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Frugal Optimization in the Design of a Shea Butter PV Transformation Center in Burkina Faso

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Abstract: The design and sizing of a transformation centre based on frugal innovation techniques are presented for an association of women producing shea butter in the Bobo-Dioulasso region of Burkina Faso. The design is aimed at preserving ancestral production methods as much as possible. Regarding the sizing of the electrical supply system, which is based on a solar photovoltaic system, in addition to the standard sizing method (worst-month method), an analytical development methodology has been applied to ensure reliability (Loss of Load Probability). To guarantee the project's sustainability, economic, energy, and environmental sustainability indicators are applied. The results are expected to serve as a replicable model for other communities facing similar challenges, providing a sustainable and adaptable solution.

Keywords: Frugal Innovation, PV solar energy, shea butter, sustainable development, loss of load probability Burkina Faso

I. INTRODUCTION

Shea butter, extracted from the fruits of the *Vitellaria paradoxa* tree, is a vital resource in West Africa, valued not only for its cosmetic and nutritional properties but also for its significant economic and social impact. Millions of women in the region are involved in its production, passing down extraction techniques from generation to generation. However, in recent decades, growing industrialization driven by foreign investors has progressively displaced traditional methods, resulting in a loss of economic and food sovereignty in the producing communities. This model prioritizes the extraction and export of raw materials, with the added value remaining in the hands of international companies. Consequently, this limits economic opportunities for local producers and increases their dependence on external markets.

To address this issue, this study proposes the design of a local processing center for shea butter production, aimed at the NDIA producers' association in Burkina Faso. The proposal is based on the principles of frugal innovation, employing accessible and efficient technological solutions that optimize processes while preserving ancestral techniques. This approach aims to increase production capacity, reduce processing times, and enhance the product's competitiveness in the market, enabling local producers to achieve greater economic benefits and greater autonomy in managing their resources.

The design of the processing center follows a zero-energy approach, relying entirely on solar photovoltaic energy. This solution not only ensures a reliable energy supply in areas with limited access to the electrical grid but also helps reduce the carbon footprint of the production process. To create an efficient and sustainable design, a detailed evaluation of the energy consumption required at each stage of production—from fruit collection to final packaging—is conducted. Based on this data, the energy system for the center is designed and sized, incorporating a stand-alone photovoltaic system with energy storage. To ensure reliable power, both the traditional worst-month method and a Loss of Load Probability (LLP) analysis are applied, optimizing system reliability. In addition, excess energy generated will be used to power a water pumping system, providing the community with access to potable water and increasing the project's positive impact.

The design process also incorporates economic, energy, and environmental sustainability criteria, ensuring the long-term viability of the model while allowing it to be managed autonomously by local producers. This approach not only improves working conditions and strengthens the local economy but also helps preserve traditional production methods and reduce the inequality in the distribution of value within the production chain.

Ultimately, the project aims to serve as a replicable model for other communities facing similar challenges, offering a sustainable alternative to industrialization driven by external actors. By empowering local producers with the right tools and knowledge, it fosters more equitable and resilient development, ensuring that the benefits generated from shea butter production remain within the communities that have cultivated and processed it for centuries.

II. DESIGN OF THE SHEA BUTTER TRANSFORMATION CENTER

The traditional production of shea butter is a physically demanding process that takes approximately 3 to 5 days. It begins with harvesting and washing the fruits to remove impurities, followed by drying. The nuts are then boiled, dried again, and sorted for quality. The shells are removed, and the kernels are crushed into small granules, which are then roasted to facilitate oil extraction. The roasted grains are ground into a paste, kneaded with water to separate the fat, and then heated to evaporate any remaining moisture. Finally, the purified butter is decanted and stored under optimal conditions. Figure 1 illustrates the interaction between resource use, the environment, and shea butter processing. A study conducted over five years quantified human energy contributions, estimating a range of 2000–6100 kJ/kg of raw shea butter based on FAO's Physical Activity Ratio (PAR) and Basal Metabolic Rate (BMR). Research on 25 kg batches of shea kernels found that kneading and emulsion recovery required 57–75 litres of water [1]. Additional studies [2,3] reported firewood consumption between 3.53–8.07 kg per 1 kg of shea butter, highlighting the significant environmental impact of traditional processing methods.

