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Renewable Energy Communities in Developing Countries

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Abstract: This study investigates the feasibility of establishing a Renewable Energy Community (REC) to improve sustainable and equitable energy access in developing countries. The case study focuses on Gujicha, a rural off-grid village in Ethiopia's Oromia region, where households rely on polluting energy sources such as coal, biomass, and kerosene. These traditional fuels hinder socioeconomic development and pose significant health and environmental risks. The proposed solution involves the design and implementation of a stand-alone photovoltaic system to supply clean energy to a community hub, primarily a school. Simulations were conducted to optimize panel selection, battery storage, and load management strategies, considering system efficiency and lifecycle cost. The design prioritizes energy use during peak solar hours and includes surplus energy recovery to reduce battery dependency. Simulation results under different seasonal conditions confirm that the system ensures stable energy access and supports essential services such as lighting, computing, and medical refrigeration. The inclusion of dynamic load prioritization enhances operational flexibility and resilience. This model demonstrates how RECs can provide long-term benefits in off-grid contexts by fostering energy autonomy, supporting education, and enabling community services. The approach is scalable and adaptable, offering a replicable pathway for sustainable electrification in similar rural environments.

Keywords: Battery; Developing countries; Energy storage; REC; Sustainable energy

1 Introduction

Access to energy is the greatest challenge we are called upon to face. In 2015, UN member countries signed the 20230 Agenda for Sustainable Development, an action program for people, the planet and prosperity [1]. The Agenda consists of 17 Sustainable Development Goals (SDGs) framed within a broader action program consisting of 169 targets or targets, associated with them, to be achieved in the environmental, economic, social and institutional fields by 2030. Among the 17 goals, number 7 aims to "ensure access to affordable, reliable, sustainable and modern energy systems for all" [2]. The alarming data reported by the International Energy Agency (IEA) and the World Bank tell us that more than 770 million people in the world do not have direct access to electricity; the most alarming data come from Sub-Saharan Africa and South Asia [3]. The lack of direct access to reliable energy sources not only hampers economic growth but also limits access to essential services such as healthcare, education and clean water. In these countries, especially in rural areas, biomass such as wood is used as the main fuel, but also coal and animal manure, which are used both for cooking and heating. The goal that must be set is to find and implement solutions that allow a reduction in the use of traditional fuels towards renewable energy sources. As reported in the World Energy Outlook 2023, demand for fossil fuels will peak within this decade, and then start to decline. Among the solutions devised, the most innovative is that of RECs (Renewable Energy Communities). RECs are defined as "a cooperative model of energy production and consumption that places citizens at the center of decision-making, promoting a more efficient and sustainable use of energy resources". These models aim not only at the energy autonomy of the community but also at reducing dependence on fossil fuels for renewable solutions with the intention of also leading to development for the local community. Given the usual structure and model of Renewable Energy Communities (RECs), particularly in developed nations, this study aims to assess the feasibility of adapting and replicating such models in the context of developing countries. To effectively develop the model, the rural village of Gujicha in Ethiopia's Oromia region was selected, as it is fully representative of the studied scenario and ensures facilitated access to information for the research team.

2 Case Study

Ethiopia is the second most populous country in Africa, with its 110 million inhabitants, but more than 46.8% of its inhabitants do not have access to electricity, a percentage that reaches 75% in rural areas, despite the fact that the country has abundant renewable energy resources, capable of generating over 60,000 MW from hydroelectric, wind, solar and geothermal sources (Figure 1).

