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Integration of Advanced Metering Infrastructure for Mini-Grid Solar PV Systems in Off-Grid Rural Communities (SoAMIRural)

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Abstract: Solar energy is considered a promising source of power generation in sub-Saharan Africa due to the high sunshine in these areas. Deploying decentralised solar-powered mini-grid systems to provide access to electricity in rural areas is fraught with difficulties in accurately predicting consumption, automatic monitoring, and operation sustainability to support the socio-economic conditions of rural communities. This study proposed SoAMIRural, which integrates solar PV mini-grid and advanced metering infrastructure for rural communities. SoAMIRural was implemented and tested for a case study community in Ghana. Solar PV Selection Equation Matrix (SPSEM) and Sample Size Equation (SSE) were used to determine the sustainable demand generation capacity of 24 kVA. Load estimations and need assessments were conducted to ascertain the rural community's electric load and priority needs. SoAMIRural was evaluated with an error margin of 5%, resulting in 95% accuracy in energy consumption threshold management and monitoring to ensure energy conservation and sustainability of the mini-grid system. This study maps out a conceptual framework for a smart solar PV mini-grid system for rural communities and its advantages in realising SDG 7 in Ghana by 2030.

Keywords: advanced metering infrastructure; smart mini-grid; off-grid rural community; solar energy; electricity; sustainable development goals

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1. Introduction

Researchers across the globe have extensively investigated solar power in recent years. The demand for electricity keeps growing and knowing the harmful effects of fossil fuels on the environment, the world is leaning toward using clean, renewable energy sources. The case is no different in Ghana, as peak electricity demand in the country has increased by 10.3% per year over the past five years before 2019 [1]. As of 2020, the peak demand in Ghana was 3090 MW, with a total installed capacity of 5132 MW and a dependable capacity of 4879 MW. As of 2017, about 83% of Ghana's population had electricity access, while 17% did not [2]. Of the 17% without electricity access, 63% are in rural areas, while 37% are in urban/peri-urban areas. Additionally, out of the 83% with electricity access, 91% are in urban areas, leaving 9% in rural areas with access to electricity [3]. This translates to approximately 1.2 million households without electricity in Ghana [2].

Access to electricity is a big part of our world today as it influences economic activities and productivity. Rural areas in Ghana are largely deprived of electricity because they are in areas the grid has not yet reached [4]. A National Electrification scheme was set up in 1990 to ensure universal electricity access. However, due to one of the most significant objectives of this scheme, which seeks to ensure universal access for only communities with a population of 500 and above, there is a likelihood that a percentage of the Ghanaian population will always be without electricity since 15% of Ghana's rural population will live in communities with populations less than 500 [4,5]. Sadly, the electricity production rates do not meet the public demand, especially for people living in rural areas who are far removed from the national grid. Mini-grids, as a decentralised solution, have become important in achieving universal electricity demand by 2030 [6]. Sustainable Development Goal (SDG) 7 envisions that all modern, sustainable, reliable, and affordable energy must be available. Electricity supply to these rural areas improves the livelihoods of the inhabitants. According to Ozturk [7], most literature reveals a positive causal relationship between electricity use and economic development. Electricity is an inevitable factor in economic growth [7]. Hence, the lack of electricity inhibits the economic growth of rural off-grid areas.

Off-grid communities can benefit from the Sustainable Energy for All (SE4All) strategy to use clean, renewable energy-based mini-grid systems as a decentralised means of supplying electricity. Solar PVs, biomass plants, or wind energy can power these mini-grids. Economic activities can be improved, leading to an increased living standard for people in rural communities. It has been realised that solar PV systems are prevalent in rural communities across the globe. However, system management and short battery lifespan are challenges due to the lack of skilled personnel stationed in these rural communities. The introduction of Advanced Metering Infrastructure (AMI) into solar PV mini-grid is of necessity to fulfil SDG 7. Implementing AMI would ensure the sustainability of solar PV mini-grids by implementing remote load monitoring and controlling, which helps mini-grid operators to visualise all hourly and daily demands on the mini-grid system [8]. Current literature fails to analyse this possibility for rural community electrification. Sun et al. investigated intrusion detection systems (IDS) that may be used to safeguard the security of AMI networks [9]. These systems examine unusual information and sound an alarm. However, current intrusion detection models perform poorly and are frequently trained on cloud servers, which poses a serious risk to user privacy and lengthens the detection period. Their work presented a transformer-based intrusion detection model to enhance intrusion detection performance (Transformer-IDM). The results show that the authors could detect intrusions in an AMI network with higher communication accuracy. However, their study did not consider sustainability for new treatments to explore AMI for rural populations employing IOT devices as supportive components for AMI. The benefits of adopting an integrated infrastructure (grid and off-grid) employing an electrification model with high geographical, temporal, and customer-class granularity as the Reference Electrification Model (REM) were examined [7,10]. The findings indicated that mini-grids could deliver grid-like service to a substantial extent and, in many situations, at a significantly reduced cost. Their study does not, however, address how to monitor the hourly demand so that every client is satisfied with the REM's mini-generation grid's capacity.

Their study examined the security of advanced metering infrastructure, its weaknesses, threats, countermeasures, and prospects [11]. The study produced countermeasures that impacted and may impact future AMI designs. The primary study objective was to determine the benefits AMI offers the utility business. Although advancements in AMI and smart grid methods provide new operational benefits, they come with some new security and privacy problems. To defend an AMI against assault, security has become a critical requirement. The design and implementation of an AMI currently face significant security challenges. The study, however, did not consider rural communities' potential to integrate AMI to mini-grid securities for universal access to energy. Malawi, one of the sub-Saharan African nations with a low electrification rate, was studied by Maliro, Diarra, and Samikannu [12]. Its electrification rate, which is 18 per cent, is significantly lower than Africa's average electrification rate, which is 44 per cent. Their study aimed to determine the viability and economic potential of expanding mini-grids to locations without grids, particularly Matekenya, a community in Malawi's Dowa district in the country's central region. The ability of these rural communities to run and maintain the installed solar PV for operational sustainability, in the long run, was not assessed in the study. Hassane et al. investigated the techno-economic feasibility of developing solar PV mini-grid systems for five case study rural communities in Chad [13]. Their study did not consider the sustainability of the solar PV mini-grid system through load monitoring and control.

The related works show that most solar mini-grid researchers have performed extensive work establishing solar PV as a supportive power system for rural communities. Despite the insights provided, these and many other related papers fail to address monitoring the total hourly demand of mini-grid systems to control and manage consumption. This work proposes Solar PV Mini-Grid Integrated Advanced Metering Infrastructure (SoAMIRural), which promises to facilitate load control and monitoring of rural communities such that even future load additions can be predicted and well planned for, therefore ensuring the sustainability and longevity of rural solar PV mini-grid system towards the realisation of SDG 7. This study sought to achieve the following:

(1) Map out a conceptual framework (SoAMIRural) for a smart solar PV mini-grid system for rural communities and its advantages in realising SDG 7 in Ghana by 2030,
(2) Integrate and explore the prospects of using AMI for load control and management in solar PV mini-grid in rural communities,
(3) Perform electric load estimations and needs assessment of a case study rural community, and
(4) Provide convenient services through IoT for power purchases with available service providers (Banks, POS, ATMs) in the rural community.

