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ARTICLE

A Techno-Economical Characterization of Solar PV Power Generation in Rwanda: The Role of Subsidies and Incentives

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ABSTRACT

Standalone Solar PV systems have been vital in the improvement of access to energy in many countries. However, given the large cost of solar PV plants' components, in developing countries, there is a dear need for such components to be subsidised and incentivised for the consumers to afford the produced energy. Moreover, there is a need for optimal sizing of the solar PV plants taking into account the solar information, energy requirement for various activities, and economic conditions in the off-grid regions in Rwanda. This study aims to develop optimally sized solar PV plants suited to rural communities in Rwanda. Likewise, it aims at characterizing the impacts of subsidies and incentives on the profitability and affordability of solar PV plants' energy in Rwanda. In the study, we have developed a model on basis of which the plant power (peak power) and costs of energy can be predicted given the load requirements using PVSyst. The model was validated using data corrected at eight different sites. Our generalized predictive model's results matched the results obtained using field measurement data as inputs. The models have been able to replicate with a by degree of accuracy the peak powers and the plants' costs for different loads and were used to evaluate the economic viability of solar PV plants in Rwanda. It was found that with incentives and subsidies of 20%, the solar PV systems' costs, the Levelised Cost of Energy would drop from a maximum of 0.098 Euro to a minimum of 0.072 Euro, the payback period was reduced from a maximum of 7.5 years to a minimum of 6.0 years while the return on investments was seen to vary between 425.72 and 615.32 per cent over the plants' lifetime of 25 years. Overall our findings underscore the importance of government subsidies and incentives for solar PV energy generation projects to be significantly profitable.

KEYWORDS

Techno-economical characterization; solar PV plants; solar-energy economy; PV energy generation; energy in Rwanda

1 Introduction

The developing world has a variety of energy-related issues that hinder its socioeconomic development. According to Ganda et al. [1], the following factors make it difficult to advance sustainable energy in developing countries: (1) continued fossil fuel subsidies; (2) insufficient initial capital, and (3) hefty costs of energy. It is worthwhile to note that focusing on issues specific to the local settings, especially those connected to financial and technological developments in the area might help ease some of these issues [2–7]. It is thought that currently available policies and investments to support sustainable energy systems need to be revised or modified.

There have been researches aiming to understand and address matters associated with clean energy integration. In fact, The high-level platform for clean energy securities in emerging markets, particularly in Africa, suggests overhauling subsidies for fossil fuels as well as introducing carbon reduction mechanisms, resource-efficient practices, and strong social and ecological guidelines which comply with energy efficiency, pollution prevention, and emission levels quality standards [8]. Hirth et al. [9] examined the impact of capital costs and carbon prices on the incorporation of renewable energy (RE) and other low-carbon technologies in the grid using the Electricity Market Model EMMA. After analyzing the data, they presented a plan to reduce the amount of gaseous carbon compounds in the grid-based energy supply in developing countries. It was suggested that among other efforts, the energy economic sector should have unique strategies for zero-carbon power supply, including proper handling of waste and roofing of large buildings with solar panels. Most importantly, nations were recommended to support renewable energy by reallocating fossil fuel subsidies to renewable energy technologies. In addition to electrification programs and grid expansion plans should promote decentralized mini-grids fueled by locally accessible renewable energy resources [9].

Based on such research findings and recommendations, there has been a dramatic technological transition from fossil fuels to environmentally friendly renewable energy generation, in the past decade [10]. Numerous initiatives to support renewable energy integration have been formed [11] and photovoltaic (PV) technology has emerged as one of the most promising among REs all over the globe [12,13]. Goldthau [14] supported the fact that a systemic shift towards more effective resources requires a strategic plan of action incorporating regulations from the local to the international authorities. Diverse regulations, including negotiable allowances for the reduction of emissions, tax waivers, and increased incentives for the generation of renewable energy, have been suggested. As stipulated by the World Trade Organisation (WTO) in its Agreement on Subsidies and Countervailing Measures (ASCM), if a policy measure confers a benefit or entails financial assistance, it qualifies as a subsidy [15,16]. Although the ASCM does not provide an exhaustive listing of subsidy types, it does refer to a few common ones, including: direct credit support; forgone taxes and provision of goods or services below market value. Other categories have often been taken into consideration as possible subsidies outside of these widely established subsidy kinds. Examples include, social and environmental externalities or using tariff policies as a kind of market price support [17].

