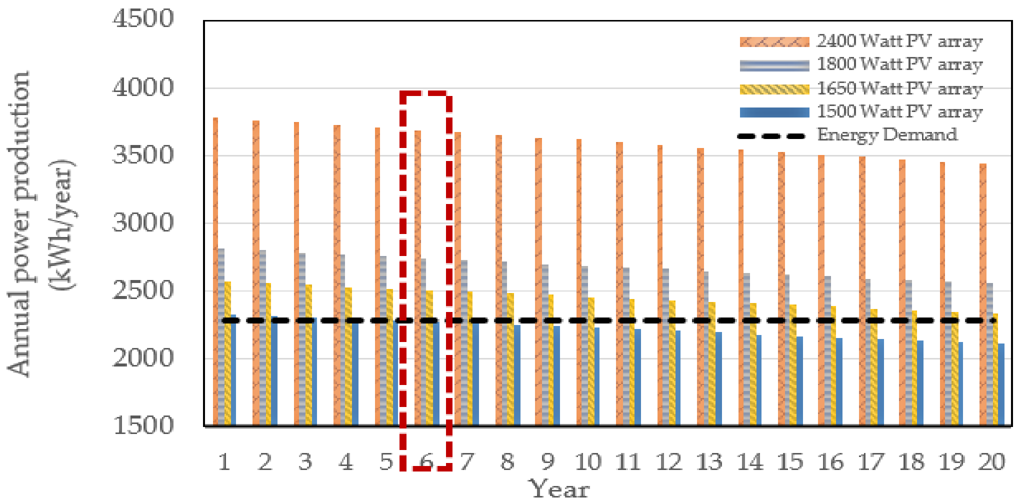

Figure 8. Annual power productions from each PV arrays at Bamako.

3.2. Economic Evaluation

Standalone PV systems require capital for the purchasing and installation of equipment, annual cost for operation and maintenance (OM), and replacement cost of some equipment such as batteries and inverters during the operational life of the project. However, PV systems have a low OM cost. (Spending is mainly required for the periodic cleaning of the PV modules). The cost of purchasing PV modules, batteries, and inverters at the beginning of the project and cost of replacing batteries and inverters during the project are dominant over other costs.

The economic evaluation for standalone PV systems was performed based on their cost comparison with diesel generators. The LCOE for two electrical systems, considering the operational lifespan cost over 20 years at discount rates of 0% and 6%, were calculated. Furthermore, using the LCOE for diesel generators as an energy benchmark (electricity selling tariffs for standalone PV systems), revenue, payback periods, and return on investments for PV systems were calculated.

The operational lifespan costs for two electrical systems were calculated using the data, as provided in Tables 10 and 11. These data have been taken from different reports and documents published on energy systems [1,53–55].

Table 10. Prices of components for PV system and diesel generator.

	Equipment	**Cost**
PV System	PV modules + BOS	2 USD/W
	Battery	0.18 USD/Wh
	Inverter	0.32 USD/W
Diesel	Diesel generator	1 USD/W

Table 11. Assumptions of fuel cost and CO_2 generation from two electrical systems.

	Description	Value
Diesel	Fuel consumption (liters/kWh)	0.4
	Fuel Price (USD/liter)	1.2
	Diesel OM (USD/kWh)	0.2
	Fuel price increase per year (%)	5
	CO_2 from diesel generator (kg/liters)	2.6
PV System	PV OM (USD/kW)	28.94
	CO_2 from PV systems (kg/kWh)	0.085

Moreover, during the calculations, the operational lifespan of each piece of equipment, as provided in Table 12, has been used.

Table 12. Operational lifespan of each piece of equipment.

Equipment	Operational Lifespan (Years)
PV modules	25
Battery	5
Inverter	10
Diesel generator	20

The cumulative expenses for a standalone PV system and diesel generator at discount rates of 0% and 6% were calculated, and the comparison of the two case studies is provided in Figures 9 and 10. The total expenses, including capital cost and OM incurred for the PV systems over 20 years, is between USD 10,575 and 12,515 for 1 autonomy day, USD 15,810 and 16,205 for 2 autonomy days, and USD 21,050 for 3 autonomy days. The total expenses for a diesel generator are USD 44,841.