2. Materials and Methods

The methods applied for the realisation of the objectives of this work are in three folds. First, the study conducted a needs assessment of the people in the case study community (Yeboahkrom) by deploying questionnaires and face-to-face interactions. Second, the study carried out load assessment and energy demand estimations of the community, and third, the study designed, implemented, and tested a solar PV mini-grid integrated with AMI.

2.1. Needs Assessment

2.1.1. Study Area Location

The case study rural community is Yeboahkrom, a small town in the Juaben Municipal Area in the Ashanti region of Ghana, shown in Figure 1, and existing housing conditions and infrastructure in Figures 2 and 3. The town is a farming community with 386 people, of which 57.2% are within the working class (ages 15–60), 22.8% are below the age of 15, and 20% are above age 60. The town has 80 households, a primary school, one palace for the chief, a church, and a mosque for the respective religious disciplines. The town has an average of 5 people per household, and 83% of the population are farmers. Other minor economic activities in the town include trade, eateries, and sewing and hair-shaving services. All indicators were ascertained using the technical and economic analysis framework designed in Figure 4.

During this phase of the study, the town of Yeboahkrom had no access to electricity, so food storage for their farm produce, lighting for night-time activities, and facilitation of services such as sewing and shaving were greatly handicapped as electricity is known to make these activities easy and efficient. Furthermore, the townspeople did not have access to any source of electricity-based recreation in the form of television, radio, or modern forms of entertainment. However, they had phones that they could only charge by walking kilometres to the nearest grid-connected town.

2.1.2. Assessment of the Needs of the Yeboahkrom Community

An assessment was conducted to ascertain the needs of the people of Yeboahkrom. Questionnaires and face-to-face interaction were employed to collect data on the needs of the people. A range of options was obtained, from which the community opinion leaders selected options from Table 1. Figure 5 shows the prioritisation needs of the community interactions. The urgent, important options that can aid the community's economic growth through access to electricity are education, health, communication, economics, and domestic activities.

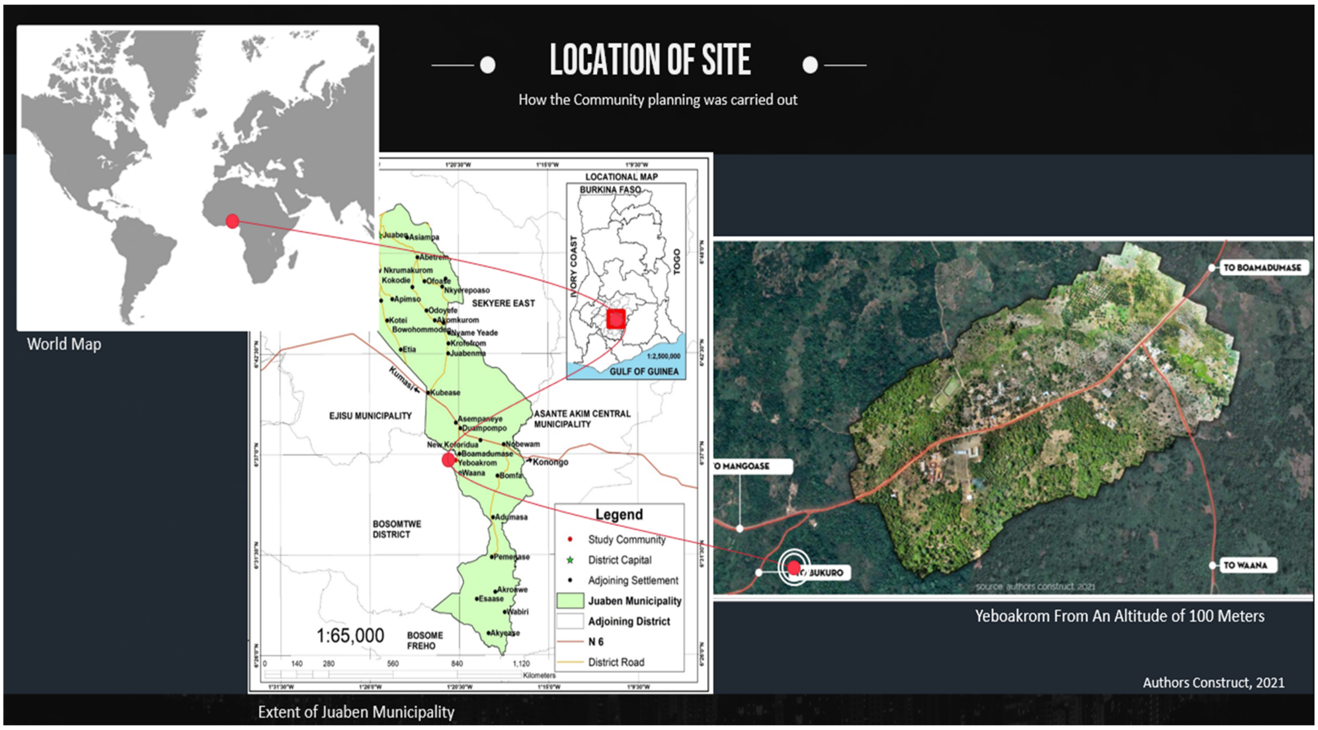

Figure 1. Location map of Yeboahkrom *(Source: Authors Construct, 2021)*.

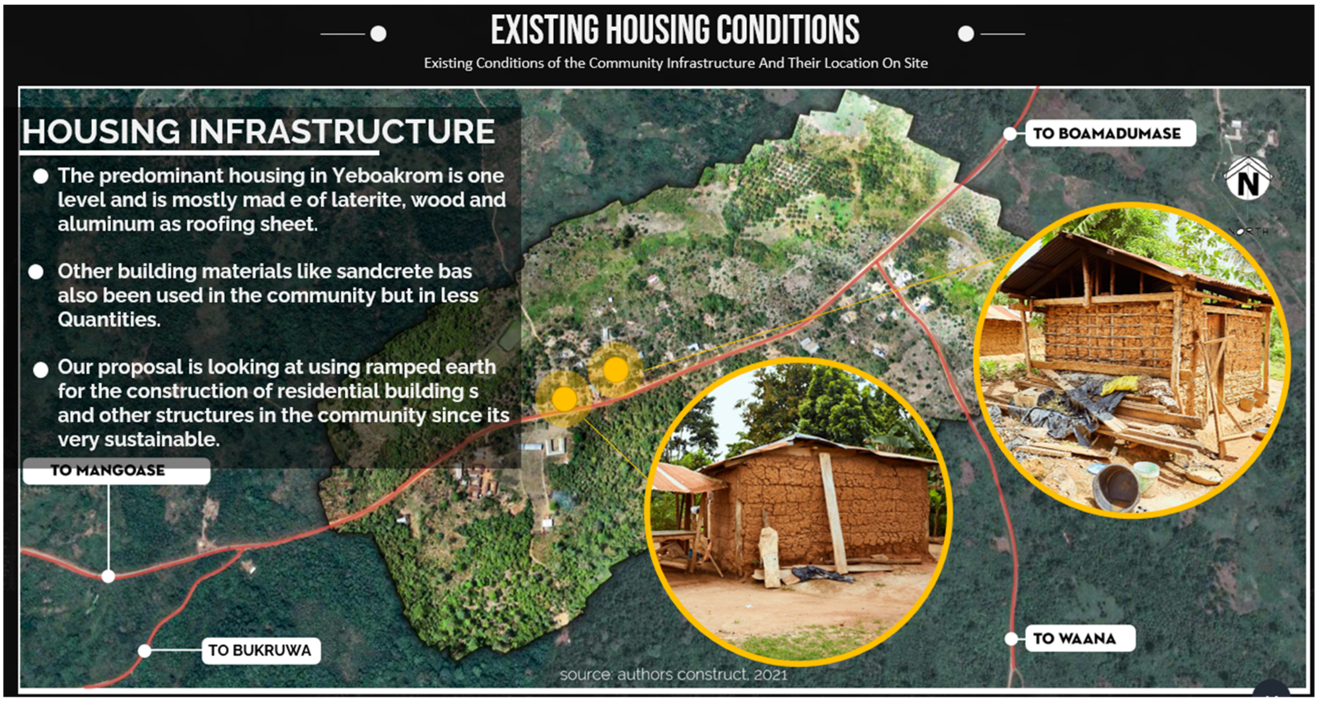

Figure 2. Existing housing conditions of Yeboahkrom (*Source: Authors Construct, 2021*).