In recent times, more than US$240 billion were subsidized annually in the global energy sector by governments throughout the world [18]. This sum is unprecedented in the history of global economic subsidy distribution [19]. Such a huge amount of subsidies prompted claims that RE technologies get unfairly large amounts of financing in relation to their installed capacity compared to other electricity-generating technologies [20,21]. However, such claims are not always backed by sufficient evidence as the concept of subsidies itself has been a controversial subject in the field [19,22]. However, whatever might be the arguments, RE development involves large, high-risk, and uncertain-return investments that certainly require special financial support from governments. Thus, extensive studies need to be carried out to ascertain the impacts of subsidies on RE penetrations and profitability in terms of variation of the Levelised Cost of Energy (LCOE) and payback periods vis a vis energy Tariffs, especially in the developing world.

It is worthwhile to note that LCOE is particularly useful for the comparison of costs of various kinds of generating technologies, and it is widely acknowledged as the measure for economic analysis of power production systems [23]. This approach calculates the average total cost of building and running an energy production asset throughout its whole plant life, divided by the asset's total power output during that period. Comparing the LCOE with the market energy tariff allows us to determine the competitiveness of various technologies and whether or not to invest in a particular renewable energy project. Furthermore, with the use of LCOE estimates, policymakers might establish regulations for renewable energy subsidization [24].

In Rwanda as in many other Sub-Saharan African nations, energy generation, access, and infrastructure are insufficient. Despite Rwanda's strong development rate, the cost of delivering energy is among the highest in the region hindering economic and industrial expansion. Most solar projects in Rwanda require large grants to be bankable. The Rwandan Energy Group (REG), the country's corporation overseeing energy production and distribution, encourages investments in the RE sector [25]. Either private forms of investments or partnerships with the government of Rwanda are highly encouraged. Among other RE systems, Solar PV power plant generation systems have lowered the cost of energy generation over the decade, and its cost is expected to decrease even further. Furthermore, under Rwanda's geopolitical location, solar production might be even more competitive and reduce power bills.

Concerning subsidies, Rwanda has put in place various incentives to attract investments in the development of PV plants. These incentives include subsidies, free transmission access, tax-free importations of equipment for PV projects, and free lands for private developers [26]. However, such efforts have not yet resulted in significant private-sector investments in the development of PV power plants in Rwanda [26]. The low level of participation of the private sector which continues to be an obstacle to the development of PV energy systems can be associated with the scarcity of information on available subsidies and incentives to stimulate investments in the development of PV energy systems. There has not been quantitative research on the contribution of available subsidies and incentives to the profitability of PV projects in different regions of the country. This study intends to develop techno-economic models on a basis of which the effects of incentives and subsidies to the LCOE, payback periods, and Return on Investment (ROI) of solar PV projects will be quantified. This study is of significant importance to energy providers as may serve as a reference while perceiving the benefits of solar PV energy production with regard to available incentives and subsidies in Rwanda.

2 Methodology

2.1 Overall Study Procedure

Fig. 1 shows the procedure used to carry out this research work. After conducting the physical assessment at 31 different locations, eight were selected for detailed load evaluation in different provinces of the country, see Fig. 2. The total load demand was obtained as a sum of the energy needed for various activities at the considered sites. These are farming activities, electrification, village activities and the use of electrical utensils in households. The estimation of the total energy required, considered inventorying equipment in use, recording their corresponding power ratings and the daily usage of each piece of equipment in terms of working hours as well as summing energy loads for all equipment for the considered activities in each village/site.

Thereafter, a techno-economic analysis that consists of design, sizing & simulation, and economic evaluation on the PV power Plants using PVSyst was carried out. Eight sites were selected based on their solar potentials, their needs in electrification as well as land configuration and availability among 31 sites where the initial assessments were conducted, see Fig. 2. It is worthwhile to note that even though design and sizing were briefly studied, this study is centred on the economic analysis on the designed PV plants.

