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Research Article

Design and Characterization of PV Minigrid Plants for Modern Farming and Rural Electrification in Rwanda

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Solar energy is among the clean, ecofriendly, and reliable energies. Standalone PV plants have great potential to fulfill specific load demands in remote villages in Rwanda. However, owing to the scarcity of information on solar energy potentials in some areas, lack of accurate load demands, and overlooking energy consumption by farming activities, PV plants can be hardly optimally sized, developed, or utilized. This study proposes and characterizes the PV plant model based on precisely quantified load demands including the energy needed for e-farming. The technoeconomic performance of these PV plants was analyzed using PVSyst software. The results confirm availability of solar resources enough to steadily satisfy the loads in the communities. Nevertheless, several factors were seen to induce energy losses for the developed PV systems, among which the heating owing to the rise of temperature being the major factor of energy loss. In fact, the solar radiation intensity exceeds 1800 kW/m^2/year, and the heating occurring at the surface of the panels causes energy losses of up to 9.46%. Also, the findings suggested that the investors will gain the financial benefits for 10 out of 25 years while the energy's price would drop from 0.252 EUR/kWh to 0.180 EUR/kWh. These findings are significant as they provide information that planners and investors could use to make informed decisions. Future studies may need to use such results to quantify the contribution of available subsidies and incentive reduction on cost of solar energy and adoption of PV plants.

1. Introduction

It is expected that the global energy need will double by midcentury owing to economic and demographic growth [1–4]. A big number of people without access to electricity, 1.3 billion plus, reside in developing nations. They lack access to electricity because of grid failure and other issues [5]. Moreover, the developing world is expanding its energy consumption at a quicker rate, even than industrialized countries. Developing countries, most of which are in sub-Saharan Africa, are required to largely and rapidly increase their current installed generating capacity to fulfill their energy demand [6, 7].

The majority of the population in the developing world lives in rural regions. They remain reliant on conventional energies [8, 9]. For example, for cooking and home heating, wood is mostly used, and for home lighting, most people use kerosene while animals and humans provide energy for agricultural activities. For crop drying and irrigation, sunshine and diesel engines are used, respectively [10, 11].

However, cooking, warming houses, food processing, and other purposes require a huge amount of energy and may lead to deforestation or air pollution. The extraction of coal, oil, and gas, commonly used as energy sources in rural villages, is among the principal contributors to environmental deterioration too [12]. As a result, it was observed that as the population and the economy grow, there is a crucial need for supplementary energy to support human sustainable economic growth with less or no harm to the environment.

It is understood that renewable energy resources are to be relied on to fulfill the aforementioned expanding energy demands. Therefore, solar PV systems which are deemed technologically, economically, ecologically, and socially suitable as a sustainable long-term response to the fast growing energy needs in developing countries [13, 14], like Rwanda, are to be given substantial consideration.

Solar irradiations are plentiful and widely available renewable energy sources [15]. Moreover, PV components have become more cost-effective than in the past three decades. In fact, solar panels' cost has decreased considerably each year while their production has been increasing by about 30% per year. Currently, the price of solar energy is less than the price of most other fuels [16].

Some remote villages in Rwanda are to be electrified by solar energy, according to the National Electrification Plan 2020 [17] as PV systems have been proven effective for electrification of remote areas [18]. While many villages are to depend on solar home systems, electrification in remote villages with a large number of households and considerable agricultural activities will rely on solar plants for electrification [19–21]. These off-grid solar photovoltaic (SPV) systems can be built at a cheap cost if they are optimally designed based on the load demand and prevailing climatic conditions at sites. They are expected to address the issue of large expenses associated with electrification for communities in remote rural areas, as grid extension to remote locations requires huge investments. Such extensions are also associated with significant energy losses.

It is worthwhile to note that the design and development of both solar home systems (SHS) and off-grid solar plants with good efficiency requires rigorous sizing and optimization based on actual and forecasted energy consumption [22–28]. Various studies have been carried out all over the world on optimizing PV systems. For example, a simulation-based study was carried out to design and optimize grid-connected and standalone PV systems to fulfill the energy demand of household equipment [24, 28]. The findings demonstrated that integrating highly efficient appliances with PV systems is an effective way to optimize energy usage while also lowering electricity costs and pollution. Similarly, [29] assessed risk factors that contribute to the failure of minigrid projects such as customer inability to pay, battery life issues, underutilization of minigrid energy supply, and poor designs. It was illustrated that these risks could be alleviated by customizing and optimizing PV system designs. The study concluded that optimized designs lead to PV systems with good performance and less pollution at the lowest total cost of the PV systems. However, one can remark that even though these studies are important in the field, they may have little impact on spreading of efficient and low-cost solar PV systems in Rwanda. This is not only due to the fact that solar resources change with geographical locations, but also the electrical load profile at a given village influences the optimum designs of the PV systems.

In the case of Rwanda, a few studies have been carried out to design minigrid PV plants for the electrification of Kayonza District [30] and at Kanazi Village in Bugesera District [12]. Nevertheless, these studies are partial. Firstly, they have been specific to one or two villages, and therefore, they might not be accurate characterizations of optimized PV system models for rural electrification in the whole country. Secondly, domestic electrification in rapidly developing rural villages in Rwanda would necessitate extensive analysis of electrical load, incorporating predictions on increments of the loads in the future modern villages. Therefore, appliances such as radios and TV, electronic devices such as computers and cellphones, fans, electric irons, and refrigerators had to be added to the domestic consumption of energy. Moreover, small businesses such as udukiriro (community workshops) and beauty salons have to be added to the energy consumption of modern villages in remote areas. Another study [31] described optimal hybrid hydrosolar plants. But, most of the regions in Rwanda bear abundant solar resources with less potential for hydropower due to the insufficiency of water and necessary heads for hydropower production. Hence, one can notice that there is lack of thorough studies on sizing and optimizing standalone PV systems that can respond to the energy need in rural areas of the country, Rwanda.

Furthermore, special consideration is needed for energy demand associated with farming activities during the sizing and optimization of PV plants in most of the villages in Rwanda. In fact, as Rwanda envisages shifting toward clean e-farming, energy demand associated with the usage of electrical tractors and farming activities needs to be carefully considered when sizing PV plants for rural areas.

Researchers have established several cases where optimized solar energy systems have been highly beneficial to farming in emerging economy countries. Among others, Ravi et al. [32] showed that the application of solar energy could lead to efficient land and water use, therefore improving farm productivity in marginal lands in India. For the sake of social and environmental sustainability, they advocated the deployment of photovoltaic systems to promote high-value crops in prime locations. Likewise, another research conducted in China observed that agrivoltaic has the potential to relieve the conflict between an increasing population and a shrinking amount of arable land, catalyze the growth of environmentally friendly farming practices, boost the livelihoods of farmers, and reduce emissions in the process [33].

It has been illustrated that putting electricity to use in the agricultural process is achievable in many areas. Electricity may replace fossil fuels for the production of nitrogen-based fertilizers, irrigation, powering agricultural equipment, powering transportation equipment, and providing energy for other farming activities [34]. Most of such farming activities have been overlooked in currently available PV optimization studies in Rwanda. Therefore, this study will be based on a deep assessment of energy requirements to design an optimum PV plant for rural electrification and e-farming in Rwanda. To extend the applicability of the model PV plant under this study, the optimized design of the PV will incorporate predictions on potential additional energy requirements due to rapid rural development and population growth in Rwanda. The research will be carried out at different sites, namely, Gishuro in Tabagwe sector, Nyagatare District; Kageyo in Rwinkwavu sector, Kayonza District; and Gashanga in Rilima sector, Bugesera District. These locations are to be electrified by solar PV plants as per the National Electrification Plan of Rwanda. Hence, the findings of this study may be able to serve as a reliable representation of the energy profile in the countryside locations with hefty needs for energy facilities.