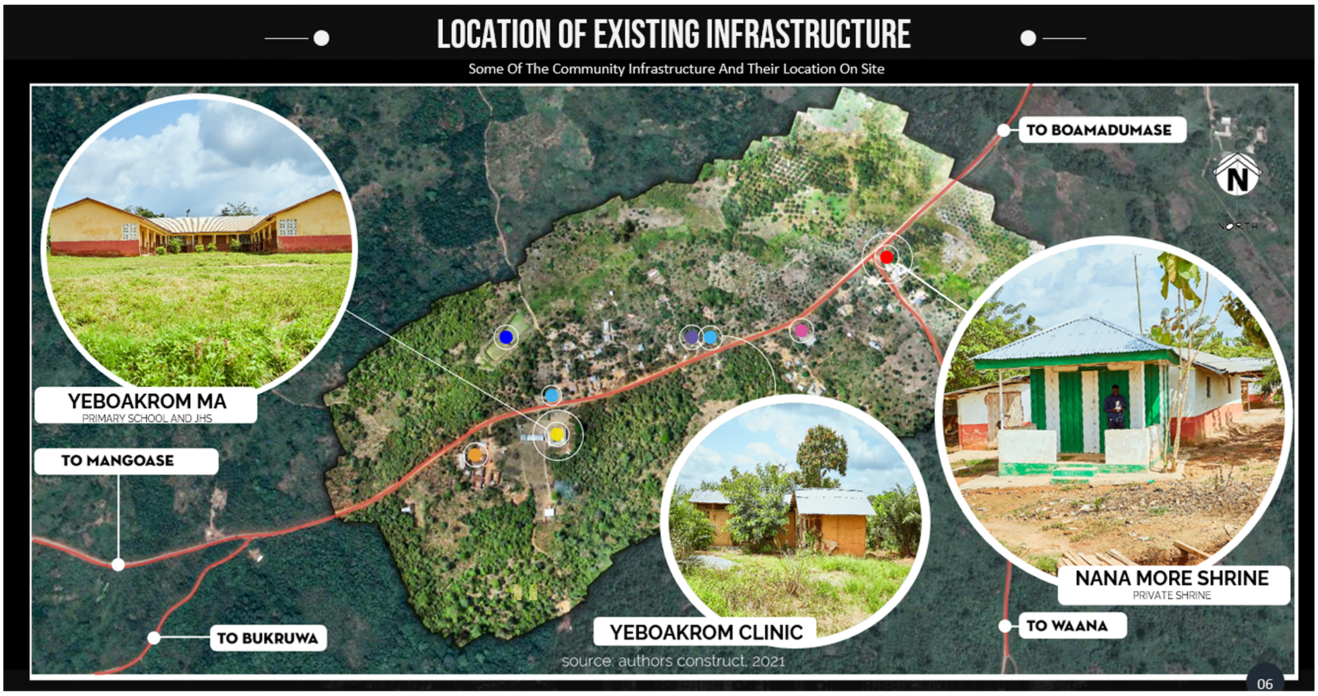

Figure 3. Existing housing conditions of Yeboahkrom (*Source: Authors Construct, 2021*).

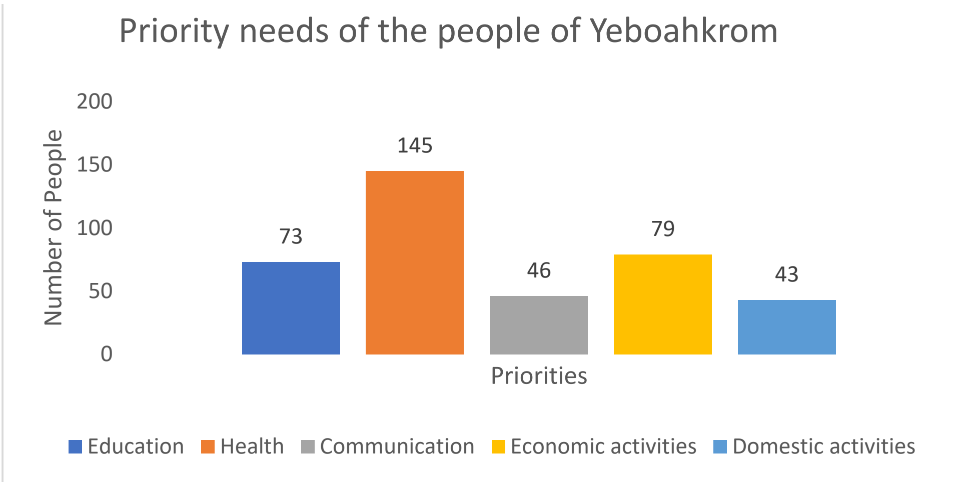

Figure 4. Priority choice of the community *(Source: Authors Construct, 2023)*.

Table 1. Assessment table for needs priorities.

Priorities	Number of People
Education	73
Health	145
Communication	46
Economic activities	79
Domestic activities	43
Total	**386**

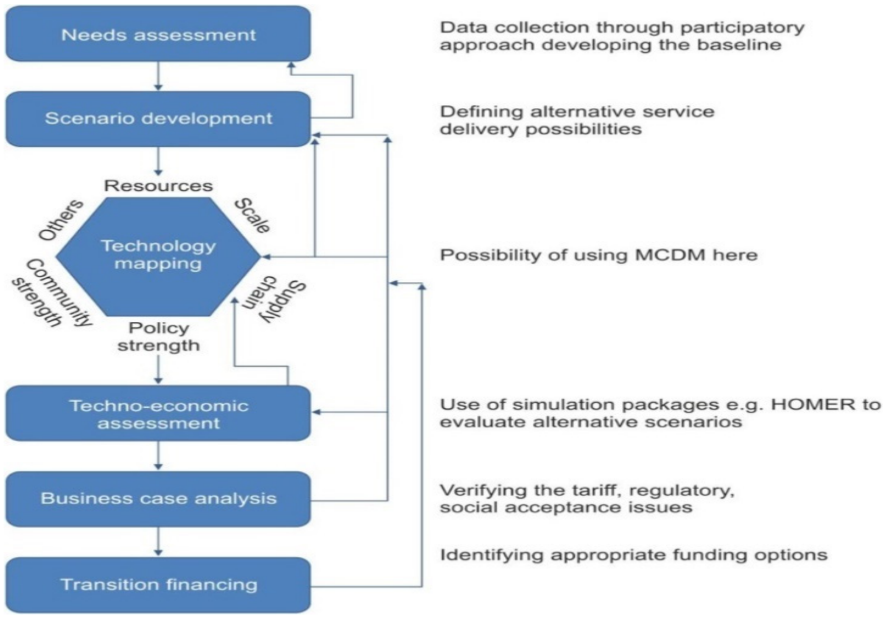

Figure 5. Framework for technical and economic analysis *(Source: Authors Construct, 2023)*.