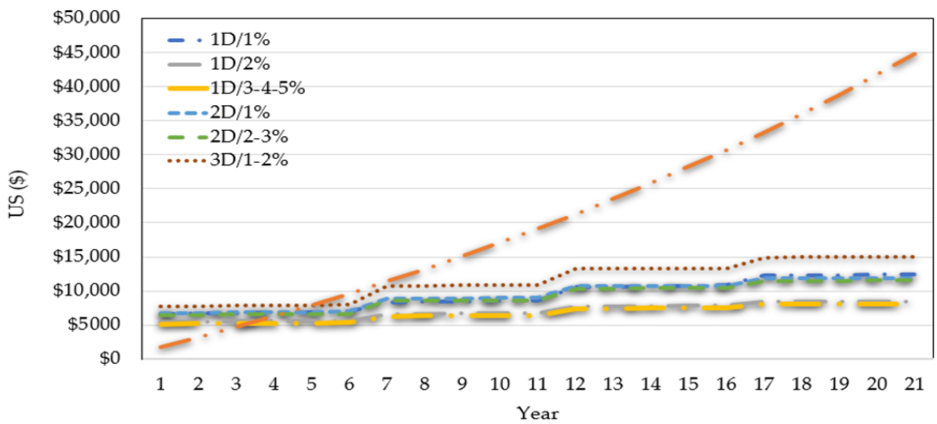

Figure 9. Cumulative annual expenses for PV and diesel generator at a discount rate of 0%. xD/y% represents conditions for x days of autonomy and y PLOL.

With annual electrical demand of 2281 kWh/year, it would reach 45,622 kWh over 20 years for a diesel generator. On the basis of calculations for 20 years, the LCOE for diesel generators was found to be 0.98 USD/kWh at a discount rate of 0% and 0.94 USD/kWh at a discount rate of 6%. In comparison to the diesel generator, the LCOE of standalone PV systems was found to be much lower. The LCOE for a standalone PV system with 1 autonomy day was between 0.23 and 0.27 USD/kWh, 0.35 and 0.36 USD/kWh for 2 autonomy days, and 0.46 USD/kWh for 3 autonomy days at a discount rate of 0%. For a discount rate of 6%, the LCOE for a standalone PV system with 1 autonomy day was between 0.31 and 0.38 USD/kWh, 0.44 and 0.45 USD/kWh with 2 autonomy days, and 0.57 USD/kWh with 3 autonomy days The summary of the cumulative expenses and LCOE for the two electrical systems over 20 years at discount rates of 0% and 6% are provided in Tables 13 and 14.

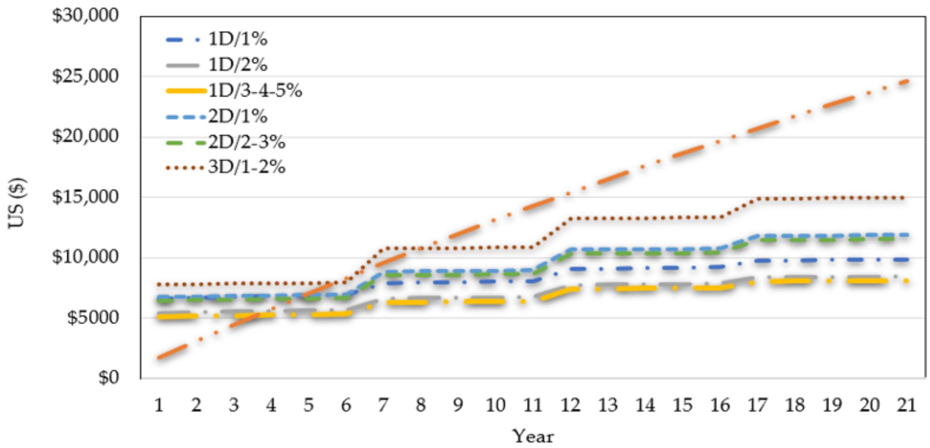

Figure 10. Cumulative annual expenses for PV and diesel generator at a discount rate of 6%. xD/y% represents conditions for x days of autonomy and y PLOL.

Table 13. Operational lifespan project expenses and LCOE for PV and diesel system at discount rate of 0%.