2. Case Study

The initial assessment was done on 32 different sites all over the country; see the map in Figure 1(a). The assessment is aimed at identifying sites with the need for access to energy or needs for additional energy to feed newly established energy loads. It was found that, among the thirty-two sites, eight (presented in Figure 1(b)) entail large energy requirements while three sites which are Gishuro in Nyagatare, Rilima (Gashanga) in Bugesera, and Kageyo in Kayonza needed a detailed technoeconomical study to characterize the PV plants that can power them. This is because these three sites will remain largely supported by off-grid energy systems as per the country's National Electrification Plan. The study evaluated the solar resources available at these sites and estimated the energy requirements at those three sites.

In addition to that, at site locations, solar irradiance was measured. Table 1 presents the coordinates and solar radiation intensities for the tree sites. According to the table, the minimum global horizontal irradiation (GHI) observed was at 1826.7 (kW/m^2/year) at Kageyo in Kayonza. This irradiance is however high enough to sustain enough solar energy production by a PV power plant.

3. Methodology

Figure 2 portrays the framework of analysis for this study. As can be seen from the figure, the theoretical background on energy production from solar irradiations, energy storage, and cost analysis is presented. After the presentation of that mathematical background, an initial assessment to obtain physical and technical parameters that serve as inputs for the PV plant model was conducted. After that stage, a technoeconomic analysis is carried out using PVSyst software to determine the optimum size, factors that may influence energy losses, and financial benefits for the designed PV plants.

3.1. Mathematical Background. The PV plant model can be modelled using equations (1), (2), (3), (4), (5), (6), (7), (8), and (9) [24, 35]. The power of the plant can be estimated from the following:

$$P_{\mathrm{PV}} = P_{\mathrm{STC}}\mathrm{DF}\left(\frac{\mathrm{IR}}{\mathrm{IR}_{\mathrm{STC}}}\right)\left[1 + a_{\mathrm{p}}\left(T_{\mathrm{mod}} - T_{\mathrm{mod,STC}}\right)\right]. \quad (1)$$

In equation (1) P_{STC} is the power of PV plant when $\mathrm{IR}_{\mathrm{STC}} = 1000\,\mathrm{W/m^2}$, $T_{\mathrm{mod,STC}} = 25^\circ\mathrm{C}$, and wind speed = 0 m/s. IR stands for solar irradiation intensity, while $\mathrm{IR}_{\mathrm{STC}}$ represents the solar irradiance at STC. For the PV panels, the dust accumulation-induced power loss is denoted by DF while a_{p} is the power temperature coefficient. T_{mod} is the panels' actual temperature and $T_{\mathrm{mod,STC}}$ stands for temperature of the PV panels under STC (standard test conditions) which are $\mathrm{IR}_{\mathrm{STC}} = 1000\,\mathrm{W/m^2}$, $T_{\mathrm{mod,STC}} = 25^\circ\mathrm{C}$, and wind speed = 0 m/s.

The power of the solar PV modules under standard test conditions is given by

$$P_{\mathrm{STC}} = \left(N_{\mathrm{series}} \times N_{\mathrm{string\,parallel}}\right).P_{\mathrm{m,STC}}, \quad (2)$$

where N_{series} and $N_{\mathrm{string\,parallel}}$ are the numbers of photovoltaic modules in series and the number of strings of modules in parallel, respectively. Under standard conditions, the rated power of the photovoltaic module is $P_{\mathrm{m,STC}}$.

The efficiency of the plant can be calculated as

$$\eta_{\mathrm{m,STC}} = \frac{P_{\mathrm{m,STC}}}{A_{\mathrm{PV}}\mathrm{IR}_{\mathrm{STC}}}. \quad (3)$$

A_{PV} is the total area of PV panels.

Modelling of the storage can be done using equations (4), (5), (6), (7), (8), and (9). Equation (4) considers the charge of the batteries from the PV plant and the discharge to the loads.

$$S_{\mathrm{o}}C(t) = S_{\mathrm{o}}C(0) + \eta_{\mathrm{c}}\sum_{k=0}^{t} P_{\mathrm{CB}}(k) + \eta_{\mathrm{d}}\sum_{k=0}^{t} P_{\mathrm{DB}}(k)s. \quad (4)$$

In equation (4) $S_{\mathrm{o}}C(0)$, P_{DB}, P_{CB}, η_{d}, and η_{c} are the initial battery charge state, power discharge, power charge, discharge coefficient, and charge coefficient, respectively.

The constraints on battery capacity are given by

$$\begin{cases} B_{\mathrm{min}} \le S_{\mathrm{o}}C \le B_{\mathrm{max}}, \\ B_{\mathrm{min}} = (1 - D_{\mathrm{o}}D)B_{\mathrm{max}}, \end{cases} \quad (5)$$

where B_{min} and B_{max} are minimum and maximum capacities while $D_{\mathrm{o}}D$ is the battery's depth of discharge.

The discharge from the battery has also to be constrained between 0 and P_{max} as indicated in

$$0 \le P_{\mathrm{DB}}(k) \le P_{\mathrm{max}}. \quad (6)$$

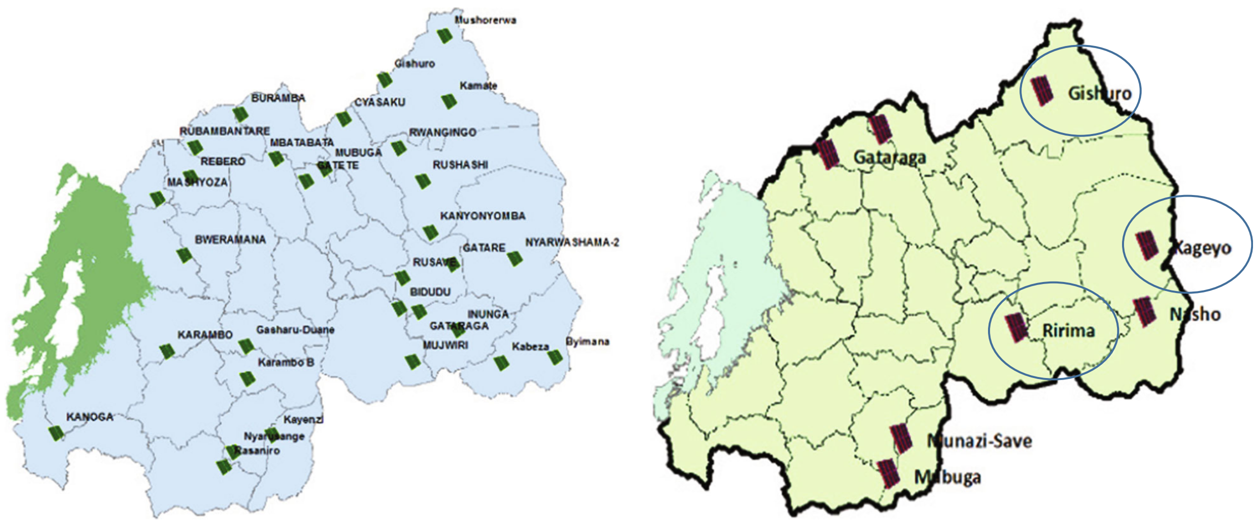
P_{max} is the maximum value of the battery's power discharge per hour.