2.2. Electric Load Estimation

The electric load of the town was split into two categories: (1) commercial load and (2) residential load. The electric load estimation was accomplished using questionnaires and electric load calculation tables. The questionnaires were used to collect data on the type of appliances used and the power rating of appliances. A sample size equation was employed to ascertain the average number of each appliance per household. Equation (1) presents the equation used to calculate the sample size. Data collected were entered into a spreadsheet with columns of 'type of appliances', 'power rating of appliance', 'some appliance types', 'average time duration of use', and 'total appliance consumption'. To calculate an appliance's total consumption per day (P_{total}), the power rating of the appliance (P_{rating}) was multiplied by the number of that appliance in use (n_{app}) and the average time duration of use (t), as shown in Equation (2).

$$N = q\% \times p\% \times \frac{z}{e\%} \tag{1}$$

where
N is the minimum sample size;
$q\%$ is the 'belonging to the specified category;
$p\%$ is the 'not belonging to the specified category;
z is the confidence level;
$e\%$ is the error margin.

$$P_{total} = P_{rating} \times n_{app} \times t \tag{2}$$

2.2.1. Threshold Classification Management

The community load data collected were used to determine the required generation capacity and manage consumption behaviour. The threshold load classification algorithm was developed and implemented in the AMI application. Algorithm 1 recorded consumption behaviour within a week and capped consumption into a class for sustainability management against supply. The system also gives clearance of 10% usage of actual consumption. This is unique in the load management for user class power off when out-of-range and user class power on when it is within range to control consumption in line with generated capacity for SoAMIRural. The pseudocode is shown below for the Algorithm 1 implemented in the management application.

Algorithm 1 *Pseudocode for threshold management*

1. Threshold Logic: Access Load (AL)
2. AL + 5 = Consumption
3. Capped threshold = Consumption + 10% of Consumption
4. if
5. consumption > capped threshold
6. then smart relay open
7. Else, return to Access load.

2.2.2. Commercial Load Estimation

The community's commercial sector was divided into three groups. The groups typify the three types of users identified in the commercial sector: **(1) small-scale users:** including small-tailoring businesses and eateries that used 0 to 1 kWh of electricity per day or 0 to 30 kWh monthly; **(2) medium-scale users:** made up of relatively bigger shops, barbering shops, bigger eateries, and facilities that use 1–3 kWh per day or 30 to 90 kWh every month; and **(3) large-scale users:** includes facilities in the town that uses more than 3 kWh per day such as cold stores, drinking bars, larger eateries, supermarkets, churches, and food storage centres. Tables 2–4 present the average load estimation for a single small-scale, medium-scale, and large-scale user in the commercial sector.

Table 2. Load estimation for small-scale users in the commercial sector.

Appliance	Power Rating (W)	Number of Appliances	Average Time Duration of Use per Day (h)	Times of Day Appliances Are Used	Total Consumption per Day (Wh)
Lights indoors	15	2	2	6 p.m.–8 p.m.	60
Outdoors lamp	20	3	12	6 p.m.–6 a.m.	720
Mobile phone	5	2	3	5 p.m.–8 p.m.	30
Radio set	10	1	12	8 a.m.–8 p.m.	120
Total	50	8	29		930

(Source: Authors Construct, 2023).

Table 3. Load estimation for medium-scale users in the commercial sector.

Appliance	Power Rating (W)	Number of Appliances	Average Time Duration of Use per Day (h)	Times of Day Appliances Are Used	Total Consumption per Day (Wh)
Lights indoors	15	3	2	6 p.m.–8 p.m.	90
Outdoors lamp	20	3	12	6 p.m.–6 a.m.	720
Mobile phone	5	3	3	5 p.m.–8 p.m.	45
TV	100	1	12	8 a.m.–8 p.m.	1200
Deep freezer	400	1	24	6 a.m.–6 a.m.	9600
Total	540	11	53		11,655

(Source: Authors Construct, 2023).

Table 4. Load estimation for large-scale users in the commercial sector.

Appliance	Power Rating (W)	Number of Appliances	Average Time Duration of Use per Day (h)	Times of Day Appliances Are Used	Total Consumption per Day (Wh)
Lights indoors	15	3	2	6 p.m.–8 p.m.	900
Outdoors lamp	20	3	12	6 p.m.–6 a.m.	720
Mobile phone	5	4	3	5 p.m.–8 p.m.	45
TV	100	1	12	8 a.m.–8 p.m.	1200
Deep freezer	400	2	24	6 a.m.–6 a.m.	19,200
Decoder	25	1	12	8 a.m.–8 p.m.	300
Total	565	14	65		22,065

(Source: Authors Construct, 2023).

2.2.3. Residential Load Estimation

For the residential load estimation, the community load was divided into three groups: small-scale, medium-scale, and large-scale users, per the definitions already defined under Section 2.2.1. From the data collected, 45% were classified under small-scale users, 35% under medium-scale users, and 20% under large-scale users. Apart from the load demand, other factors that could affect the load demands were the number of people living in the house, the size of the house, the economic activity of the family, the size of their properties, and the scale of the economic activities. Tables 5–7 present the load estimation for a single small-scale, medium-scale, and large-scale user in the residential sector.

Table 5. Average load estimation for a small-scale user in the residential sector.

Appliance	Power Rating (W)	Number of Appliances	Average Time Duration of Use per Day (h)	Times of Day Appliances Are Used	Total Consumption per Day (Wh)
Lamps (CFL)	20	4	13	5:30 p.m.–6:30 a.m.	1040
Mobile phone	3	2	4	5 p.m.–9 p.m.	24
Radio set	11	2	6	6 a.m.–7 a.m., 4 p.m.–10 p.m.	132
Total	34	8	23		1196

(Source: Authors Construct, 2023).

Table 6. Average load estimation for a medium-scale user in the residential sector.

Appliance	Power Rating (W)	Number of Appliances	Average Time Duration of Use per Day (h)	Times of Day Appliances Are Used	Total Consumption per Day (Wh)
Lamps	15	8	12	6 p.m.–6 a.m.	1440
Mobile phone	6	5	4	5 p.m.–9 p.m.	120
Radio set	10	3	5	5 a.m.–7 a.m. 5 p.m.–8 p.m.,	150
Fan	60	2	12	6 p.m.–6 a.m.	1440
TV	95	2	6	4 p.m.–10 p.m.	1140
Total					4290

(Source: Authors Construct, 2023).

Table 7. Average load estimation for a large-scale user in the residential sector.

Appliance	Power Rating (W)	Number of Appliances	Average Time Duration of Use per Day (h)	Times of Day Appliances Are Used	Total Consumption per Day (Wh)
Lamps	10	7	12	6 p.m.–6 a.m.	8400
Mobile phone	8	5	5	5 p.m.–9 p.m.	200
Fan	60	2	12	6 p.m.–6 a.m.	1440
Freezer	450	2	24	6 a.m.–6 a.m.	21,600
Paid TV.	20	2	5	5 p.m.–10 p.m.	200
Stereo	30	2	5	5 p.m.–10 p.m.	300
Irons	1200	2	1	6 a.m.–7 a.m.	2400
TV Set	105	2	5	5 p.m.–10 p.m.	1050
Total					35,590

(Source: Authors Construct, 2023).