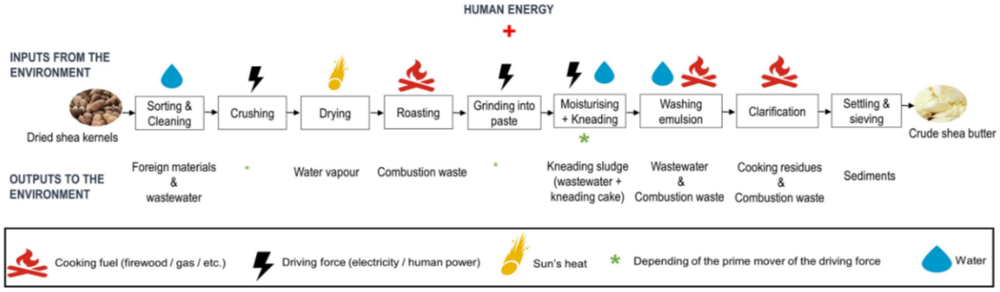


Figure 1. Environmental input-output during the different production steps on the shea butter traditional management.

A. *Energy demand*

When designing the transformation center, all traditional tasks have been preserved while incorporating appropriate industrial or semi-industrial machinery. Table 1 presents the selected equipment, along with its required power and estimated operating time [4]. The drying process will be carried out using a hybrid solar dehydrator module, specifically designed with open-source technologies for this project [5].

TABLE 1: Overview of transformation center components, power demand, operating hours, and daily energy consumption. O the rigth a image of the traditional transformation tasks

Process	Equipment	Power (kW)	Use h/day	Number equipment	Daily Consumption (kWh/day)
Drying	Dehydrator	1.98	13	1	25.74
Roasting	Industrial oven	1.00	2	10	80.00
Cooking	Kneading machine	2.40	14	2	38.40
Grinding					
Beating					
Cooling	Refrigerator	0.21	24	10	50.40
Lighting	Lighting system	0.06	4	8	1.92
Decanting	Decanter	1.40	2	1	2.80
Daily Total Consumption (kWh/day)					199.26

To estimate the average monthly consumption, it has been considered that during the winter months, from May to August, there is a harvesting period when women will not perform the processes of drying, roasting, cooking, and beating the shea butter because no butter will be produced. However, it has been decided that the center will continue to operate, so lighting and the refrigerator used for storing the butter will remain part of the consumption. Task simultaneity criteria have not been considered.

B. Solar Energy resources

Historical solar radiation data from Bobo-Dioulasso, shown in Table 2, which includes the average energy per square meter per day for each month wll be used. This tropical area -Koppen-Geiger classification- has a rainy, mostly cloudy season in summer and a warm, dry season year-round. Temperatures range from 15 to 37°C. The high sunlight hours and solar radiation ensure sufficient energy.

TABLE 2 Monthly average of Sunlight daily hours and Solar Peak Hours (HPS) in Bobo-Dioulasso.

	January	February	March	April	May	June	July	August	September	October	November	December
Sunlight time (h)	11.6	11.8	12.1	12.4	12.6	12.8	12.7	12.5	12.2	11.9	11.6	11.5
Solar Peak Hours(h)	5'8	6'2	6'2	5'9	5'6	5'5	5'2	5'0	5'3	5'6	5'7	5'5

III. SIZING THE PHOTOVOLTAIC SYSTEM

Given the lack of an electricity grid in the implementation area, the only viable solution for powering the transformation center is an off-grid photovoltaic system. This will include a solar panel array, a storage system, and an inverter/charger. Based on local climate conditions [6], we have selected the A-550 Atersa monocrystalline photovoltaic module (550Wp) [7]. The storage battery chosen is the UOPZS U-POWER 24V 975Ah 23.4 kW [8]. The selected inverter is the Victron Multiplus 24V 3000VA 70+50A, offering 93% efficiency[9]. A fixed azimuthal inclination equal to the latitude, β=11 degrees will be used, with the orientation facing south.