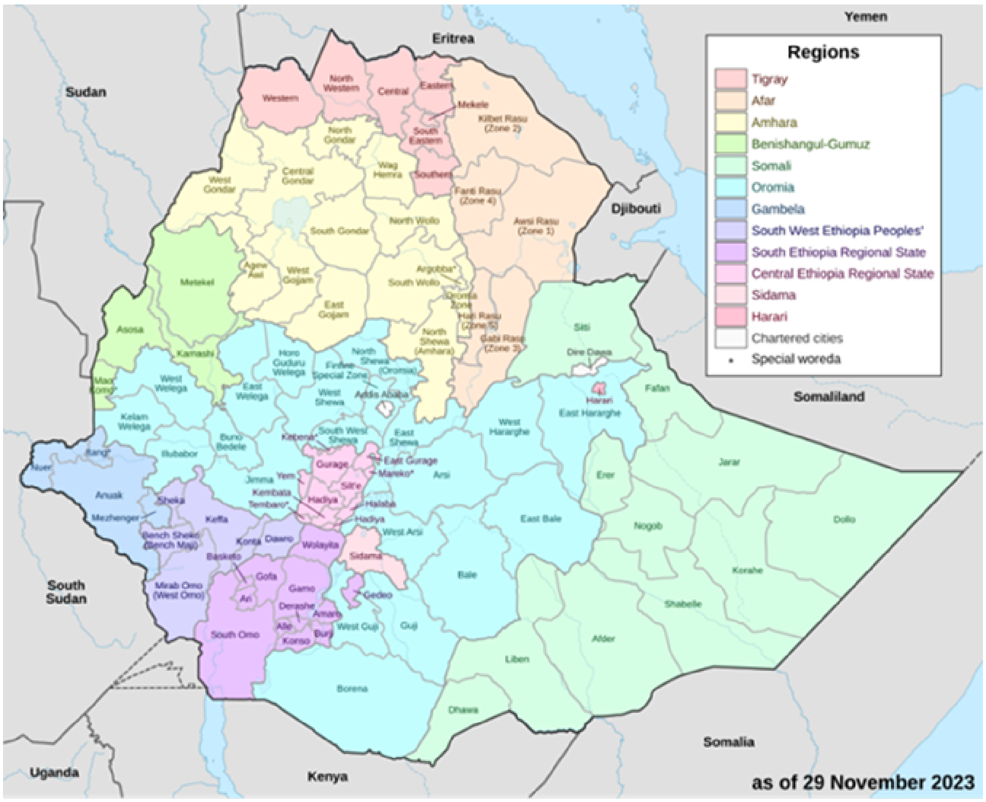

Figure 1. Map of Ethiopia

Currently, however, the majority of the population depends on unsustainable energy sources, such as wood and coal, to meet their basic energy needs, with serious consequences for both health and the environment [4]. To address these issues, it was decided to design a Renewable Energy Community (REC) following a process divided into several key phases:

•Study of the village: Analysis of living conditions, habits of the population, local needs and potential.
•Identification of a community building: Choice of a structure that will become the energy hub.
•Consumption analysis: Detailed assessment of current and potential energy consumption.
•Climate and resource assessment: Study of climatic conditions and natural resources available in the area.
•Solution design: Development of the most suitable energy solution for the specific context.
•Simulations: Running simulations to optimize and validate the design before implementation.

2.1 Study of the Village

Gujicha is located 243 km from the capital, Addis Ababa, and is characterized by dense forests and mountains. Households in the village are not connected to the national electricity grid and do not have access to electricity, which severely limits access to the latest information and advanced technology (Figure 2). Located halfway between the towns of Kersa and Gambo, which are connected to the national network, Gujicha has no connection.

Because of this lack, the energy needed is obtained through traditional sources of biomass such as wood, agricultural waste, cow dung, and charcoal, which are used for cooking, making enjera, tea, coffee, and lighting using kerosene lamps. Currently, the village has 2069 families, with a total of 9,932 inhabitants. There are a few government institutions, including the Gujicha Kalacha Elementary School and the Gujicha Kebele Administration, but they lack a farmer training center, a health center, and a kindergarten. In addition, the village does not have access to drinking water, nor small sources of solar energy, diesel generators, or grinders, making the implementation of sustainable energy solutions even more urgent.