Autonomy Days/PLOL	System Size	Expenses—PV ($)	Expenses—DG ($)	LCOE-PV ($/kWh)	LCOE-DG ($/kWh)
1D/1%	2400 W 606 Ah	12,512	44,841	0.27	0.98
1D/2%	1800 W 606 Ah	10,965	44,841	0.24	0.98
1D/3–4–5%	1650 W 606 Ah	10,578	44,841	0.23	0.98
2D/1%	1800 W 1212 Ah	16,201	44,841	0.36	0.98
2D/2–3%	1650 W 1212 Ah	15,814	44,841	0.35	0.98
3D/1–2%	1650 W 1818 Ah	21,050	44,841	0.46	0.98

Table 14. Operational lifespan project expenses and LCOE for PV and diesel system at discount rate of 6%.

Autonomy Days/PLOL	System Size	Expenses—PV (USD)	Expenses—DG (USD)	LCOE-PV (USD/kWh)	LCOE-DG (USD/kWh)
1D/1%	2400 W 606 Ah	9864	24,676	0.38	0.94
1D/2%	1800 W 606 Ah	8465	24,676	0.32	0.94
1D/3–4–5%	1650 W 606 Ah	8115	24,676	0.31	0.94
2D/1%	1800 W 1212 Ah	11,901	24,676	0.45	0.94
2D/2–3%	1650 W 1212 Ah	11,551	24,676	0.44	0.94
3D/1–2%	1650 W 1818 Ah	14,988	24,676	0.57	0.94

A comparison of the LCOE for the two electrical systems at discount rates of 0% and 6% is provided in Figure 11.

To calculate the profitability of the standalone PV systems, the LCOE for a diesel generator from was considered as a benchmark. It was assumed that the energy produced from the PV arrays equals the total energy demand and is sold to community health centers at the price of the LCOE of diesel generators. Using the LCOE for diesel generators, the total revenue, profitability, return on investment (ROI), and payback periods for standalone PV systems at discount rates of 0% and 6% were calculated and are presented in Tables 15 and 16.

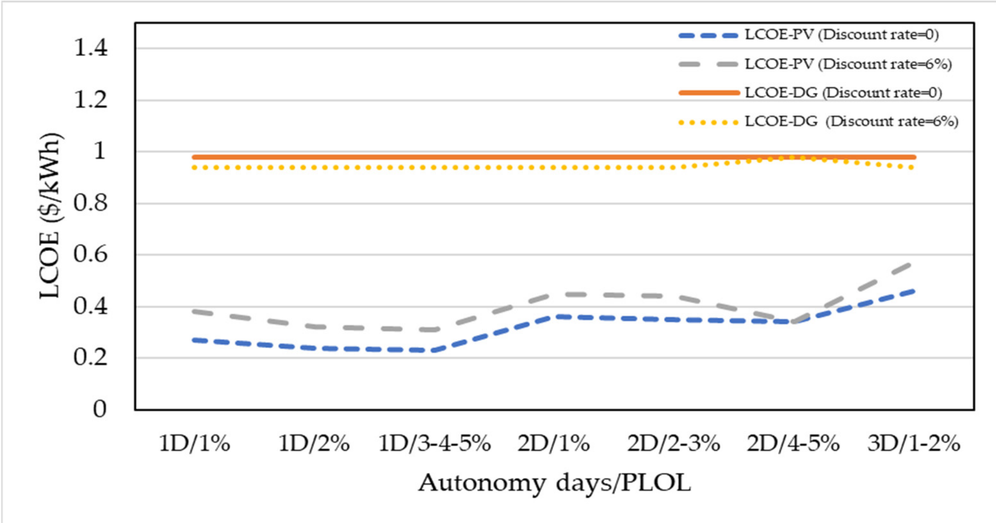

Figure 11. Comparison of LCOE for PV and diesel generator at discount rates of 0% and 6%. The values on x-axis (xD/y%) represent conditions for x days of autonomy and y PLOL.

Table 15. Summary of operational lifespan economic analysis for standalone PV system at discount rate of 0%.