The mathematical representation of conversion for the converter connected between the DC and AC busses for DC to AC conversion is as follows:

$$P_{\mathrm{InvOut}} = P_{\mathrm{InvIn}}\eta_{\mathrm{Inv}}, \quad (7)$$

where $P_{\mathrm{InvIn}} = P_{\mathrm{PV}} + P_{\mathrm{DB}}$ for the standalone PV plant and $P_{\mathrm{InvIn}} = P_{\mathrm{PV}}$ for the plant connected to the grid. η_{Inv} is the converter's efficiency. It is assumed constant. P_{InvOut} is the power output from the converter while P_{InvIn} stands for power input to the converter.

The total load requirement includes the energy consumption by the E-tractor, the energy consumption for other activities in the farm and villages, and the energy consumption in households. In case of the on-grid photovoltaic plant,



(a) Sites for PV systems

(b) Selected sites for PV systems

Figure 1: (a) Sites at which a preliminary physical study was done and (b) sites selected for detailed technoeconomic study on solar PV plants.

Table 1: Input parameters.

Site description	Site coordinates		Global horizontal irradiation (kW/m^2/year)
	Latitude	Longitude	
Site (1)—Nyagatare (Gishuro)	-1.29°	30.18°	1831.4
Site (2)—Bugesera (Rilima-Gashanga)	-2.14°	30.24°	1850.3
Site (3)—Kayonza (Kageyo)	-1.83°	30.71°	1826.7

the load should correspond to the sum in equation (8) while for standalone plant, the total load can be obtained by equation (9).

$$P_{\mathrm{L}}(k) = P_{\mathrm{PV}}(k) + P_{\mathrm{DB}}(k), \tag{8}$$

$$P_{\mathrm{L}}(k) = P_{\mathrm{PV}}(k) + P_{\mathrm{Grid}}(k). \tag{9}$$

3.2. Data Collection and Input Designs. The initial stage of the data collection was to gather physical data to enable the evidence-based selection of sites. First, a physical assessment was conducted on 32 sites among which 3 sites were selected for detailed analysis in this study. The parameters of most interest collected were coordinates of the location, solar radiation intensities, the inventory of electrical appliances used in villages, and their power ratings. Solar irradiations are worth to be determined as the total power can be determined based on the solar radiation intensities for a given PV plant.

In this study, the load was quantified for different activities. Among these are farming activities, household usage, and village activities. For farming, the energy was calculated considering the power of the tractor, the type of soil, and the slopes. On the other hand, for household usage and village activities, the total energy load was obtained through inventories of pieces of equipment and their corresponding power ratings as well as the previous invoices paid by different consumers in some cases. The study includes the estimation of potential electrical load for the next five years. Such an estimation allows for accommodating the increment of energy associated with the development in the rural villages.

3.3. Technoeconomic Analysis. The technical and economic analyses were supported by the use of PVSyst software. The PVSyst software was used to design and size the PV plants that can power farming, village businesses, and households. It is also used to analyze the performance and sensitivity of the designed PV plants vis-à-vis to factors influencing energy losses. To assure accuracy in energy requirements (AC load), in this research, data were conducted at three different villages from different districts in the Eastern Province of Rwanda. PV plant components such as PV panels, batteries, and a converter were included in the sizing and analysis on the standalone solar plants' models as can be seen in Figure 3.

For this research, a flat PV solar panel with a maximum power output of 370 W was used. The chosen efficiency of the PV panels is 22.39 percent. In terms of temperature, the working temperature is 25°C and the temperature coefficient is -0.33%/°C. The DF (in Equation (1)) of 92% was considered. The selected PV system's unit price is EUR 400. The cost of operating and maintaining the plant was EUR 2000 per year. The solar photovoltaic (PV) system has a 25-year lifespan. A bidirectional converter of 98 percent of efficiency is used in DC power into AC power conversion.

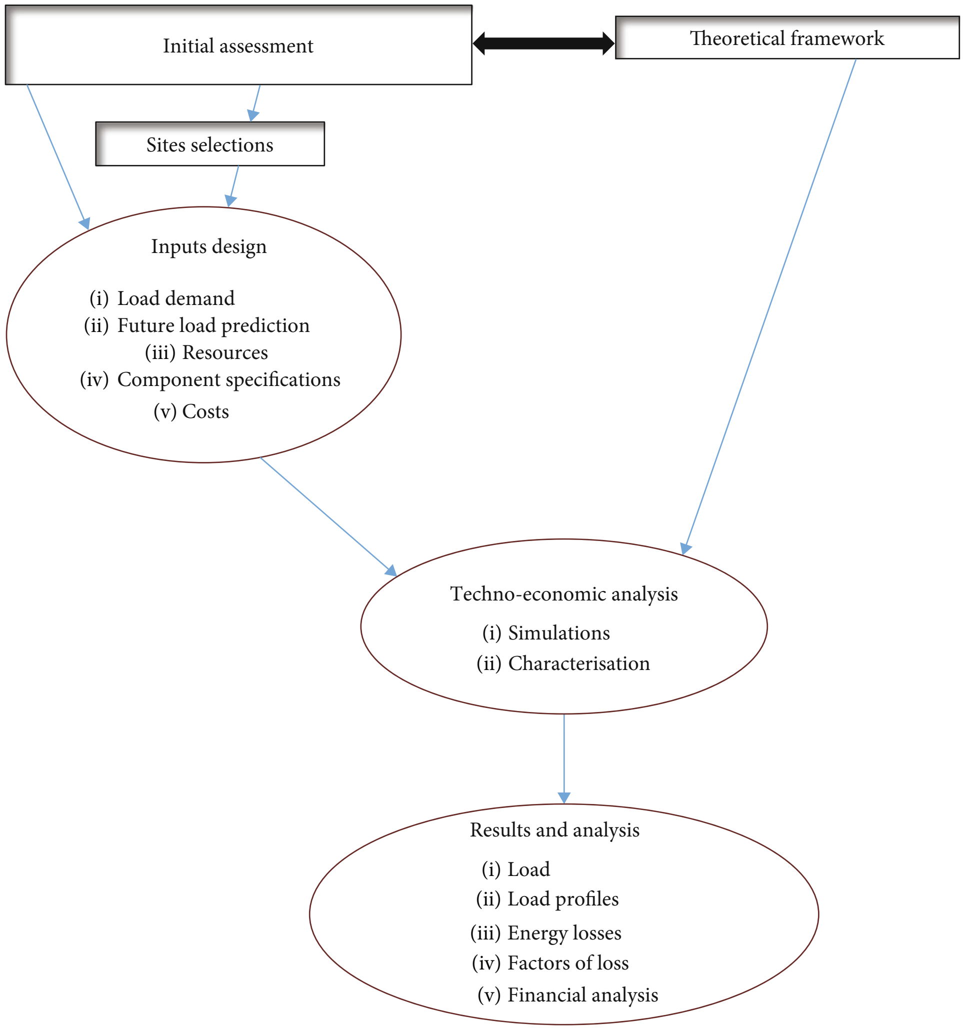


Figure 2: Study framework.