2.2.4. Total Load Estimation

From the survey, 174 people were categorised as small-scale users, 135 as medium-scale users, and 77 fall under the large-scale users for the residential sector. It was estimated that there was an average of 5 people per household; hence the number of households for small-scale, medium-scale, and large-scale users were 35, 27, and 16, respectively. A household's total consumption per day was multiplied by the number of households under each category to derive the collective total consumption of all households under the various user-type categories. Tables 8 and 9 present the total daily consumption of residential buildings and commercial facilities. The same arithmetic was applied for the commercial sector with 6 small-scale facilities, 5 medium-scale facilities, and 5 large-scale facilities (details of facilities are presented in Table 10).

Table 8. Total consumption of residential buildings in the community.

Total per Day Consumption for Single Household (Wh)	Number of Households	Total per Day Consumption of All Residential Buildings (Wh)
1196	174	208,104
4290	135	579,150
35,590	77	2,740,430

(Source: Authors Construct, 2023).

Table 9. Total consumption of commercial facilities in the community.

Total per Day Consumption for Single Household (Wh)	Number of Facilities	Total per Day Consumption of All Residential Buildings (Wh)
930	6	5580
11,655	5	58,275
22,065	5	110,325

(Source: Authors Construct, 2023).

Table 10. Commercial facilities.

Facility	Small-Scale	Medium-Scale	Large-Scale
Eatery	0	2	1
Church	0	0	1
Mosque	0	1	0
Shop	3	2	1
Barbering salon	1	0	0
Sewing shop	2	0	0
Storage unit	0	0	1

(Source: Authors Construct, 2023).

2.3. Conceptual Design of SoAMIRural

SoAMIRural integrates solar PV mini-grid and advanced metering infrastructure for rural communities deprived of electricity access. AMI is a recent technology employed in the management of electric power. AMI is a network of smart metres, communications systems, and data management systems that facilitate the remote and automatic collection of data on customer energy usage. Data collected can be used for customer billing, giving real-time feedback on customer energy consumption, and remote managing of the distribution grid. This study employs AMI in the solar PV mini-grid rural community electrification project. The aim of using the AMI is to enable remote load control and monitoring to prevent consumers from exceeding the consumption threshold of the solar PV mini-grid, especially during peak times, ensuring the sustainability and longevity of the mini-grid system. This is particularly beneficial for rural electrification due to the lack of skilled personnel to physically manage the network at these locations. The long distances from the city centre make it challenging for skilled personnel to go to such locations often to conduct operational adjustment works. This study designed and tested AMI on the case study rural community, Yeboahkrom. Figure 6 depicts the conceptual framework of SoAMIRural and Figure 7 is a schematic diagram of the solar PV with accessories for generation.

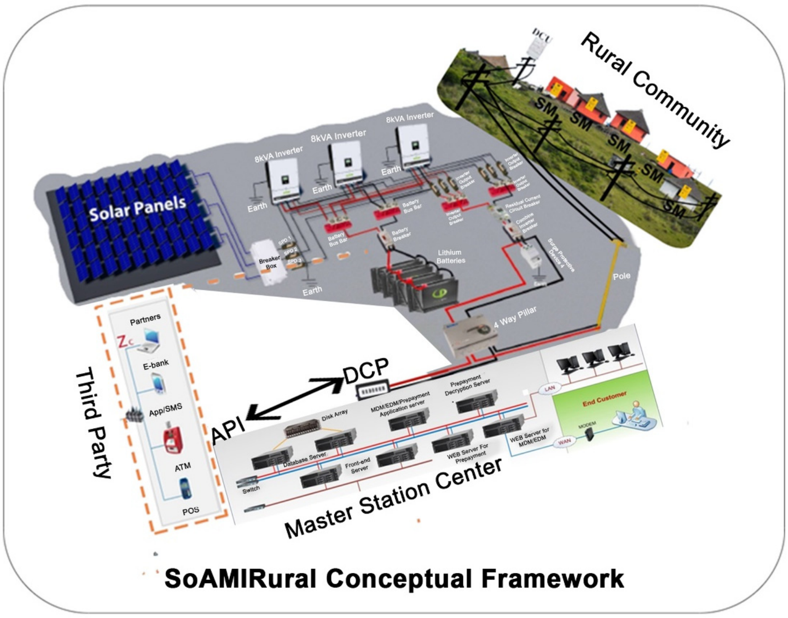

Figure 6. Conceptual framework of SoAMIRural *(Source: Authors Construct, 2023).*

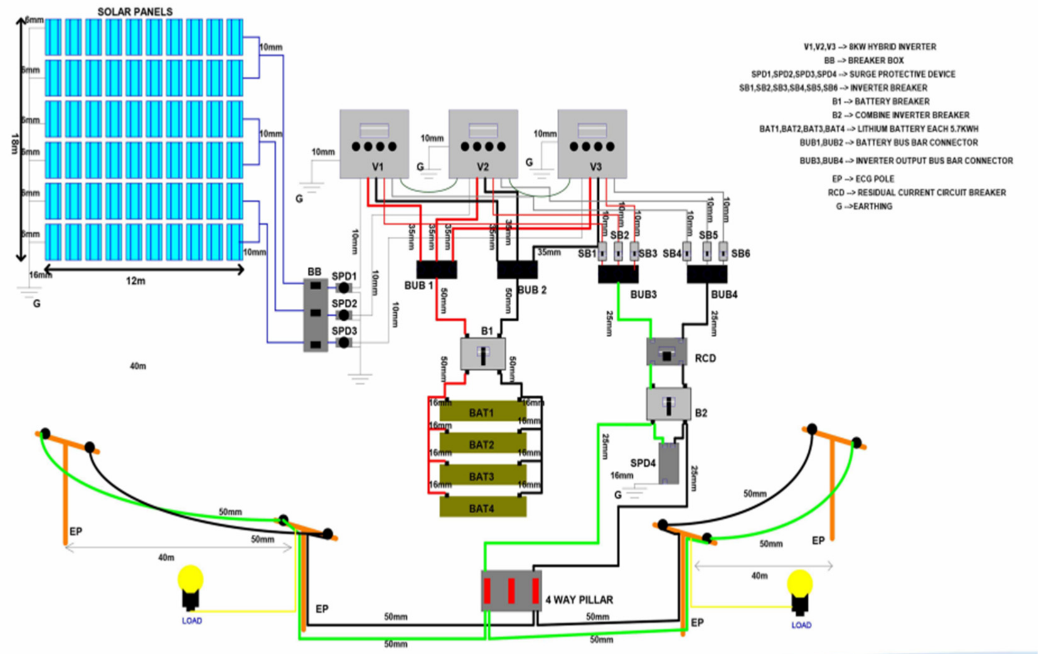

Figure 7. The schematic diagram for the 24 kva Solar PV generation substation *(Source: Authors Construct, 2023)*.

From the schematic diagram, SoAMIRural is made up of an automated solar PV substation, smart metres, Data Concentrator Units (DCUs), a Master Station Centre (MSC), and a Customer Monitoring Centre (CMC). The DCU serves as a communication path for system management between the Data Collection Platforms (DCPs), and the MSC acts as a control centre to house all servers (HES-END, WEB SERVER AND DATABASE). The CMC serves as a monitoring centre for triggers, threshold load management for demand-side sustainability, and supply-side management. Supply-side management is useful in future solar PV scalability.