Autonomy Days/PLOL	System Size	Revenue (USD)	Profit (USD)	ROI (%)	Payback Period (Years)
1D/1%	2400 W 606 Ah	44,841	32,328	258.36	5.58
1D/2%	1800 W 606 Ah	44,841	33,876	308.92	4.89
1D/3–4–5%	1650 W 606 Ah	44,841	34,262	323.88	4.72
2D/1%	1800 W 1212 Ah	44,841	28,640	176.77	7.23
2D/2–3%	1650 W 1212 Ah	44,841	29,027	183.54	7.05
3D/1–2%	1650 W 1818 Ah	44,841	32,328	113.02	9.39

Table 16. Summary of operational lifespan economic analysis for standalone PV system at discount rate of 6%.

Autonomy Days/PLOL	System Size	Revenue (USD)	Profit (USD)	ROI (%)	Payback Period (Years)
1D/1%	2400 W 606 Ah	24,676	14,812	150.17	7.99
1D/2%	1800 W 606 Ah	24,676	16,211	191.52	6.86
1D/3–4–5%	1650 W 606 Ah	24,676	16,561	204.08	6.58
2D/1%	1800 W 1212 Ah	24,676	12,775	107.34	9.65
2D/2–3%	1650 W 1212 Ah	24,676	13,124	113.62	9.36
3D/1–2%	1650 W 1818 Ah	24,676	9688	64.64	12.15

From the results, it was determined that the payback period and return on investment for standalone PV systems are affected by the value of the discount rate used. At a discount rate of 0%, the payback period for a PV system with 1 autonomy day is between 4.72 and 5.58 years, 7.05 to 7.23 years for 2 autonomy days, and 9.39 years for 3 autonomy days. At a discount rate of 6%, the payback periods for PV system were seen to be slightly extended. For 1 autonomy day, it ranges between 6.58 and 7.99 years, 9.36 to 9.65 years for 2 autonomy days, and 12.15 years for 3 autonomy days. The ROI is between 113.02–258.36% at a discount rate of 0% and between 64.64–150.17% at a discount rate of 6%.

In addition to Bamako, operational lifespan cost analyses for Kayes, Kolokani, Sikasso, and Barouéli were also carried out, and a summary of undiscounted LCOE and payback periods for each location is provided in Table 17. Considering the total expenses, the LCOE, and payback period with two different discount rates, standalone PV systems for community health centers are still economically viable in all cases.

Table 17. Summary of undiscounted LCOE and payback periods at Kayes, Kolokani, Sikasso, and Barouéli.

Location	Autonomy Days	System Size	LCOE-PV (USD/kWh)	LCOE-DG (USD/kWh)	Payback Periods
Kayes	1	1650 W 606 Ah	0.23	0.98	4.72
	2	1500 W 1212 Ah	0.34	0.98	6.88
	3	1500 W 1818 Ah	0.45	0.98	9.22
Kolokani	1	1500 W 606 Ah	0.22	0.98	4.55
	2	1500 W 1212 Ah	0.34	0.98	6.88
	3	1500 W 1818 Ah	0.45	0.98	9.22
Sikasso	1	1500 W 606 Ah	0.22	0.98	4.55
	2	1500 W 1212 Ah	0.34	0.98	6.88
	3	1500 W 1818 Ah	0.45	0.98	9.22
Barouéli	1	1500 W 606 Ah	0.22	0.98	4.55
	2	1500 W 1212 Ah	0.34	0.98	6.88
	3	1500 W 1818 Ah	0.45	0.98	9.22

3.3. Environmental Evaluation

In general, PV systems are considered environmentally friendly, whereas diesel generators produce 2.6 kg CO_2 for each liter of diesel they consume during the production of electricity [53]. PV systems do not use any type of fossil fuel during the production of electricity; however, the production of the PV modules, batteries, and the balance of system (BOS) contribute to the production of CO_2 and other greenhouse gas emission during their manufacturing processes [56]. The calculation for the total CO_2 contributed by standalone PV systems was performed through the use of gCO_2eq/kWh, proposed by the International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) [55]. Considering the battery sizes for community health centers for 1, 2, and 3 autonomy days, the equivalent CO_2 produced by a standalone PV system is 0.085 tCO_2eq/kWh. Using the equivalent CO_2/kWh from a PV battery system and CO_2/liter from a diesel generator for Bamako were calculated and are provided in Table 18.