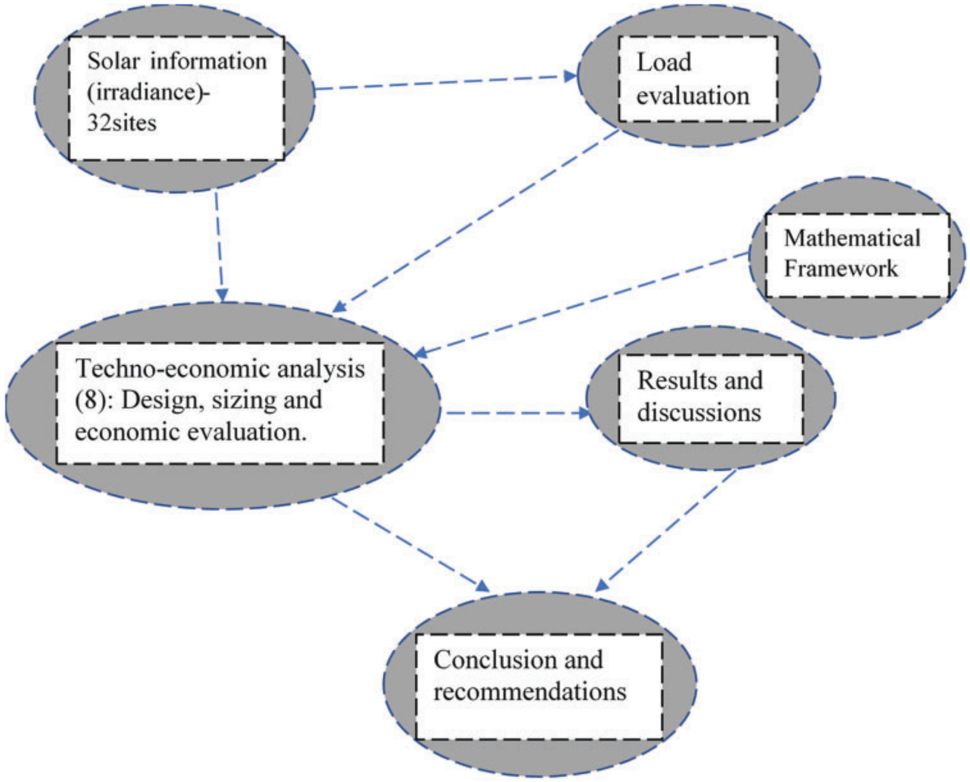

Figure 1: Analysis framework

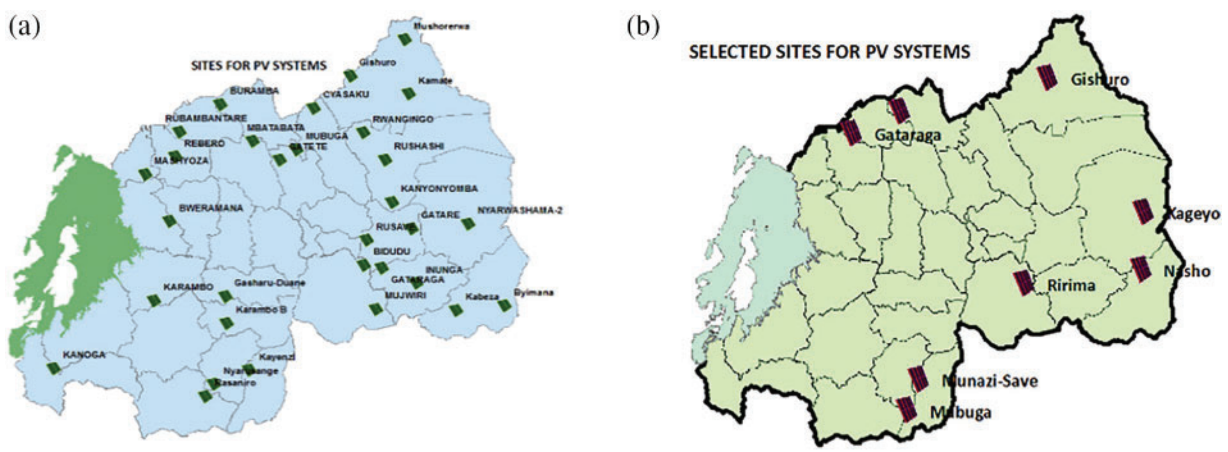

Figure 2: (a) Sites at which a preliminary-physical study was done and (b) sites selected for detailed techno-economic study on solar PV plants

2.2 Mathematical Framework

The economic modelling of PV plants in this study was adapted from reference [27]. It consists of the determination Net Present Cost of the plant and the cost of energy based on the PV plant components. NPC is the fundamental economic measure of the financial viability of PV power plants over the lifetime of the project. It is determined as the sum of NPC_s of all system components using Eq. (1), where k is one of the considered components.