The sizing process was carried out in two stages: first, an initial rough sizing using the well-known "worst case month" method (WCM), followed by a second analytical approach based on the probability of load loss (LLP). This method ensures an appropriate level of reliability, optimizes costs, and minimizes energy waste by reducing the amount of energy produced but not utilized.

A. Sizing using the "Worst-Case Month" Method

The WCM method ensures the system can meet energy demands during the month with the lowest solar radiation. This approach guarantees a reliable energy supply even in periods of low sunlight, optimizing performance and minimizing the risk of shortages. However, a downside of this method is that it can result in an oversized system, generating more energy than needed during sunnier months, leading to underutilization of capacity and higher costs. Additionally, designing for the worst-case scenario requires a larger initial investment, and the system may produce excess energy during high-sunlight months, which could be wasted if not properly stored or used.

TABLE 3 : Both the monthly energy consumption and the monthly production of the photovoltaic (PV) system.

	January	February	March	April	May	June	July	August	Setember	October	November	December
Energy Demand (Wh/day)	213.21	213.21	213.21	213.21	55.98	55.98	55.98	55.98	213.21	213.21	213.21	213.21
Energy Production (Wh/day)	240.8	249.4	249.4	240.8	232.2	223.6	215	206.4	215	232.2	232.2	223.6

Starting with the worst month, which is September (see Tables 1 and 2), and accounting for a 10% loss due to wiring, an additional 5% for emergency power, and the inverter efficiency, the system will be sized with 86 panels of 550Wp each (see table 3 for details). In the sizing of the solar array, the required losses were factored in to ensure the system provides sufficient energy. The storage system was designed to ensure a reliable energy supply during periods of low solar radiation, such as nighttime or cloudy days. A battery bank with the appropriate capacity was selected to meet the daily consumption of 213.21 kWh. accounting for efficiency losses and safety margins. This requirement is met with 9 battery units. Additionally. the estimated nighttime consumption of 1.92 kWh/day is fully covered. ensuring uninterrupted operation.

B. LLP-Based Sizing

The Loss of Load Probability (LLP) [10] method was used to ensure a reliable energy supply by minimizing the risk of system failure. considering both energy demand and the variability of solar radiation. This method optimizes the system design by balancing the risk of energy shortages with the system's capacity. ensuring consistent performance and reducing the likelihood of unfulfilled energy needs.

Considering a target reliability of 99.99%. which corresponds to an LLP value of 0.01. Figure 2 presents the iso-reliability curve. This curve provides (CA. CS) pairs that guarantee the desired reliability level and is defined by Equation 1:

$$C_A - m \cdot C_S^{-n} \qquad \text{(eq. 1)}$$

Where:

- C_A represents the capture field. with CA = 1 as the reference value obtained using the WCM.
- C_S denotes the accumulation field. with CS being the corresponding WCM value.
- m and n are LLP method parameters dependent on the clarity index and latitude of the installation site. For this specific case. based on the climatic characteristics of the implementation area (Köppen-Geiger classification for desertic clima). the parameter values are: m=0.8 and n=0.16.