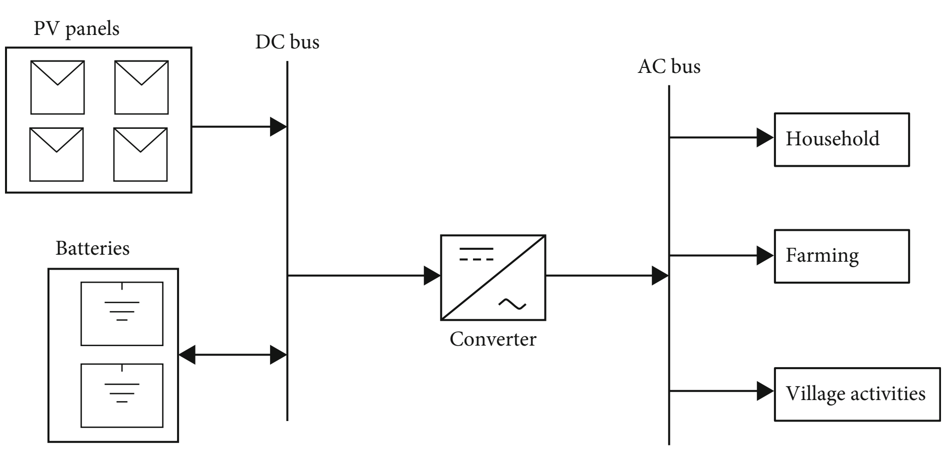


Figure 3: Solar PV minigrid design.

A universal controller with an MPPT converter with a power of 1000 W was used. Its total capital cost is EUR 800, and it has no replacement cost as its lifespan is expected to be 25 years. For energy storage, lithium-ion batteries, LG Chem M4860P2S model, with a capacity of 64 Ah are used when an off-grid case is considered. Their maximum power output is 92.5 kWh at the voltage of 51.8 V, and a maximum charge of 58 AMPs was considered. Each battery is assumed to hold a minimum charge of 40% when it is completely depleted which was included in the sizing and analysis.

The battery's life expectancy of 10 years was considered while its price was taken to be EUR 450 and the cost of a replacement was set to be EUR 900, meaning two replacements in 25 years.

4. Findings

4.1. A Technical Study. To quantify the total load (energy requirement) for three different sites under this study, an inventory of electrical equipment used by the community and their corresponding power ratings was made (see Table 2). Moreover, the daily usage of each piece of equipment in terms of working hours was recorded, and these parameters were used to calculate the load for the three villages. As can be seen from the table, the load in the villages does not greatly vary. The maximum electrical load of 4,353,465 Wh/days at Gashanga Village differs from the minimum electrical load of 3,997,214.80 Wh/days at Gishuro Village only by 8.02%. It is, however, to be noted that at Gishuro, the Integrated Development Programme (IDP) model village (a) considered in this study is fully established unlike Gashanga (b) and Kageyo (c) villages, and the PV plants are supposed to provide additional energy to the energy that is currently available.

Some similarities in the energy requirement can be explained by the fact that the model villages have most items in common and the number of households in the villages does not differ significantly. To explore the variability of load requirement at the three considered sites, the pattern of energy consumption by different groups of types of equipment is presented in Figure 4. According to the figure, the items with serial numbers 12 to 16, namely, fridges, microwaves, cooking stoves, and washing machines, are likely to consume a larger portion of energy. It is also worthwhile to note that most of the households in the villages under this study do not own these types of equipment. However, given that they are likely to contribute to rapid socioeconomic development in villages in rural parts of the country, it is projected that many households will own such equipment in the near future.

On the horizontal axis in Figure 4, the serial numbers 1 to 28 represent the loads as follows: (1) lamps inside, (2) lamps outside, (3) TV screen, (4) radios, (5) printers, (6) scanners, (7) laptops, (8) phone chargers, (9) ceiling fans, (10) kettles, (11) irons, (12) fridges, (13) microwaves, (14) cooking stoves, (15) washing machine, (16) air conditioners, (17) juicer machine, (18) blender machine, (19) batteries for E-tractors, (20) common market, (21) bar and restaurants, (22) hairdressing salons, (23) community workshop, (24) food storage, (25) butchers, (26) MCCs, (27) farming activities, and (28) irrigation systems, respectively.

Even though there is significant variation in the energy load associated with the types of equipment considered in the study, the electrical energy requirement at the three sites under this assessment does not change much. Figure 5 characterizes the variation of annual energy need vis-à-vis the solar energy that can be produced at the sites. From the figure, it is noticeable that the electrical load in the three villages under the study is always below the energy that can be produced from the sunshine over the year. This implies that solar plants can steadily satisfy the loads at the selected sites when they are properly designed.

The losses owing to different factors (see Figure 6) were determined as difference the solar energy that could be produced by the panels and the energy available for use. The energy stored in the battery for backup purposes also contributed to these differences. For instance, the minimum available energy was observed at Kageyo while the highest used energy was also observed at the same site. At that site, the unused stored energy is only about 7.5%; thus, the difference between available solar energy and used solar energy was much reduced. One can notice that there are considerable energy losses at the site as can be seen in Figure 7. But, one could be misled to overlook the effects of these large losses by the fact the total difference between the available solar energy and the used energy got smaller due to lesser energy storage. It is clear that to optimize the PV plants' utilization and the costs associated, such details need to be considered during the PV plants' design and development.

Figure 7 presents the effective energy produced by three designed PV plants. The plants are designed for (a) Gishuro Village in Nyagatare District, (b) Gashanga (Rilima) Village in Bugesera Village, and (c) Kageyo Village in Kayonza District. As can be seen from the figure, the plants at Gishuro and Gashanga start generating output energy at the solar radiation intensity as low as 0.5 kWh/m^2/day while at Kageyo, the plant generated the energy at a minimum threshold sunshine intensity of 1.5 kWh/m^2/day. The difference in threshold radiation intensity at which the solar energy is produced may be due to the fact that the used solar panels are different. In fact, for the Gishuro and Gashanga sites, Eco Green Energy EGE 166-M-60-HC 370 Wp solar panels were used, while at the Kageyo site, the Eco Green Energy EGE 156-M-60 270 Wp solar panels were used. One may note that the panel used at Gishuro and Gashanga bear a higher power rating 370 Wp than the ones used at Kageyo, 270 Wp. That enables the plants at the sites (a) and (b) to produce energy at low solar radiation intensities. It is clear that whenever one plans to develop efficient solar plants, the panels to be used need to be selected carefully after a deep analysis of their capacity to easily produce energy, i.e., producing energy at even low radiation intensities and minimizing energy losses.

It can also be noticed from Figure 7 that the large energy losses occurred at the site (a) Gishuro and site (c) Kageyo. Respectively, at sites (a) Gishuro and (c) Kageyo, the energy loss began when the intensities of solar radiation reach approximately 3.8 kWh/m^2/day and 4.2 kWh/m^2/day. Moreover, the amount of lost energy increases as the solar radiation intensity increases. At site Gashanga, the energy loss started when the radiation intensity reaches 5.1 kWh/m^2/day (Figure 7(b)) and the rate of the energy loss is not much as for the other sites. These variabilities in energy loss can be explained by different factors as shown in Figure 6. According to the figure, the major factor of energy loss in both cases is associated with temperature. When the irradiation intensity are extremely high, the temperature at the surfaces of the panels increases considerably and leads to heating of

Table 2: Load requirement at three considered sites.