Figure 2. Map of Gujicha

2.2 Identification of a Community Building

The analyses carried out showed that the most viable and sustainable solution was to convert an existing community building into an energy hub that could be directly used by the community and provide energy for additional services. Based on the information provided by the school principal, the design of the building will be based on the specific needs and equipment required. The focus was on the Gujicha Kalacha primary school. Located in the village of Gujicha, this not-for-profit public institution provides primary education in two cycles: first to fourth grade and fifth to eighth grade. The curriculum includes English, a national language (Amharic and Afan Oromo), mathematics, natural sciences (physics, chemistry and biology), social sciences (civics, geography and history) and physical education. The school currently has a staff of 15 and is considered the primary educational center for the community, making it an ideal candidate for implementing an energy sustainability model within the village.

2.3 Consumption Analysis

Once the building was selected, a detailed analysis of energy consumption of the building throughout the day was carried out. Based on the information available, it was possible to outline a typical day's activities:

•Office hours: 6:00 to 18:00.

•School hours: 7:00 to 11:00.

The school year starts in September and ends in May. An assessment was then made of all the equipment in the school, analyzing its energy consumption and running time (Table 1).

Table 1. Breakdown of consumption in schools

Devices	Amount	Capacity [W]	Daily Operation [hours/day]	Peak [kW]
Lighting	10	14	4	0.13
Computer	4	70	6	0.28
Printer	1	40	5	0.04
TV	2	30	8	0.06
Wi-Fi	2	10	8	0.02
CM	1	200	2	0.20
Lab.	—	60	5	0.06
C. Lab.	20	70	8	2.80
Other	—	60	8	0.003

To improve energy allocation efficiency and ensure resilience during periods of limited solar availability, a load prioritization strategy was developed. The classification of different loads based on their usage patterns, power requirements, and criticality is presented below (Table 2), and the priority of each load was assigned based on a set of criteria:

•Criticality to health and education: Loads directly supporting health services (e.g., refrigeration for medicines) or education (e.g., lighting and classroom computers) were ranked highest.

•Operating duration and schedule flexibility: Loads with strict, continuous operation needs (e.g., the refrigerator) were prioritized over those with flexible or intermittent use (e.g., the millstone).

•Energy intensity: Devices with high energy consumption were analyzed for their contribution to daily peaks and managed accordingly to balance system load.

•Nighttime dependence: Loads operating at night were considered carefully due to limited solar availability and higher battery reliance.

Table 2. Load classification

Load	h_{use}	E_{daily}	E_{day}	E_{night}	Priority	Days of Use
School	8	27	3375	/	High	5
Refrigerator	24	1.5	62.5	62.5	High	7
Purification plant	4	4	1000	/	Media	2
Millstone	2	1.5	750	/	Media	2
LED	12	0.8	/	67	Low	7

This classification supports a responsive and flexible energy management system, allowing priority-based power allocation. It is also worth noting that:

•During weekday activation, the total energy consumption is approximately 29.3 kWh, with a daytime load of 3438 W and nighttime demand of 130 W.

•During holiday activation, when the school is not operational, the total consumption decreases to 9.8 kWh, primarily due to the refrigerator and nighttime lighting needs.

This structured understanding of consumption patterns and load prioritization enables strategic design and simulation of the energy system, as discussed in Section 3.

2.4 Climate and Resource Assessment

Following the estimation of daily energy consumption, a comprehensive assessment of the local energy resources was performed. To support this analysis, the New_LocClim [5] and HOMER Pro [6] software tools were utilized to evaluate and quantify the renewable energy potential in the target area. Using these tools, fundamental data such as solar irradiance, wind speed and precipitation were obtained, which represent the main resources available for renewable energy production in the area (Figure 3).