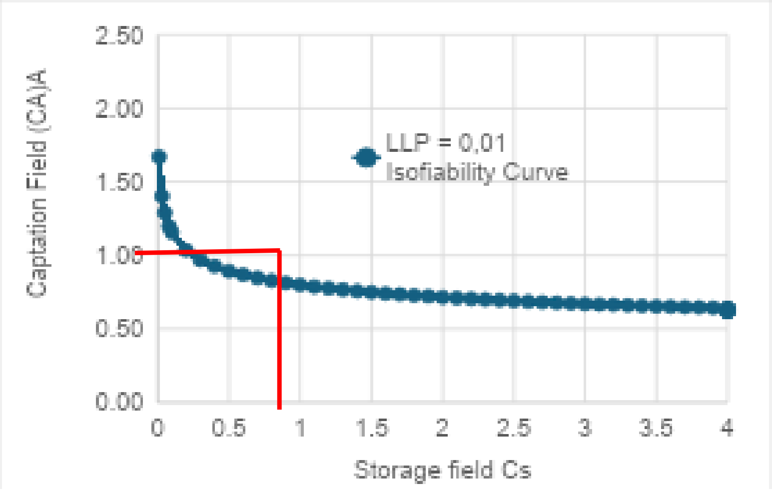


Figure 2. Isoreliability curve for LLP = 0.01 under the climatic conditions of a desert climate (Köppen-Geiger classification). Red line: (CA,CS) = (1,1).Green line: (CA, CS) = (1.03, 0.2)

The results indicate that the WMM-based sizing exceeds the proposed iso-reliability threshold as expected. Notably, a reduction of approximately in battery capacity is feasible maintaining the 99,99 % of reliability.

IV. OPTIMIZED SIZING IN TERMS OF RELIABILITY AND SUSTAINABILITY

Optimized sizing balance reliability and sustainability by ensuring continuous energy supply while minimizing environmental impact. Using the Loss of Load Probability (LLP) method, the system is designed to meet energy demands despite solar fluctuations. Sustainability is further addressed by the Sustainability Index (SI). which ensures environmental. energetic. and economic benefits. promoting efficiency. reducing waste. and enhancing long-term viability. Table 4 shows the sustainable indicators values used in the analysis.

TABLE 4. The baseline values used for the calculations [11, 12].

Component	Price (€)	EPBT (years)	Emissions (kg CO₂-eq/kW)
Solar Panels (€/kW)	153,43	1.2	1200
Batteries (€/kWh)	127,82	3.4	95000

To assess sustainability, we employ the Sustainability Index (SusInd) [13], which integrates multiple sustainability estimators:

- Energy sustainability (Energy Payback Time. EPBT)
- Economic sustainability (Internal Return Time. IRT)
- Environmental sustainability (Impact on Climate Change Mitigation. IMPcc)

Figure 3 illustrates the results for each sustainability indicator. To facilitate comparison, all curves are normalized to the reference configuration (CA, CS) = (1,1).

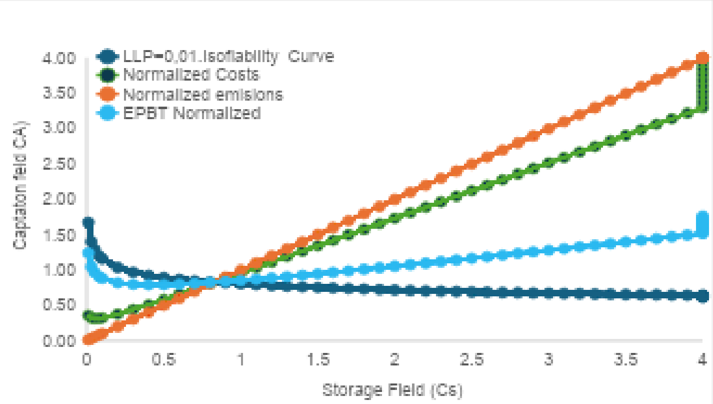
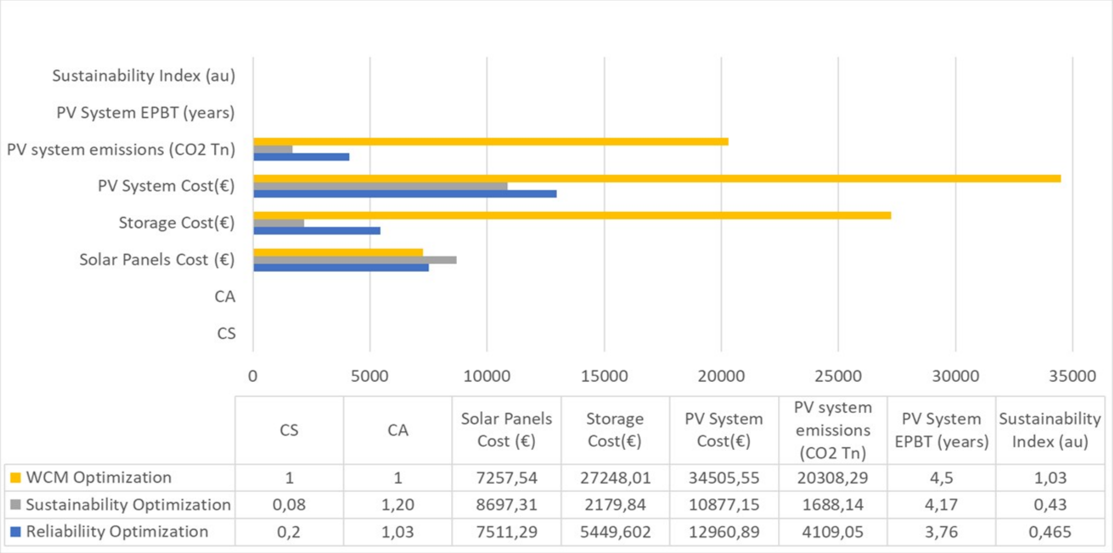