S/N	Equipment	(a) Gishuro Qty	Tot number of items	Unit power (watt)	Time/day (hour)	Tot energy/day (Wh/day)	(b) Gashanga Qty	Tot number of items	Unit power (watt)	Time/day (hour)	Tot energy/day (Wh/day)	(c) Kageyo Qty	Tot number of items	Unit power (watt)	Time/day (hour)	Total energy/ day(Wh/ day)
1	Lighting (lamps)	L.in: 6 L.out: 2	L.in: 1398 L.out: 466	L.in: 15 L.out: 18	L.in: 5 L.out: 10	188730	L.in: 5 L.out: 2	L.in: 1600 L.out: 640	L.in: 12 L.out: 15	L.in: 5 L.out: 10	192000	L.in: 5 L.out: 2	L.in: 1500 L.out: 600	L.in: 12 L.out: 15	L.in: 5 L.out: 10	180000
2	Entertainment (TVs and radios)	Tvs: 1 Radn: 1	Tvs: 233 Radn: 233	Tvs: 100 Radn: 50	Tvs: 6 Radn: 4	186400	Tvs: 1 Radn: 1	Tvs: 160 Radn: 320	Tvs: 100 Radn: 50	Tvs: 6 Radn: 4	160000	Tvs: 1 Radn: 1	Tvs: 150 Radn: 300	Tvs: 100 Radn: 50	Tvs: 6 Radn: 4	150000
3	Libraries (printers, scanners)	Pt: 1 Scn: 1	Pt: 20 Scn: 20	Pt: 20 Scn: 40	Pt: 0.5 Scn: 0.5	600	Pt: 1 Scn: 1	Pt: 10 Scn: 10	Pt: 20 Scn: 40	Pt: 0.5 Scn: 0.5	300	Pt: 1 Scn: 1	Pt: 10 Scn: 10	Pt: 20 Scn: 40	Pt: 0.5 Scn: 0.5	300
4	Charging electronic gadgets (laptops, phones)	Lap: 1 Phn: 2	Lap: 233 Phn: 466	Lap: 25 Phn: 5	Lap: 12Phn: 1	72230	Lap: 1 Phn: 2	Lap: 160 Phn: 640	Lap: 25 Phn: 5	Lap: 12 Phn: 1	51200	Lap: 1 Phn: 2	Lap: 150 Phn: 600	Lap: 25 Phn: 5	Lap: 12 Phn: 1	48000
5	HVAC (fans, air conditioners)	Fn: 2 AC: 1	Fn: 466 AC: 233	Fn: 100 AC: 3500	Fn: 2 AC: 1	908700	Fn: 2 AC: 1	Fn: 640 AC: 160	Fn: 100 AC: 3500	Fn: 2 AC: 1	688000	Fn: 2 AC: 1	Fn: 600 AC: 150	Fn: 100 AC: 3500	Fn: 2 AC: 1	645000
6	Kitchen appliances (fridges, microwaves, cooking stoves, kettles, juicers, blenders)	Kt: 1 Fg: 1 Mw: 1 Costv: 2 Jc: 1 Blnd: 1	Kt: 233 Fg: 233 Mw: 233 Costv: 466 Jc: 233 Blnd: 233	Kt: 1000 Fg: 150 Mw: 1000 Costv: 3000 Jc: 200 Blnd: 300	Kt: 0.25 Fg: 18 Mw: 0.5 Costv: 0.5 Jc: 0.25 Blnd: 0.25	1415475	Kt: 1 Fg: 1 Mw: 1 Costv: 2 Jc: 1 Blnd: 1	Kt: 320 Fg: 320 Mw: 160 Costv: 640 Jc: 1 Blnd: 320	Kt: 1000 Fg: 150 Mw: 1000 Costv: 3000 Jc: 200 Blnd: 300	Kt: 0.25 Fg: 18 Mw: 0.5 Costv: 0.5 Jc: 0.25 Blnd: 0.25	1246400	Kt: 1 Fg: 1 Mw: 1 Costv: 2 Jc: 1 Blnd: 1	Kt:300Fg:300Mw:150 Costv:600 Jc:300 Blnd:300	Kt: 1000 Fg: 150 Mw: 1000 Costv: 3000 Jc: 200 Blnd: 300	Kt: 0.25 Fg: 18 Mw: 0.5 Costv: 0.5 Jc: 0.25 Blnd: 0.25	1897500
7	Cleanliness (washing machines, irons)	W.m: 1 Ir: 1	W.m: 233 Ir: 233	W.m: 2400 Ir: 1100	W.m: 0.5 Ir: 0.25	343675	W.m: 1 Ir: 1	W.m: 320 Ir: 320	W.m: 2400 Ir: 1100	W.m: 0.5 Ir: 0.25	472000	W.m: 1 Ir: 1	W.m: 300 Ir: 300	W.m: 2400 Ir: 1100	W.m: 0.5 Ir: 0.25	442500
8	Farming (batteries for E-tractors, irrigation, other farming activities)	B-E: 24 Ign: 1 F.A: 1	B-E: 24 Ign: 1 F.A: 1	B-E: 4800 Ign: 25750 F.A: 12450	B-E: 1 Ign: 1 F.A: 1	153400	B-E: 24 Ign: 1 F.A: 1	B-E: 24 Ign: 1 F.A: 1	B-E: 4800 Ign: 28100 F.A: 11160	BE: 1 Ign: 1.00 F.A: 1.00	154460	B-E: 24 Ign: 1 F.A: 1	B-E: 24 Ign: 1 F.A: 1	B-E: 4800 Ign: 23400 F.A: 11160	B-E: 1 Ign: 1.00 F.A: 1.00	46080

Table 2: Continued.

		(a) Gishuro					(b) Gashanga					(c) Kageyo				
S/N	Equipment	Qty	Tot number of items	Unit power (watt)	Time/day (hour)	Tot energy/day (Wh/day)	Qty	Tot number of items	Unit power (watt)	Time/day (hour)	Tot energy/day (Wh/day)	Qty	Tot number of items	Unit power (watt)	Time/day (hour)	Total energy/day(Wh/day)
9	Common village use (common market, bar and restaurants, hair salons, community workshops)	Cmt: 1 B&R: 1 H.Sln: 3 CWps: 1	Cmt: 1 B&R: 1 H.Sln: 3 CWps: 1	Cmt: 1620 B&R: 6910 H.Sln: 4410 CWps: 37000	Cmt: 6 B&R: 586 H.Sln: 6.4 CWps: 3.15	251434.6	Cmt: 1 B&R: 1 H.Sln: 3 CWps: 1	Cmt: 1 B&R: 1 H.Sln: 3 CWps: 1	Cmt: 1620 B&R: 6910 H.Sln: 4410 CWps: 37000	Cmt: 6 B&R: 5.86 H.Sln: 6.40 CWps: 3.15	25134.6	Cmt: 1 B&R: 1 H.Sln: 3 CWps: 1	Cmt: 1 B&R: 1 H.Sln: 3 CWps: 1	Cmt: 1620 B&R: 6910 H.Sln: 4410 CWps: 37000	Cmt: 6 B&R: 5.86 H.Sln: 6.40 CWps: 3.15	251434.6
10	Food processing and storage (food storages, butchers, MCCs)	F.S: 1 Bu: 1 Mcc: 1	F.S: 1 Bu: 1 Mcc: 1	F.S: 4600 Bu: 2765 Mcc: 25500	F.S: 13.33 Bu: 2.82 Mcc: 11.41	360070.3	F.S: 1 Bu: 1 Mcc: 1	F.S: 1 Bu: 1 Mcc: 1	F.S: 4600 Bu: 2765 Mcc: 25500	F.S: 13.33 Bu: 2.82 Mcc: 11.41	360070.4	F.S: 1 Bu: 1 Mcc: 1	F.S: 1 Bu: 1 Mcc: 1	F.S: 4600 Bu: 2765 Mcc: 25500	F.S: 13.33 Bu: 2.82 Mcc: 11.41	360070.3
	Total load			3,997,214.90					4,353,465					4,124,564.90		