2.3.1. Solar PV Selection

The study used the selection matrix to accurately select the right panels that best give system efficiency (direct sunlight) (%), low-light performance factor, the cost in USD/W, land area/kW efficiency, and long-life span that supports the sustainability objective of the project. Finally, AMI can integrate panels with IoT devices to control energy conservation and sustainability. Figure 7 shows the total substation capacity of 24 kVA generated using the following equipment, 500 W solar PV, 8 kVA hybrid inverters, lithium-ion battery 5.7 kWh, and other accessories for the Solar Substation.

Table 11 shows the efficiency, cost, land area, low-light performance factor, and life span of three solar PV types (thin film, monocrystalline, and polycrystalline). These values were used to compute the selection matrix values ($Mat_{val}(k)$) in Table 12 using Equation (3).

Table 11. Parameter values for solar PV types.

Parameters	Parameter Values (P_{val})			Interpretation
	Thin Film	Monocrystalline	Polycrystalline	
Efficiency (direct sunlight) (%)	7	17.5	14.5	The higher, the better
Cost in USD/W	0.50–1.00	0.60–0.90	0.40–0.60	The lower, the better
Land area/kW (m^2)	13–20	6–9	8–9	The lower, the better
Low-light performance factor	7	4	4	The higher, the better
Life span (years)	10	25	25	The higher, the better

(Source: Authors Construct, 2023).

Table 12. Solar PV selection matrix.

Parameters	**Selection Matrix Values** $Mat_{val}(k)$		
	Thin Film	**Monocrystalline**	**Polycrystalline**
Efficiency (under direct sunlight)	17.95	44.87	17.18
Cost	31.25	31.25	37.5
Land area	24.62	38.46	36.91
Low-light performance	46.67	26.67	26.67
Life span	16.67	41.67	41.67
total	137.16	182.92	159.93

(Source: Authors Construct, 2023).

For each parameter that has an interpretation of 'the higher, the better, all three values were summed up, and each value was expressed as a percentage of the sum to obtain $Mat_{val}(k)$ as depicted in Equation (3). For parameters with the interpretation 'the lower, the better', the computed parameter value was subtracted from 1 to obtain the higher side of the value, as shown in Equation (4). This was done to bring them on the same scale as parameters with an interpretation of 'the higher, the better'. Table 12 presents the values obtained for $Mat_{val}(k)$. The solar PV type with the highest total was selected as the most suitable for the mini-grid development.

For parameters with the interpretation 'the higher, the better',

$$Mat_{val}(k) = \frac{P_{val}}{\sum_{i=1}^{n} P_{val}} \times 100 \quad (3)$$

For parameters with the interpretation 'the lower, the better',

$$Mat_{val}(k) = \frac{1 - \frac{P_{val(r)}}{\left(\sum_{i=1}^{n} P_{val(n)}\right)}}{\sum_{j=1}^{r}\left(1 - \frac{P_{val(r)}}{\left(\sum_{i=1}^{n} P_{val(n)}\right)}\right)} \times 100 \quad (4)$$

$$r = k = n = \{monocrystalline\ polycrystalline\ thin\ film\ \}$$

2.3.2. Solar Mini-Grid Sizing

Having selected the solar PV type, the solar mini-grid was sized per the load estimated for the community. Sizing was performed for the solar PV array and battery bank. In sizing the PV array, the total daily load was divided by the product of peak sun hours and a combined efficiency of the inverter, battery bank, and charge controller using Equation (5). The equivalent DC daily load was calculated per the hybrid inverter's efficiency to ascertain the battery size needed for the system. This is because, on the load side, the power consumed is AC, so the DC energy required from the battery has to be oversized to factor in the inverter's efficiency. Having done this, the calculated equivalent DC daily load was divided by the product of system voltage, depth of discharge, and battery efficiency. The result was then multiplied by the total days of autonomy to obtain the battery size in Equation (6). Figures 8 and 9 show the PV-designed diagram and mounted structure based on the load calculated. Table 13 shows the resultant components for the solar PV used.

$$\text{PV array size} = \frac{total\ daily\ load}{peak\ sun\ hours \times \eta_c} \quad (5)$$

where η_c = combined efficiency of the inverter, battery bank, and charge controller

$$\text{Battery size} = \frac{equivalent\ DC\ daily\ load}{system\ voltage \times depth\ of\ discharge \times battery\ efficiency} \times days\ of\ autonomy \quad (6)$$

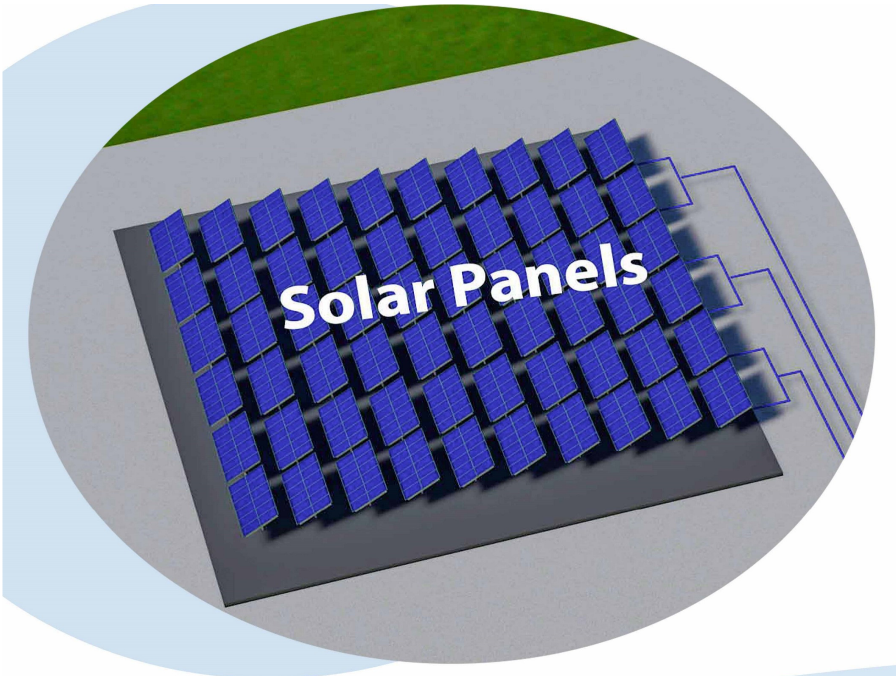

Figure 8. Solar PV implemented design systems based on load estimation *(Source: Authors Construct, 2023)*.