Figure 3. Isoreliability curve for LLP = 0.01 under desert climate conditions (Köppen-Geiger classification). along with economic. energy. and environmental sustainability indicators.

The optimal system configurations for different sustainability criteria are obtained from the minima of each distribution:

- Economic sustainability: (CA. CS) = (1.29, 0.05)
- Environmental sustainability: (CA. CS) = (1.67, 0.01)
- Energy sustainability: (CA. CS) = (0.93, 0.4)

Finally, figure 4 summarizes the final optimized configurations, balancing both reliability and overall sustainability. The overall sustainability metric is derived through the direct. unweighted convolution of normalized individual indicators.



	CS	CA	Solar Panels Cost (€)	Storage Cost(€)	PV System Cost(€)	PV system emissions (CO2 Tn)	PV System EPBT (years)	Sustainability Index (au)
🟨 WCM Optimization	1	1	7257,54	27248,01	34505,55	20308,29	4,5	1,03
⬜ Sustainability Optimization	0,08	1,20	8697,31	2179,84	10877,15	1688,14	4,17	0,43
🟦 Reliabiliity Optimization	0,2	1,03	7511,29	5449,602	12960,89	4109,05	3,76	0,465

Figure 4. Optimized configurations in terms of iso-reliability and sustainability. with an adjacent table detailing the key characteristics of each option.

Key findings indicate that. in all cases, increasing the capture field is preferred over expanding the accumulation field. Ensuring overall sustainability leads to a 16% reduction in system costs and a 59% decrease in emissions, though it also results in an 11% increase in energy payback time.

Due to the system's nighttime power demand, the accumulation field required for full sustainability is not feasible. Therefore, an intermediate configuration is selected as the optimal trade-off.

According to the previous analysis, nighttime consumption is well covered in both approaches. Even during the rainy season, considering the short but intense duration of rainfall, it is highly unlikely that the batteries will be fully discharged, so an emergency load factor of one can be assumed. However, considering the technology used, its implementation is maintained, ensuring an emergency load factor of 1.37. This excess guaranteed coverage for the system's degradation process. Therefore, an optimized sizing in terms of sustainability is adopted, with an optimal sustainability index of 0.43. Table 5 summarizes the final sizing of the photovoltaic installation for the transformation centre. It is important to highlight the excess energy that remains unused. Addressing how to effectively utilize this wasted energy will be the focus of the next section.

Table 5: Final sizing design of the photovoltaic installation for the transformation centre

Production field Power (KWp)	Energy Production (MWh/year)	Storage Field (KWh)	Wasted Energy (MWh/year)
56,76	100.70	17,06	42.22

In the breakdown of the details, the total cost of the system is estimated in 10.877 euros approx. 80% is allocated to the solar panels and 20% to the batteries. The energy needed to implement the system will be generated within 4.17 years and the total emissions calculated over the system’s lifespan amount to 1668.14 CO2 equivalent tons (at least 40 times fewer emissions compared to a diesel generator).