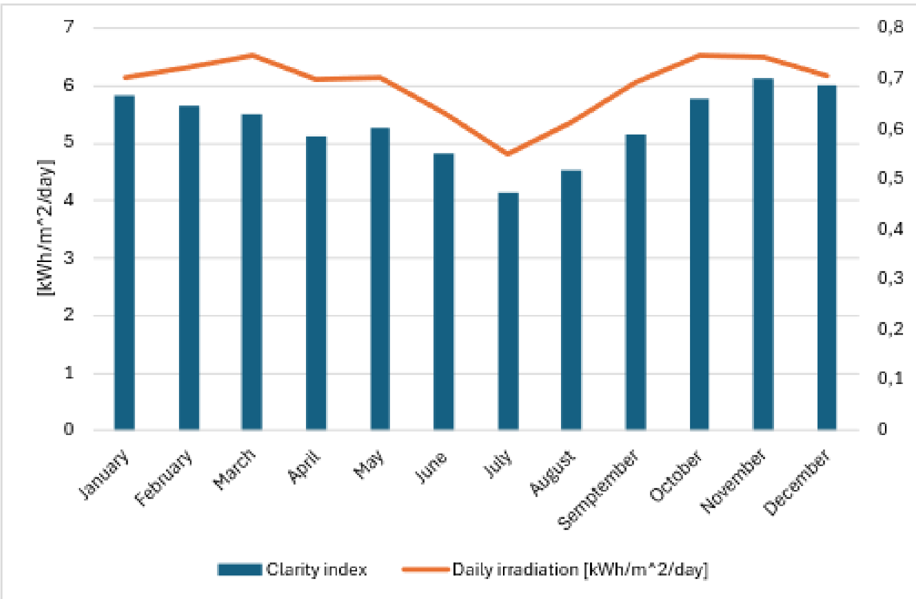

Figure 3. Solar irradiation

The data obtained show that solar irradiance varies throughout the year, with a daily average of 6.02 kWh/m^2.

2.5 Solution Design

After collecting and analyzing climate data, it was decided to adopt solar radiation as the main resource for energy production, opting for the installation of photovoltaic panels [7]. Photovoltaic panels offer several distinct advantages. Compared to technologies such as wind turbines and hydroelectric systems, they entail lower installation and operational costs, along with significantly reduced maintenance requirements—aspects that are crucial for successful deployment in developing countries. Additionally, their expected lifespan of at least 25 years ensures long-term reliability and a strong return on investment. These qualities make photovoltaic systems a cost-effective and practical solution, well-suited to the needs of the selected context. Solar radiation is abundant and constant, especially during the dry season and in months with high irradiation. This continuous availability of solar energy ensures that the photovoltaic panels can reliably meet the daily needs of the school, ensuring a stablesupply of energy. From the literature review, it has been highlighted which are the cheapest and most convenient solar panels available on the local market. The models selected for their efficiency and cost are as follows:

•LONGI LR4-60-HPB-350 [8].

•Hanwha Q CELLS 340WQ PEAK DUO [9].

•Canadian Solar Model CS1H-315MS [10].

As soon as the daily consumption is known, the panels can be dimensioned.

The first step is to calculate the power output of the system (P):

$$P = \frac{\text{Daily consumption [kWh]}}{\text{Average irradiation}\left[\frac{\frac{kWh}{m^2}}{day}\right] * \text{system efficiency}} \tag{1}$$

with an average system η_{system} efficiency of:

$$\eta_{\text{system}} = \eta_{\text{pan}} \times \left(\frac{1}{\text{Losses}}\right) \tag{2}$$

where, η_{pan} is the panels efficiency. The losses were estimated to be 20%.

The assessment of the optimal tilt angle considers the latitude of the area under consideration. Considering the excellent sun exposure, it can be considered appropriate to incline the panels 7° towards the south to maximize the energy efficiency.

Once the power of a single panel is known, it is possible to accurately calculate the number of panels required and the total surface area they will occupy (Table 3).

Table 3. Evaluation of individual panels

Type	Price [$]	η_{pan} [%]	P_{system} [kW]	P_{pan} [kW]	N	A_{pan} [m^2]	A_{tot} [m^2]
LONGI LR4	225	20.3	4.39	0.35	13	1.67	21.8
Hanwha-Q Cell	240	19.0	4.69	0.34	14	1.79	25.1
Canadian Solar	225	18.6	4.77	0.31	15	1.66	24.9

At the end of the first design phase, it is necessary to think about a storage system for the photovoltaic system. This step represents one of the main challenges of the project, especially in this context, where solar production varies significantly according to the season. It is therefore essential to size the system correctly to avoid both wasted energy and excessive costs. In order to make the most of the energy produced during periods of higher irradiation, the excess energy was used to power a rainwater treatment system, which was already being collected in an existing tank at the school. The solution adopted combines sand filtration and UV disinfection, ensuring an effective, sustainable and energy-efficient process. This approach integrates energy and water needs, contributing significantly to the resilience and well-being of the community.