$$NPC = \sum_{k=PV.Bater\_storage,Inv} NPC_k \tag{1}$$

For each component, NPC_k is the sum of the initial capital, operation cost and maintenance costs, and cost replacement minus salvage cost, see Eq. (2).

$$NPC_k = IC_k + RC_k + OMC_k - SC_k \tag{2}$$

In Eq. (2) IC_k stands for the sum of initial costs for the component k, RC_k is the sum of replacement cost for a component k; OMC_k is the sum of operation and maintenance for the item k while SC_k represents the total salvage cost for the item k.

The total initial cost of any item in the PV can be calculated as a product of its unit price, IPR_k, and the number of used items of type k, N_k as per Eq. (3).

$$IC_k = N_k.IPR_k \tag{3}$$

The total replacement cost for given components RC_k is determined by Eq. (4).

$$RC_k = N_k.DF\left(d_r, T_k\right).RPR_k \tag{4}$$

where DF is the discount factor, d_r is the discount rate, RPR_k is the price for the replacement for item k and T_k is the component's lifetime.

Having defined the rate of discount DF as a function of the discount rate and lifetime of the PV plant's component, the total cost for operating and maintaining the PV plant system, OMC_k, over 25 years can be found by using the Eq. (5).

$$OMC_k = N_k.\sum_{y=1}^{25} DF(d_r, y).OMPR_k \tag{5}$$

In Eq. (5), $OMPR_k$ stands for the cost of operation and maintenance for a given component k.

The salvage value of the plants' components, SC_k, is determined as per Eq. (6) where T_k, rem is its remaining life for a particular item k.

$$SC_k = RC_k.\left(\frac{T_k, rem}{T_k}\right) \tag{6}$$

The remaining lifetime for the components, k, depends on both the lifetime of that component and the project lifetime, see Eq. (7), T_{Proj} being the project lifetime.

$$T_k.rem = T_k - \left[T_{Proj} - T_k.INT\left(\frac{T_{Proj}}{T_k}\right)\right] \tag{7}$$

The discount factor used in Eqs. (4) and (5) is calculated using Eq. (8).

$$DF\left(d_r, y\right) = \frac{1}{(1 + d_r)^y} \tag{8}$$

The Levelised Cost of Energy (LCOE), which is the price of a unit of energy for a PV plant project, can be calculated as the system's total annual cost and associated services ($C_{tot,ann}$) divided by the system's total usable yearly electricity output, E_{gen}, see Eq. (9).

$$LCOE = \frac{C_{tot,ann}}{E_{gen}} \tag{9}$$

The yearly cost of the plant is determined from Eq. (10) based on the capital recovery factor, (CRF) and the total net present cost (TNPC) for the plant system.

$$C_{tot,ann} = CRF\left(d_r, T_{proj}\right) TNPC \tag{10}$$

where the capital recovery factor is calculated using Eq. (11).

$$CRF\left(d_r, T_{porj}\right) = \frac{d_r.(1+d_r)^{T_{proj}}}{(1+d_r)^p - 1} \tag{11}$$

In Eq. (11), the capacity recovery factor is dependent on the discount rate, which in turn is calculated from Eq. (12).

$$d_r = \frac{d_n - f_r}{1 + f_r} \tag{12}$$

where dn is the nominal discount rate while f_r is the inflation rate.

For solar panels, the power output, efficiency, and cost are modelled by Eq. (13) through Eq. (17). The power output is determined by Eq. (13)

$$P_{PV,o}(t) = P_{PV,n}..F_{PV}..\left(\frac{\lambda(t)}{\lambda_{STC}}\right).\left[1 + \beta_t.\left(T_C(t) - T_{c,STC}\right)\right] \tag{13}$$

Here, $P_{PV,o}$ stands for power output, $P_{PV,n}$ is the nominal power, F_{PV} is the derating factor for solar panels, λ is the hourly solar irradiance on one square meter of the panel, λ_{STC} is the solar radiation intensity under standard conditions i.e., $T_{c,STC} = 25°C$, and speed of wind = 0 m/s. T_C is the temperature of the solar cell and β_t is the temperature coefficient.