V. REMAINING ENERGY

The design of an off-grid photovoltaic system, even with optimized sizing, often results in oversizing, which leads to excess energy production—especially due to seasonal variability in consumption. This makes it challenging to avoid energy waste, as an oversized storage system increases both costs and emissions. thereby reducing overall sustainability. To address this, the proposal is to use the surplus energy to meet other user needs. In our project, the main vulnerability is water access. The region where the project is located has low rainfall and is at risk of desertification, making water a scarce resource; therefore, a deep-well water pumping system is proposed. This solution will maximize resource utilization. optimize energy use. and enhance the project's overall sustainability.

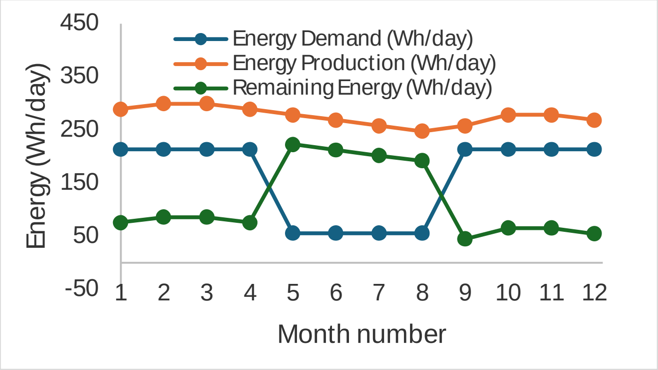


Figure 5. PV system characteristic monthly energies (kWh/day). Green curve corresponds to the remaining energy to be used for pump powering.

In this section, the remaining monthly energy to determine the required motor power for a deep-well water pumping system is calculated (see figure 5). This system will operate seasonally, running at maximum capacity during periods of low energy consumption. To optimize its performance and ensure water availability throughout the year, an appropriately sized storage tank will be incorporated into the system. The sizing of a water extraction system in this area presents a challenge due to the region's characteristics. Although the water table is shallow, water is scarce, so large daily extractions should be avoided to allow for the renewal of the water source.

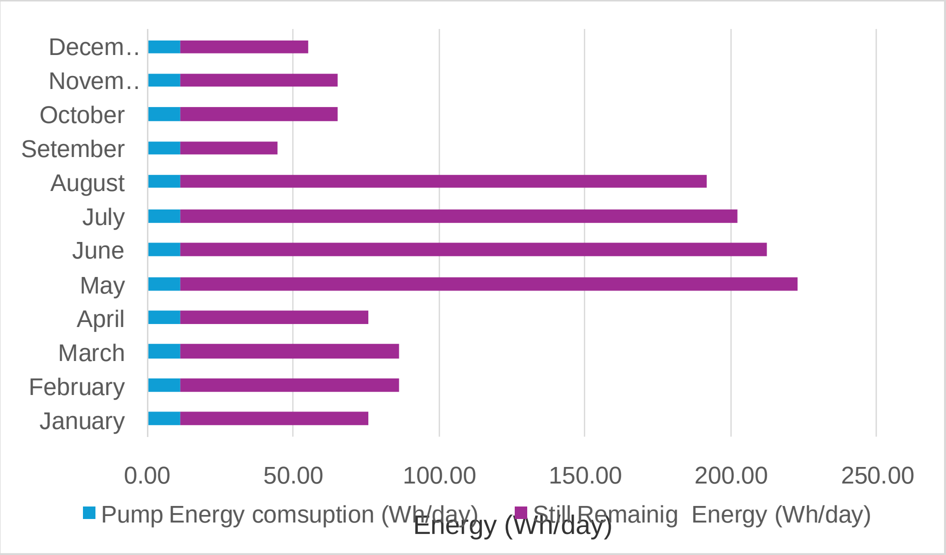


Figure 6. PV system characteristic monthly energies (kWh/day). Cian curve corresponds to the remaining energy to be used for pump powering. Purple line, remaining energy after pumping,