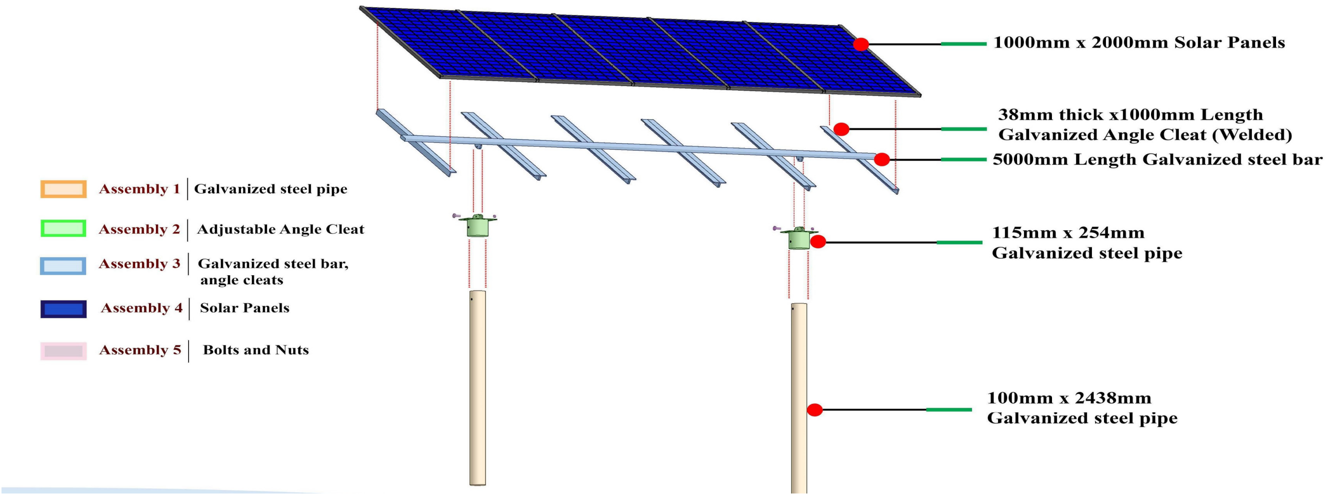

Figure 9. Structural design dimension for panel mount support.

Table 13. Size of various components and specification of the solar PV mini-grid.

Components	Size
Solar PV Array	24 kW
Battery bank	28.5 kWh
Hybrid Inverter	8 kVA × 3 = 24 kVA

(Source: Authors Construct, 2023).

3. Results

3.1. Priority Needs of the Yeboahkrom Community with Reasons for Access to Electricity

Table 14 presents the various needs, the number of people who chose them, and the reason given for selecting the needs. It can be observed from the table that the people of Yeboahkrom have different scales of priorities with different but equally valid reasons why the presence of electricity is of great importance to them. Health had the highest number of people (267), selecting it as a priority need, whilst domestic activity had the least number of people (80). This finding is plausible as it is commonly known that health issues are more rampant in remote communities where electricity access is a challenge [14,15]. It also implies that attention must be given to health facilities in future projects in remote communities.

Table 14. Priority needs of the people of Yeboahkrom with reasons for the need for access to electricity.

Priorities	Number of People	Reasons for the Need for Electricity Access
Education	73	• To help students study at night. • To get access to good studying materials, e.g., laptops and internet access.
Health	145	• To give the townspeople access to 24/7 healthcare services • For good storage facilities for drugs and vaccines. • To improve existing healthcare facilities.
Communication	46	• Keep in contact with friends and family members who have moved from Yeboahkrom to other towns or cities. • To stay informed about national and global news through radio, television, the internet, etc.
Economic activities	79	• To give farmers access to state-of-the-art storage equipment for farm produce. • To increase productivity and efficiency to reduce strain on farmers. • To help traders store perishable goods for longer periods and sell cold products such as ice water and ice cream to students.
Domestic activities	43	• To provide households with an alternate form of cooking to alleviate the problems with traditional cooking methods. • To provide better storage for cooked foods. • To provide lighting to aid visibility during night-times and reduce the risk of fire outbreaks that candles and lanterns can cause

(Source: Authors Construct, 2023).

Based on the reasons presented in Table 14, the presence of electricity in the community will greatly benefit the citizens of Yeboahkrom, directly affecting their livelihood and the development of the community. Access to electricity will upscale domestic activities in cooking, food storage, and lighting. The townspeople can explore new forms of cooking, such as electric cooking. Additionally, modern forms of food storage, such as refrigeration, will be possible [16]. Access to electricity will enable women to engage more in economic and educational activities as they become free from the labour of collecting biomass for cooking.

The risk of lighting such as candles and lanterns will be averted since the townspeople can use harmless electric bulbs. A study in Bangladesh showed that the presence of electricity reduced the use of kerosene lamps, which are inferior to electric bulbs in terms of lumens per metre square. Kerosene lamps pose a health risk as they are a source of indoor pollution and ambient black carbon emission [17]. Ref. [18] also showed that the people of Assam, Bangladesh shifted from using their traditional forms of lighting to the mass usage of lightbulbs. With access to electricity, farmers can employ modern mechanisms to facilitate farming activities, such as irrigation systems using water pumps in greenhouse farming. Farmers in Yeboahkrom can also easily communicate with their business partners, retailers, and suppliers in and outside Yeboahkrom due to modern communication devices that will be made possible through electricity access, and the community's economic activities have improved the livelihood of the townspeople. The SoAMIRural conceptual framework generates a total capacity of 24 kVA and a peak demand capacity of 16 kVA from the load estimation of various households. Figures 10–12 show the implemented SoAMIRural in Yeboahkrom.

Figure 10. Implemented solar PV farm in Yeboahkrom *(Source: Authors Construct, 2023)*.

Figure 11. Simulation of generation capacity and output voltage monitoring from AMI *(Source: Authors Construct, 2023)*.

Figure 12. Configured AMI control station *(Source: Authors Construct, 2023)*.

3.2. Load Monitoring and Control of Yeboahkrom Solar PV Mini-Grid

The SoAMIRural conceptual design was tested to monitor user energy consumption in the Yeboahkrom community, as shown in Figures 9 and 10. It is important to state that based on the SoAMIRural, the design energy threshold for each household was monitored and controlled to meet the generation capacity of the total energy generated. With the introduction of SoAMIRural, demand-side (DS) management, compared to the supplier side (SS), was managed according to the generation capacity, which is most often ignored in the mini-grid architecture designed for implementation.

Figure 13 presents the individual household hourly consumption of the Yeboahkrom community. The graph shows the hourly kWh consumption of a typical Yeboahkrom household on 26 February 2022. Figure 14 also presents a daily energy consumption of a typical household in the Yeboahkrom community from 29 December 2021 to 9 January 2022. The SoAMIRural system controls energy consumption by monitoring and cutting off a household when it consumes beyond the daily allocated energy threshold. This helps to eliminate system imbalance and overloading, which cause system instability and excess tripping. Figure 15 depicts the overall mini-grid consumption of the Yeboahkrom community. The graph shows that energy consumption is lowest between 7 a.m. and 5:30 p.m. This is because 7 a.m. to 5 p.m. is when most of the community goes out to do farming and other commercial activities. This agrees well with the findings from [8,15], who asserted that there is a mismatch between the peak consumption and actual maximum generation period of the solar PV. With these data and the AMI infrastructure, the mini-grid operator can monitor and maintain the mini-grid from distant locations. The household energy threshold management helps preserve the battery's life, the single most expensive component of the mini-grid. These ultimately lead to the sustainability of the mini-grid system.