2.6 Simulation

The simulation phase builds directly upon the load prioritization framework established in Section 2.3. With each device and service assigned a specific level of priority—high, medium, or low—the energy management system was designed to dynamically allocate power based on availability and necessity. The primary objective of the simulation was to evaluate the hourly interaction between solar photovoltaic (PV) energy generation, battery storage, and variable energy consumption, considering both environmental fluctuations and the established hierarchy of loads.

A MATLAB-based model was developed to simulate the energy flow over a representative week (168 hours), using real irradiance data sourced from PVGIS [11] for Gujicha.

The system was analyzed under four key seasonal scenarios:

•Week 1 – Dry Season (January): High solar irradiance and full school activity.

•Week 2 – Early Rainy Season (April): Moderate cloud cover and fluctuating solar input.

•Week 3 – Cloudy Season (July): Persistent overcast conditions and school closure.

•Week 4 – Critical Case: Three consecutive days with solar irradiance below 3 kWh/m^2 and active school operations.

During the operation of the school, the solar energy produced must be directed primarily to the school itself and to the refrigerator (which consumes about 1.5 kWh per day and must remain active 24 hours a day for the storage of medicines). Residual energy can be stored in batteries for use at night or in low production conditions.

On non-school days and in the summer months (June, July and August), energy can be used for secondary loads, including:

•Water purification system (consumption of about 0.9 kW during brief operations lasting approximately 30–60 minutes per use).

•Millstone (requires 1–1.5 kWh per day for about two hours).

•LED lighting at night (estimated at approx. 0.8 kWh per day for 12 hours with 3–4 light points).

At each simulation step, the model:

•Estimated PV energy generation considering panel efficiency and ambient temperature.

•Assessed battery state-of-charge (SOC) and its ability to buffer energy for nighttime or low-sun periods.

•Scheduled loads based on their assigned priority: high-priority loads were supplied first, followed by medium and low-priority ones as capacity allowed.

Two battery configurations were tested:

•A 30 kWh battery ensuring high autonomy and performance under all conditions.

•A 5 kWh battery relying on strict load prioritization to balance cost and service continuity.

The simulation demonstrated that under favorable conditions (Weeks 1 and 2), the system was able to satisfy 100% of the high and medium priority loads with minimal curtailment. In Week 3, despite reduced solar input, essential services continued uninterrupted due to the lower base demand.

During the critical stress scenario (Week 4), the model confirmed that while non-essential services were suspended, all high-priority loads including school operations and the refrigerator were successfully maintained using the 5 kWh configuration, validating the effectiveness of the prioritization strategy.

Overall, the simulation highlighted the importance of flexible load management and battery sizing in off-grid energy systems and provided a robust validation of the design proposed in this study.

3 Battery System Design

In standalone photovoltaic (PV) systems designed for rural electrification, battery storage plays a critical role in maintaining energy availability during periods of low or absent solar irradiance. The selection and sizing of the storage component were guided by a multi-criteria decision framework that considered technical reliability, cost-effectiveness, environmental resilience, and system simplicity factors especially important in remote and underserved areas.

3.1 Battery Technology and Configuration

Among various technologies evaluated, Lithium Iron Phosphate ($LiFePO_4$) emerged as the most suitable option for the context of Gujicha. Despite a higher initial cost, this technology offers long-term benefits due to its extended lifecycle, safety, and minimal maintenance requirements. Two battery capacities were considered: a 30 kWh system, which ensures complete autonomy even under prolonged stress, and a 5 kWh system, which is significantly more affordable and relies on dynamic load prioritization strategies as described in Section 2.3. The latter configuration achieved over 90% coverage of priority loads under normal conditions, reducing capital investment by approximately 45%.