Abbreviations: L.in: lamp inside house; L.out: lamp outside house; Radn: radios; Pt: printers; TVs: televisions; Scn: scanners; Lap: laptop; Phn: phones; Fn: fans; AC: air conditioners; Kt: kettles; Fg: fridges; Mw: microwave; Costv: cooking stove; Jc: juicers; Blnd: blenders; W.m: washing machine; B-E: batteries for E-tractors; Ir: iron; Ign: irrigation; B&R: bar and restaurant; Cmt: common market; H.sln: hair salons; CWps: community workshops; F.S: food storages; Bu: butchers; Mcc: milk collection center.

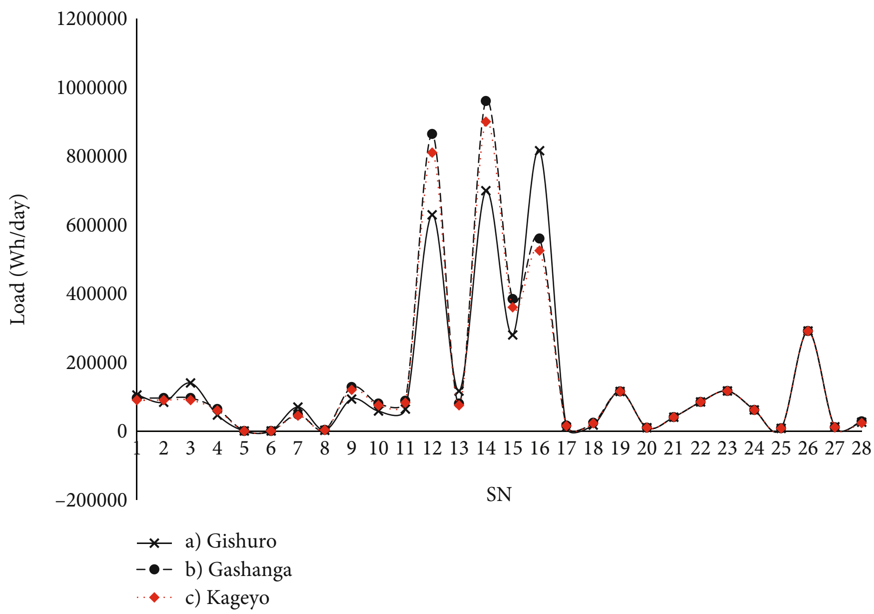


Figure 4: Energy load for different pieces of equipment.

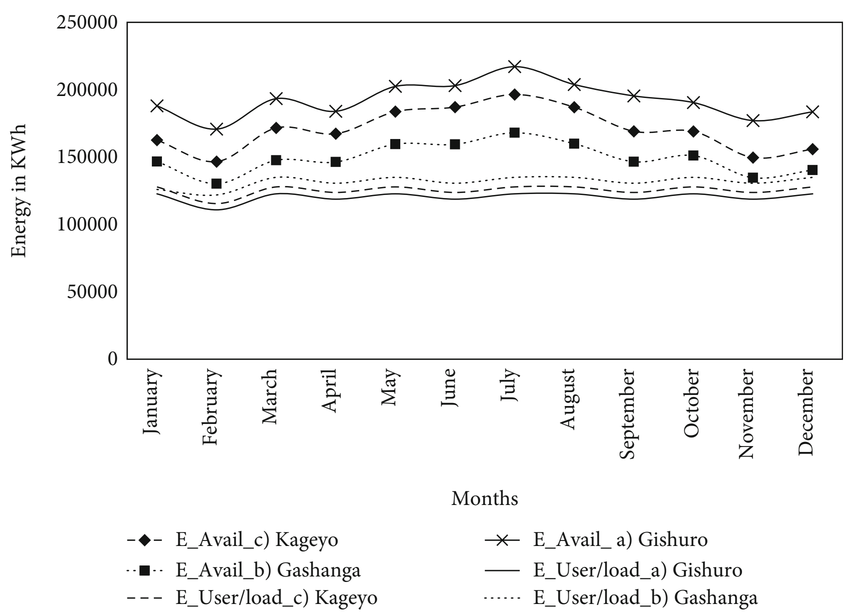
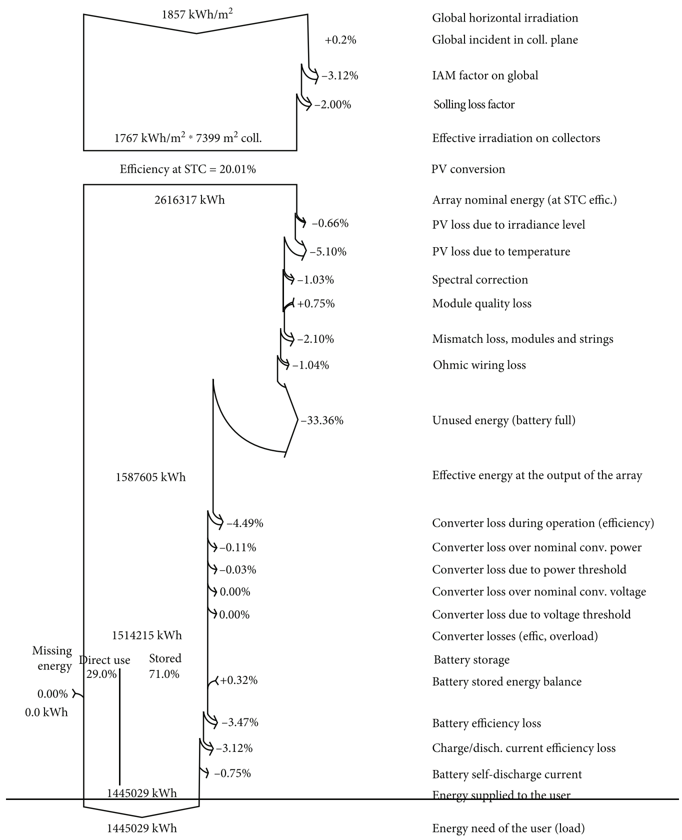


Figure 5: Temporal variation of solar energy and electrical energy requirement.