Table 18. Lifetime CO_2 emissions for standalone PV systems and diesel generators.

	Lifetime CO_2 Emission (tCO_2eq)		
	2400 watts	1800 watts	1650 watts
PV System	6.77	5.03	4.60
Diesel generator	82.78	61.57	56.28

The equivalent CO_2 emissions of a standalone PV system for its lifetime was estimated to be 4.6–6.8 tons compared to 56.3–82.8 tons from a diesel generator. Please note that CO_2 emissions from a standalone PV system and a diesel generator are calculated based on the lifetime expected power production from the PV arrays and not on the amount of electricity used from them. This is due to the fact that the electricity produced from these PV arrays would have been fully utilized if they were connected to a grid [57,58]. Depending on the chosen design of the standalone PV system, 51.68–76.1 tons of CO_2 could be saved compared to a diesel generator to power a typical community health center at Bamako.

4. Conclusions

This paper has presented the optimal sizing and assessment of standalone PV systems for community health centers in Mali. The optimization for standalone PV systems was performed through simulation and modeling using Pvsyst, and then through the assessment of the technical, economical, and environmental benefits. For the system design, 1–3 autonomy days and 1–5% for the probability of the loss of load (PLOL) were considered. To assess Mali's solar potential, we have considered the solar data for solar resources in Bamako, Kayes, Kolokani, Sikasso, and Barouéli.

Considering the total expenses, the LCOE and payback period for two cases (a discount rate of 0% and a discount rate of 6%), standalone PV systems have been found to be economically viable for Mali. In comparison to the LCOE for diesel generators of 0.98 and 0.94 USD/kWh, the LCOE of standalone PV systems in Bamako has been found to be between 0.23 and 0.46 USD/kWh at a discount rate of 0% and 0.33 and 0.60 USD/kWh at a discount rate of 6%. The ROI was found to be between 113.02 and 258.36% and between 64.64 and 150.17% for discount rates of 0% and 6%, respectively. Using the equivalent CO_2/kWh from a PV battery system and CO_2/liter from a diesel generator, we have also evaluated the environmental impact of standalone PV systems in comparison with a diesel generator. It has been shown that the installation of standalone PV systems alone in Bamako could help to save 51–76 tons of CO_2 compared to a diesel generator over the operational lifespan of the installation.

This research confirms the viability, both economically and environmentally, of using photovoltaics and batteries as replacements for a diesel generator for supplying electricity to health centers. A method has been proposed and applied for sizing such a system and can be reproduced for other locations in Mali or elsewhere. The results from this study can guide policy makers, energy planners, investors, and stakeholders such as the United Nations Development Program (UNDP) in optimizing system design and developing cost-effective and sustainable renewable energy projects in developing African countries for several applications including the electrification of remote healthcare centers.

5. Directions for Further Research

The current study, as a first step, has focused on the method of optimal sizing of standalone PV systems, considering the site-specific weather conditions of different locations in Mali, whereas a generic load profile was assumed to be the same for each community health center. The future studies should take into account the performance of standalone PV systems beyond their planning and installation phase, by considering the quality-based issues found during their operational lifespan. Future studies should also focus on the development of robust energy management programs and their integration with other sources of sustainable energies to cope with the temporally varied mismatches in supply and demand. Finally, the societal impact of providing photovoltaic electricity to healthcare centers, and the use of the technology by local populations in developing countries remain to be assessed.

Author Contributions: Conceptualization, M.D.; methodology, A.A., M.V. and M.D.; software, A.A.; validation, M.V. and M.D.; formal analysis, A.A., M.V. and M.D.; investigation, A.A.; resources, M.D.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, M.V. and M.D.; visualization, A.A.; supervision, M.D.; project administration, M.D.; funding acquisition, M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out through the SanDi project, with financial support from the UNDP (United Nations Development Program) and was implemented by the CIDIS (Centre Interdisci-plinaire de Développement International en Santé—www.CIDIS.ca).

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Acknowledgments: We would especially like to thank SanDi project directors, Gabriel Blouin Genest and Sarah Stecko, as well as the SanDI project manager, Natalia Torres Orozco.

Conflicts of Interest: The authors declare no conflict of interest.

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