Given the high ambient temperatures in the region, thermal protection was a fundamental design element. The battery system includes active ventilation controlled by temperature sensors and a Battery Management System (BMS) to prevent overcharging, deep discharging, and imbalance across cells. These protections extend the system's life and ensure safety in areas with limited access to technical maintenance.

3.2 Sustainability and Performance Assessment

The compact and modular approach contributes to sustainability: it limits the use of critical raw materials, simplifies disposal and recycling, and offers the possibility of future expansion. During periods of reduced school activity, surplus solar energy can be redirected to auxiliary services, such as water purification, improving the community's overall resilience. A comparison of the two battery systems under different seasonal stress conditions is presented in the associated Figure 4.

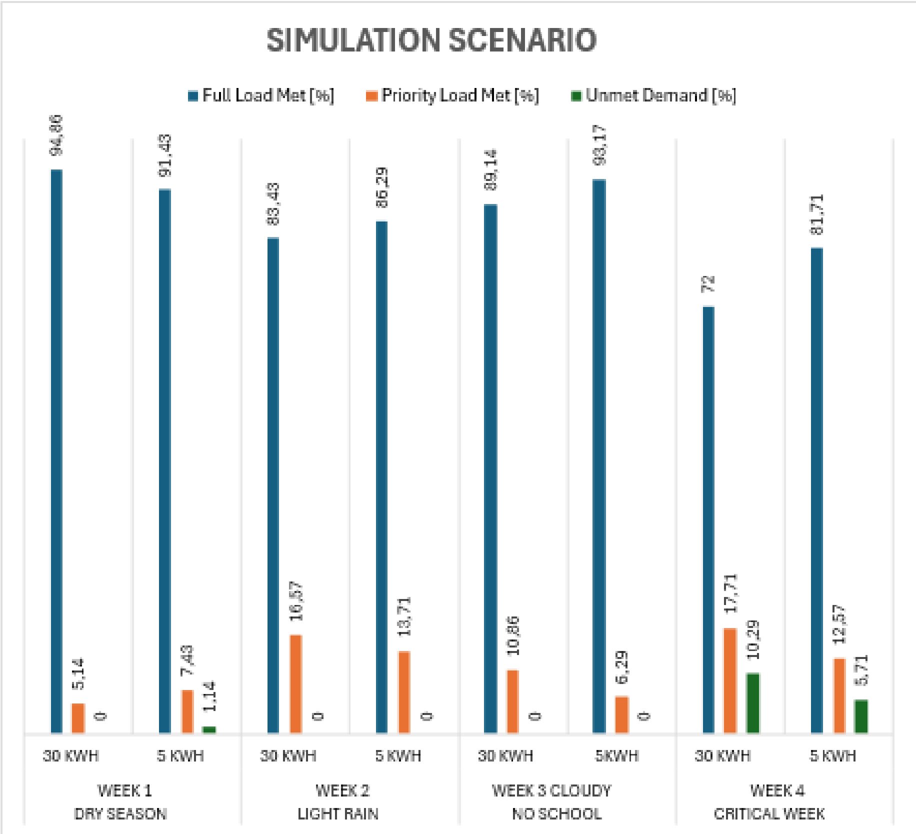

Figure 4. Simulation scenarios

While the 30 kWh setup offers slightly higher performance during extreme scenarios, the 5 kWh configuration ensures the continuity of essential services at a fraction of the cost.

This confirms the effectiveness of a lean, modular solution for rural mini-grids operating under financial and logistical constraints.

The results indicate that while the larger battery configuration yields marginally better performance in critical scenarios, the 5 kWh system maintains adequate service continuity especially for high-priority loads with significantly lower capital investment. This confirms the suitability of the leaner configuration for rural mini-grids where budget and logistics constraints prevail. This confirms the effectiveness of a lean, modular solution for rural mini-grids operating under financial and logistical constraints.