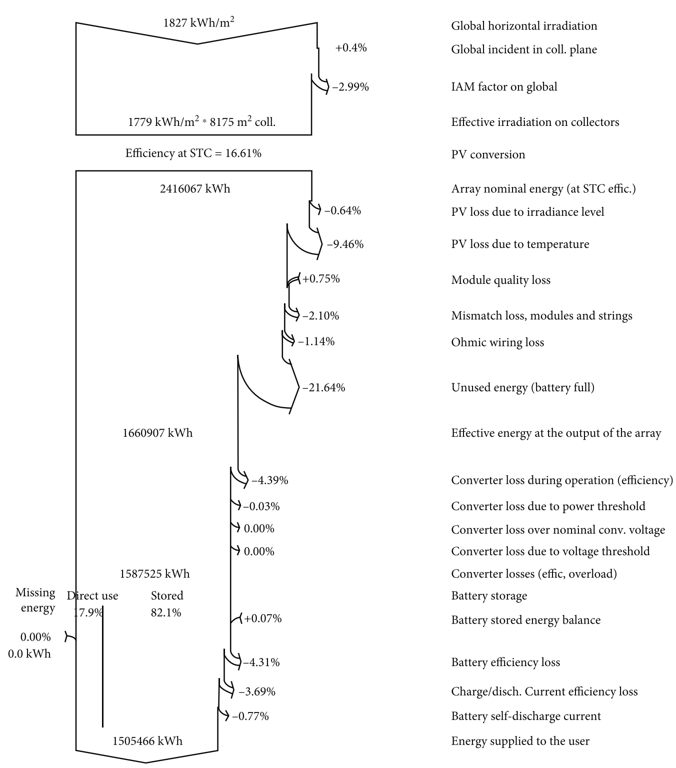
panels, hence impeding the panels' conversion efficiency. A portion of solar energy gets lost during the heating process. For example, much of the energy loss,9.46%, was associated with the panels' heating at one of the plants' sites (Gashanga) as can be seen from Figure 6(b).

It may seem that the major loss rather than being associated with the rise of panels' temperature is associated with the unused energy. The unused energy that remains in the battery is seen to be apparently considered as energy loss. The results show that the least unused energy of 7.54% was observed for the plant designed at Kageyo while the highest unused energy was 33.36% at Gishuro. However, this means that some batteries remain full for backup purposes. Therefore, it is always important to leverage its amount, the hours of autonomy that might be needed, and the amount of stored energy that remains unused.

Furthermore, one can infer from Figure 6 that the components of the PV plants need to be carefully chosen. In fact, there are considerable losses associated with the specific characteristics of the PV plant's components in all designed PV plant models. Among these losses, one can highlight the energy losses associated with the quality of PV modules, resistance of ohmic wiring, type of converter, and the efficiency of storage system. It is also worth noting that energy

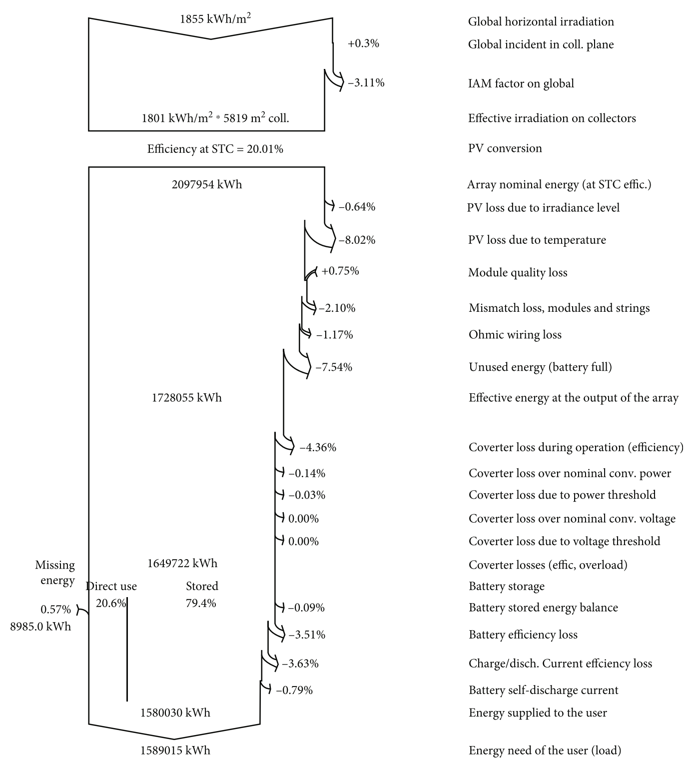


(a)



(b)

Figure 6: Continued.



(c)

Figure 6: Energy loss for the plants at (a) Gishuro, (b) Gashanga, and (c) Kageyo.

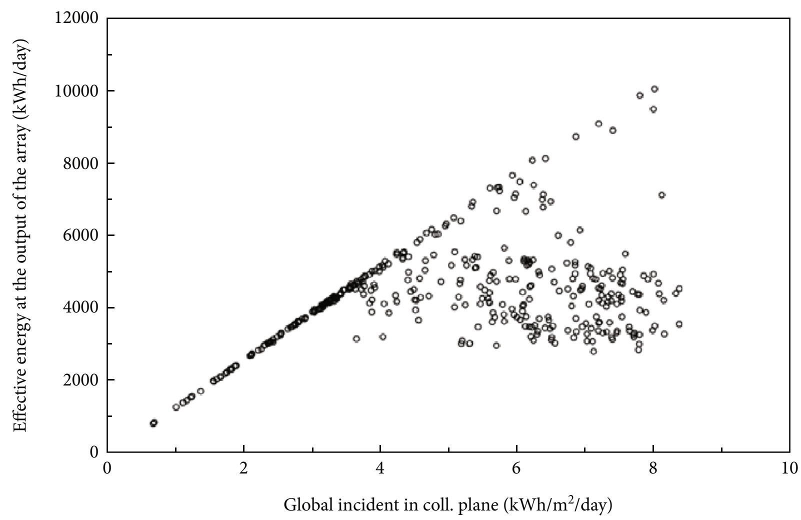
losses can arise from the installation, maintenance, operating conditions, and ambient conditions. The reduction of radiations reaching the solar cells due to changes in incidence angle (IAM factor on global), losses due to solar spectrum variation, losses due to variation irradiance levels, and soiling losses due to grime and dust accumulations are such sorts of losses. The results show that at site (b) "Gashanga" the soiling loss was eliminated as we assumed more frequent cleaning.

It is clear that proper design of the PV systems considering the ambient conditions at the sites together with developing local skills to operate and maintain the PV systems is key to minimizing these losses.