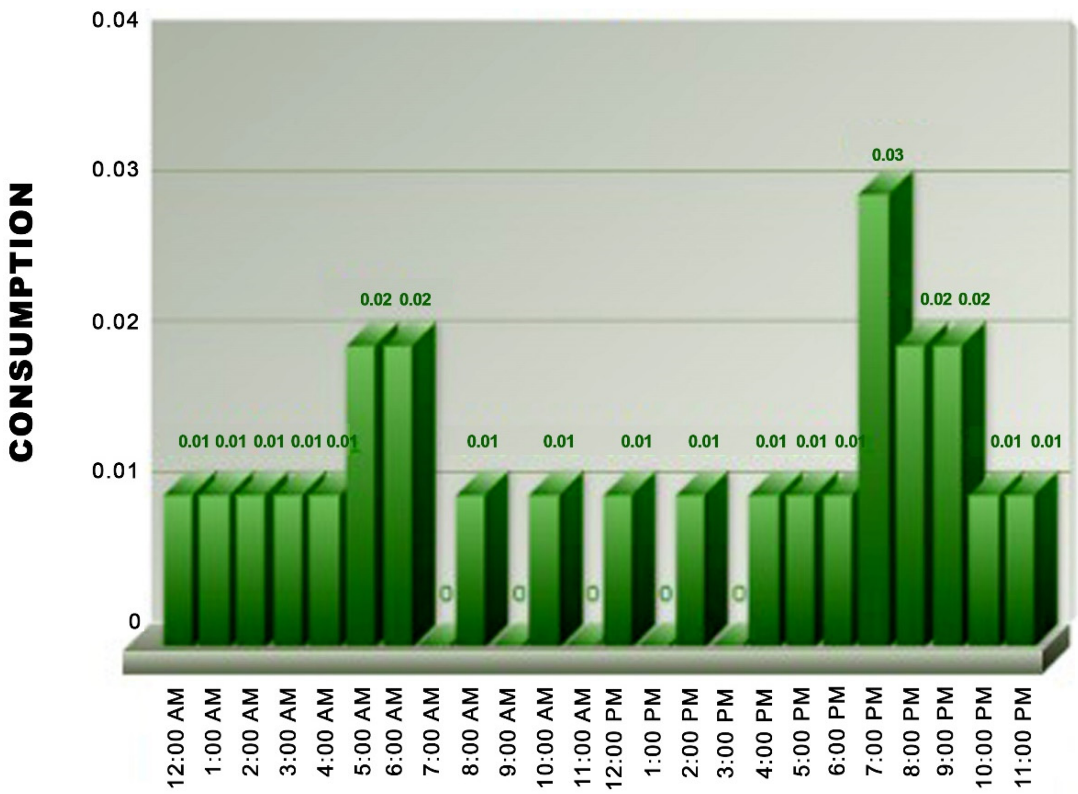

Figure 13. Individual household hourly consumption *(Source: Authors Construct, 2023)*.

Figure 14. Individual household daily consumption *(Source: Authors Construct, 2023)*.

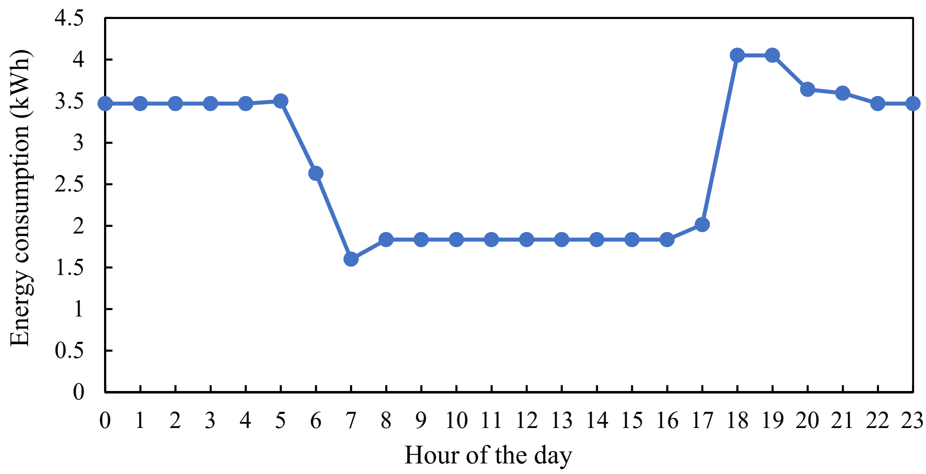

Figure 15. Overall mini-grid hourly consumption *(Source: Authors Construct, 2023)*.

As illustrated in Figure 6, the AMI system has a Data Collection Platform (DCP) agent as a very important device for AMI solutions; all modules or execution for data, traffic, and energy transmission are carried out at this stage. All communication within the AMI system starts with smart metres, communicating through a communication medium, either Radio Frequency (RF), Zigbee, Powerline Communication (PLC), or Dynamic-PLC. The DCP then collects all incoming data from the Data Concentrator Unit (DCU) and converts it to the appropriate information for its destination. The generated capacity from the solar PV (supply side) and demand side (Consumer Load) is all recorded in SoAMIRural and controlled using the developed algorithm in SoAMIRural to manage and control the end-to-end solution proposed and implemented for rural electrification and sustainability. Finally, introducing a third party within SoAMIRural integrates various facility providers using Application Programming Interface (API) to interact with the energy provider without any challenges and in consumers' comfort.

3.3. Comparative Analysis with a Similar Project without AMI

Considering the scope of this study, three different mini-grid communities in the Oti and Bono East regions of Ghana were visited as case studies for the mini-grid development. The communities include Wayokope, Aglakope, and Kudorkope. Table 15 presents the capacity of the mini-grid and the number of households, and the current impact. These communities' mini-grid were connected without AMI technology for load monitoring. It was observed that some only functioned during the day, and others were not functioning due to automatic system monitoring and classification challenges to meet the generation demand for sustainability. The AMI technology integrated into the design showed effective monitoring, management, and sustainability changes.

Table 15. Other mini-grids in Ghana without AMI and their impact.

Community	Generation Capacity (kVA)	Household	Impact
Wayokope	20	57	System not working
Aglakope	33	128	Works only during the day
Kudorkope	33	175	Works only during the day
Yeboahkrom (SoAMIRural)	**24**	**80**	**Working smoothing with AMI for load monitoring**

(Source: Authors Construct, 2023).

4. Conclusions

This study has explored the prospects of integrating AMI into solar PV mini-grids (SoAMIRural) for load monitoring and control in rural communities. The study performed needs assessment and electric load estimations of a case study of an off-grid rural community in Ghana (Yeboahkrom). The needs assessment has shown that rural African communities (Case Study, Ghana-Yeboahkrom) are duly deprived of energy accessibility, which impacts their livelihoods in education, health, and the socio-economic capacity of the citizens. AMI successfully monitors and controls the load on the rural community mini-grid, which is essential to ensure the operability and sustainability of the mini-grid system. SPSEM and SSE have been proven to accurately estimate the sustainable demand generation capacity to match the supply side with the demand side of SoAMIRural for the Yeboahkrom community. One major contribution of SoAMIRural is its ability to manage and sustain the entire renewable generation system from end to end and its great impact on the community's education enrolment, health, and socio-economic livelihoods.

Furthermore, SoAMIRural also serves as a research tool for remotely collecting data on renewable energy systems without necessarily visiting the site. Faults can also be resolved using the end-to-end solutions of AMI, a technology in the AMI that integrates all modern IT tools to ensure complete and all-encompassing functionality of the AMI. SoAMIRural can integrate an Application Programming Interface (API) for other services, such as banking, ATM, and post services, to be accessed by rural communities. From the needs assessment, health was found to be the greatest need, and the presence of electricity can help enhance the development of the Yeboahkrom community. Health conditions in the community will be improved because hitherto unavailable health facilities will be made possible due to access to electricity. Other beneficial sectors include education, economy, communication, and domestic activities. This study has provided a framework within which future mini-grid studies for rural communities can be conducted.

Further investigation or research can examine the initial system setup and operating costs for sustainability and the ability to pay on the Time-of-use (TOU) of energy generated by the community. Finally, the possibility of AMI vulnerabilities by attackers must be considered in further research.

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

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