Considering the needs of the population, focused on shea butter production, local crop irrigation, and other basic needs such s hydration, hygiene, and cooking, the required flow is estimated at 900 litres/day. According to standard calculations [14], and considering a 30m deep pumping system, a 3 HP (Submersible well solar pumps 4" SERIE FST-FK motor FRANKLIN) well pump can meet these needs. Daytime operation will be prioritized, so no additional storage system is required. The proposed pumping system ensures a flow rate of 226,8 litres/hour, which guarantees a daily flow of 11 litres, adequately covering the population's needs. Figure 6 shows the system's consumption, operating 5 hours per day to ensure daily resource renewal. That remaining energy after the pumping powering (also in the figure 5) can be used in the future for other population needs, as well as to ensure the reliability of the PV system even with the degradation associated with use.

VI. CONCLUSIONS

This study aimed at designing, optimizing, and implementing a standalone photovoltaic (PV) system for a transformation center, ensuring a balance between system reliability, energy supply, and sustainability. The system sizing was approached using two primary methodologies: the worst-month method and the loss-of-load probability (LLP) method. These methods were applied to determine the best configuration to ensure the system could meet the energy demands of the center while considering variability in consumption patterns, especially seasonal fluctuations. Sustainability indicators, including economic, energy, and environmental metrics, were incorporated to ensure the system operated responsibly and economically, while minimizing its environmental footprint.The key findings of the study include the following:

1) Sizing Methodology: The system was sized using the worst-month method, for a first estimation. Additionally, the Loss of Load Probability (LLP) method and a sustainability index were introduced to further optimize the sizing process. This resulted in the installation of 104 photovoltaic panels (550 Wp each), estimated to generate 100.7 MWh annually. Although this output meets the center's energy needs, seasonal fluctuations in demand still result in surplus energy. Although the panels' output and stationary batteries system of 23,4 KWh meet the center's energy needs, seasonal demand fluctuations still result in surplus energy, assuring an emergency load of 1,37.
2) Energy Surplus: Despite the optimized sizing, energy overproduction remains a significant challenge, particularly during periods of low energy demand, such as in the summer months. The seasonal variability in consumption creates a mismatch between supply and demand. Monthly energy surpluses were calculated, with values ranging from 213,2 kWh during high-demand months to 55,98 kWh during low-demand months. These surplus energies represent a critical issue in terms of resource utilization and waste.
3) System Costs and Emissions: The total cost of the PV system was estimated at 10877,15 €. Of this, 80% was allocated for the photovoltaic panels, and 20% was designated for the batteries.

The estimated emissions reduction over the system's lifetime is significant, with projected CO2 emissions amounting to 1688,14 tons, compared to traditional fossil fuel-based energy sources. Furthermore, the energy payback period for the system is approximately 3,76 years, which highlights the system's ability to recover its energy costs in a relatively short period.

4) Sustainability Index: The sustainability index for the system was calculated to be 0.43, indicating a solid balance between energy generation, environmental impact, and costs. This value is relatively close to the optimal level, suggesting that the project's design and implementation have prioritized sustainability, energy efficiency, and minimal environmental harm.
5) Utilization of Surplus Energy: To address the challenge of energy overproduction, the surplus energy is effectively utilized by powering a deep-well water pumping system. This innovative solution ensures that the excess energy generated during low-demand periods is used to meet another critical need: water access for the community. The deep-well water pumping system, which operates seasonally, can pump water at a flow rate of 226.8 liters per hour, ensuring a daily water flow of 1,134 liters, which is sufficient to meet the daily needs of the population, including shea butter production, crop irrigation, and other basic requirements like hydration, hygiene, and cooking.

In conclusion, the combination of these methodologies resulted in a well-optimized photovoltaic system, addressing both energy overproduction and excess capacity issues. The surplus energy that would have otherwise been wasted is now used effectively to power a water pumping system, which enhances the project's sustainability by utilizing all available energy resources. This approach not only reduces waste and lowers emissions but also helps meet critical community needs, improving both the environmental and social impact of the system. Future research may explore other uses for excess energy and assess potential optimizations for similar systems in different contexts.

VII. ACKNOWLEDGMENT

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