4 Results and System Performance

The simulation produced detailed time-series that allowed for a comprehensive evaluation of the energy system's behavior. Key metrics include PV production, battery state of charge (SOC), load satisfaction rates, and energy shortfalls or curtailments. Each weekly scenario highlighted specific system dynamics and stress points, confirming the importance of a well-balanced design between generation, storage, and prioritized consumption. The Table 4 summarizes the main results obtained from each simulated week.

•Week 1 highlighted system overperformance during peak irradiance. PV production exceeded load demand, allowing full satisfaction and considerable energy curtailment due to battery saturation.

•Week 2 showed mild intermittency, with the system mostly coping, though brief SOC dips triggered minimal unmet demand.

•Week 3, with low base load and no school activity, confirmed that essential services could be sustained even with limited solar input.

•Week 4 acted as a stress test. Prolonged low irradiance exposed the system's limits, forcing major load shedding despite full initial battery SOC.

The results show that the system is fully self-sufficient during favorable seasons, with production exceeding demand and allowing for energy storage or use for secondary loads. The selected configuration ensures stable operation, with the battery's state of charge generally ranging between 40% and 100%.

Table 4. Summary of simulations results

Scenario	$\overline{L}$	E_{PV}	SOC	L_S	E_{curt}	E_{unmet}
Week 1 (Dry Season)	29.3	39.1	Stable (70–100%)	100%	18.2	0
Week 2 (Light Rain)	29.3	33.7	Slight dip (40–100%)	99.3%	9.6	1.4
Week 3 (Cloudy, No school)	9.8	14.2	Fluctuating (30–90%)	100%	1.7	0
Week 4 (Critical Case)	29.3	11.8	Sharp drop (20–50%)	82.5%	0	35.7

In more critical conditions, as observed in the fourth scenario, energy availability is not always sufficient to meet all priority loads. However, the implemented energy management logic still ensures continuity of essential services, such as medical refrigeration and school lighting. The system's design and its adaptability through load prioritization and conservative strategies allow it to cope with extreme weather conditions. The design consideration:

•The sizing of the photovoltaic system proved adequate for most of the year.

•The 5 kWh storage configuration, combined with intelligent load control, ensures a balance between performance, reliability, and cost.

•Dynamic load management is essential for system resilience.

•The use of surplus energy for water or agricultural services enhances the social value of the system.

5 Conclusion

This study demonstrated the technical, economic, and social feasibility of implementing a Renewable Energy Community in an off-grid rural context in Ethiopia. The photovoltaic system, combined with a small lithium battery and a priority-based energy management strategy, showed good levels of autonomy, sustainability, and adaptability to local conditions.

The proposed model is easily scalable and replicable in similar contexts, where access to energy is limited and renewable resources especially solar are abundant. The possibility of integrating the system with additional services, such as water treatment and small productive uses, makes the proposal not only sustainable but also generative for local development.

Renewable Energy Communities thus represent a concrete opportunity to foster sustainable electrification in developing countries, strengthen community resilience, and contribute to achieving the Sustainable Development Goals.

Data Availability Statement

The data that support the findings of this study are available from the author, R.S, upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Nomenclature

A_{pan}	surface area of one PV panel, m^2
A_{tot}	total PV surface area, m^2
N	number of panels
P_{pan}	power output of a single PV panel, kW
P_{system}	required power output of PV system, kW
h_{use}	daily hours of use, h/day
E_{daily}	daily energy consumption, W
E_{day}	daytime energy consumption, kWh/day
E_{night}	nighttime energy consumption, W
$\overline{L}$	average daily load, kWh/day
E_{PV}	PV energy production, kWh
L_{S}	load satisfaction rate, dimensionless
E_{curt}	energy curtailment (unused energy), kWh
E_{unmet}	unmet energy demand, kWh

Subscripts

PV	Photovoltaic
SOC	Battery State of Charge
pan	Panel
CM	Copy Machine
C.Lab	Computer Laboratory
Lab.	Laboratory