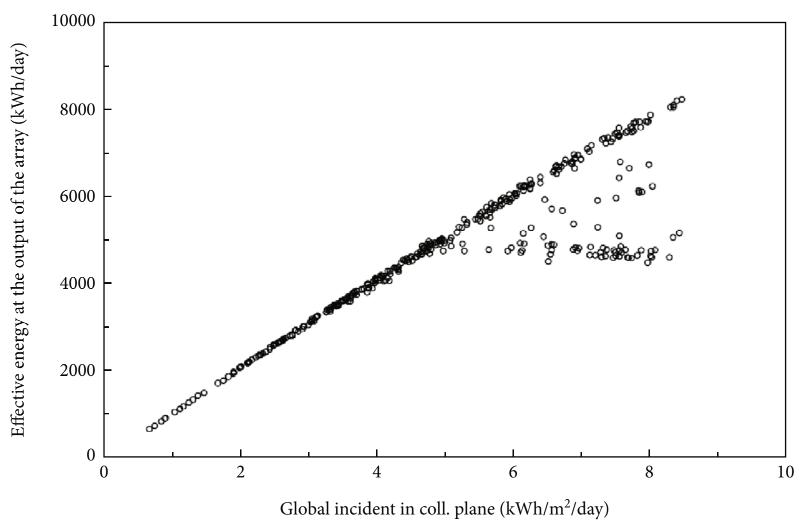
4.2. Economic Analysis. The preliminary financial analysis summarized in Table 3 shows that on average, the designed PV plants can cost from 2,338,823 EUR up to 4,322,260 EUR. These amounts may look huge, but noting that they will be used to supply energy for a village with more than 300 households powering 28 different activities as listed in Table 2 and Figure 4 for 25 years, the sum remains reasonable. Moreover, as can be seen from Table 3, the payback period for such PV plants is 9.43 years on average. That means that out of 25 years, more than 14 years will consist of accruing the financial benefits. Finally and most importantly, the energy cost is predicted to be 0.18 EUR/kWh on average; i.e., it is 28.8% lower than the current minimum tariff of 0.252 EUR/kWh for households' electrification from the national grid [36]. The large energy cost of 0.24 EUR/kWh was observed only at Gishuro, site (a). Nevertheless, it is still slightly less than the current electricity cost on the national grid.

Moreover, from the table, it can reasonably be argued that such projects may not be feasible owing to the requirement of large investments as well as running costs. As can be seen from Table 3, on average, 3,165,393.50 EUR is required as an investment while the running cost is 293,562.15 EUR per year on average. However, owing to available subsidies, funding programs available in the field of clean and sustainable energy in Rwanda, grid extension funds, and the importance of these PV plants in benefiting residents as well as the perceived financial benefits, developers can mobilize considerable funding support for PV plant deployment. The financial evaluation indicates that in 10 years or a little less, the total investments can be recovered. The annuities were estimated to be 141,885.69 EUR/yr on average.

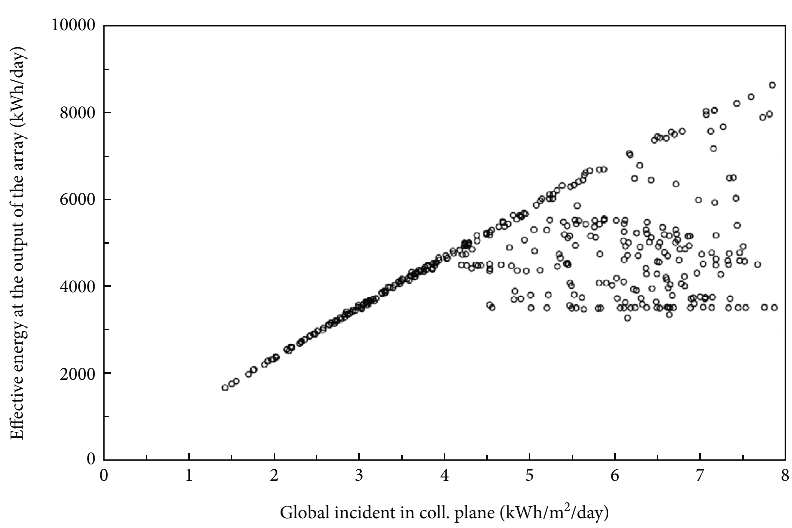
4.3. Challenges and Opportunities of Photovoltaic Minigrid Systems in Rwanda. The biggest challenge, as our results indicate, is the need for relatively large initial investments and running costs in the initial stages of the PV plants' operation. In addition to significant upfront capital costs, it is also worthwhile to note that the development and operationalization of photovoltaic minigrid systems in Rwanda may face hindrances associated with a lack of enough technical capacity to design, install, operate, and maintain these systems. Moreover, given that a large part of the plant cost goes to storage systems, one may suggest the PV system integration into the existing national grid infrastructure; but the



(a) Gishuro



(b) Gashanga



(c) Kageyo

Figure 7: Daily input vs. daily power output energy loses.

Table 3: Economic evaluation.

Sites\financial parameters	Investment	LCOE	Payback period	Annuities	Running costs
(a) Gishuro	4,322,260 EUR	0.24 EUR/kWh	10 yrs	87,749.68 EUR/yr	72,843.26 EUR/yr
(b) Gashanga	2,338,823 EUR	0.17 EUR/kWh	9.3 yrs	195,371.60 EUR/yr	261,045.56 EUR/yr
(c) Kageyo	2,835,097.5 EUR	0.14 EUR/kWh	9 yrs	142,535.80 EUR/yr	326,078.73 EUR/yr
Averages	3,165,393.50 EUR	0.18 EUR/kWh	9.43 yrs	141,885.69 EUR/yr	293,562.15 EUR/yr

grid integration can be complex and requires cautious planning and synchronization, which is also a challenge.

However, photovoltaic minigrid systems, for Rwanda, have many potential benefits. Among others, the provision of promising electrification of rural areas to bridge energy gaps and enable the community to access clean and reliable electricity for use in household, in agriculture, and in business centers is considered the chief benefit. Moreover, contribution to the reduction of dependence on fossil fuels as per country's commitment to transitioning to clean energy sources, creation of employment opportunities in PV installation, and operation and maintenance as well as enhancement of resilience and security of energy provision as normal remote area is prone to frequent power outages are also substantial benefits of solar PV plants. Another significant importance of such PV plants is that they are likely to mitigate climate change. These PV plants have potential to the reduction of emission of greenhouse gases. Reducing green house gas emission aligns with Rwanda's ambition to reduce carbon footprint and battle climate change.

Given the aforementioned potential benefits associated with the deployment of solar PV plants, the Government of Rwanda has put in place various incentives and subsidy schemes to stimulate investments in off-grid PV plant development. These incentives and subsidies are potential to reduce the cost of PV plants' development and deployment and increase financial benefits for investors. Nevertheless, further studies are still needed to quantify the effects of such incentives and subsidies on the cost of solar energy for improvement of agriculture production and rural electrification.

5. Conclusion

This study is aimed at designing optimally sized models of PV plants in rural villages in Rwanda based on an extensive assessment of solar energy potential and energy requirement/load. The study showed that model ideal villages in Rwanda would require an energy supply of around 4 MWh/day and that the energy requirements/loads change only slightly over the year. The findings indicate that the optimized PV plants based on the developed models will sufficiently respond to these needs of energy in the rural villages in Rwanda.

Various factors have been found to induce loss of energy for PV plants. The major losses have been associated with the heating when the temperature of the solar panels increases. Thus, further studies need to be conducted to assess how these losses could be minimized during energy production.

Even though the cost to develop such plants is seen to be generally high, the investment in such energy systems is worthy as the study predicted a break-even point of around 10 years while the plant lifetime is 25 years and the systems would drop the cost of energy by around 29%. However, studies may also be needed to assess the contribution of various incentives and subsidies available nationally and internationally in the field for further reductions of price of PV energy, especially in rural in the villages.

The findings of this study are considerable as they can serve as references for the development of PV plants to supply energy in rural villages. Furthermore, the study is likely to promote mechanized farming as it has counted for the energy requirement for the use of an electric tractor and energy requirement for other farming activities during the sizing and optimization of the PV plants.

Data Availability

The data used to support the findings of this study are included within the article. Any additional information can be provided when requested.

Conflicts of Interest

We would like to declare that we know of no conflicts of interest regarding this manuscript and its publication.

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