The efficiency of the PV module is determined by Eq. (14) where η_{STC} is the module efficiency under standard operating conditions.

$$\eta_{PV}(t) = \eta_{STC}.\left[1 + \beta_P.\left(T_C(t) - T_{c,STC}\right)\right] \tag{14}$$

The efficiency of the PV module under standard η_{STC} conditions can be calculated from Eq. (15). In Eq. (15), A_{PV} represents the surface area of the PV module.

$$\eta_{STC} = \frac{P_{PV,n}}{A_{PV}.\lambda_{STC}} \tag{15}$$

The temperature of the solar cell is determined by Eq. (16). T_a, here is the ambient temperature, $T_{c,\,NOCT}$ is the minimum temperature at which a solar panel operates properly, $T_{a,\,NOCT}$ is the minimum operating temperature of the panel under standard conditions and λ_{NOCT} is the solar irradiance at the nominal operating condition of 0.8 kW/m^2.

$$T_C(t) = T_a(t) + \lambda(t).\left[\frac{T_{c,\,NOCT} - T_{a,\,NOCT}}{\lambda_{NOCT}}\right] \tag{16}$$

The cost estimation (NPV_{PV}) of PV panels is calculated over the plant's lifetime by Eq. (17).

$$NPV_{PV} = P_{PV,n}\left[IC_{PV} + OMC_{PV} = IPR_{PV} + \sum_{y=1}^{25} \frac{OMPR_{PV}}{(1+d_r)^y}\right] \tag{17}$$

where IC_{PV}, OMC_{PV}, IPR_{PV} are respectively initial cost, operating and maintenance cost, and initial price for the panels. $OMPR_{PV}$ is the price for the operation and maintenance of the panels.

The energy storage in batteries can assure the dependability of the energy systems. Consequently, it is necessary for maintaining the reliability of PV plants by incorporating energy storage in the batteries. The capacity of battery storage, the battery charge, and the batteries' discharge are modelled by Eqs. (18)–(20), respectively.

$$E_{BES} = \frac{E_{load,d}.DA}{\eta_{INV}.\eta_{BES}.DOD} \tag{18}$$

Eq. (18) E_{BES} represents the energy storage capacity, $E_{load,d}$ is the daily energy demand DA stands for days of autonomy, η_{INV} is the efficiency of the inverter, η_{BES} is the efficiency of the storage system while DOD stands for depth of discharge for the battery energy storage system.

$$E_{BES,\,ch}(t) = E_{BES}(t-1).(1-\mu) + \eta_{BES}.\left[E_{gen}(t)\eta_{INV} - \frac{E_{load}(t)}{\eta_{INV}}\right] \tag{19}$$

Here $E_{BES,\,ch}$ is the quantity of energy gained through charge and μ is the self-discharge rate for the battery storage system.

$$E_{BES,disch}(t) = E_{BES}(t-1).(1-\mu) + \left[\frac{E_{load}(t)}{\eta_{INV}} - E_{gen}(t).\eta_{INV}\right]/\eta_{BES} \tag{20}$$

In Eq. (20), $E_{BES,disch}$ is the energy discharged from the battery storage system.

$$SOC_{BES}(t) = \frac{E_{BES,\,st}(t)}{C_{BES}} \tag{21}$$

In Eq. (21), the state of charge of a battery equals the energy stored in the battery, $E_{BES,\,st}$, divided by the storage capacity available, C_{BES}. It should remain bound between the maximum and minimum acceptable values namely SOC_{max} and SOC_{min}, Eq. (22).

$$SOC_{min} \le SOC_{BES}(t) \le SOC_{max} \tag{22}$$

Same as for the state of charge for the battery storage system, the stored energy has to be limited between the acceptable minimum and maximum values too, as indicated by Eq. (23).

$$E_{BES,min} \le SOC_{BES}(t) \le E_{BES,max} \tag{23}$$

The maximum energy storage one could expect can be calculated from Eq. (24).

$$E_{BES,max} = (1 - DOD).E_{BES} \tag{24}$$

The cost estimate (NPV_{BES}) of energy storage batteries is calculated over the plant's lifetime by Eq. (25) [27].

$$\begin{aligned} NPC_{BES} &= N_{BES}.[IC_{BES} + RC_{BES} + OMC_{BES} - SC_{BES}] \\ &= N_{BES}.\left[IPR_{BES} + \frac{RPR_{BES}}{(1+d_r)^{10}} + \sum_{y=1}^{25}\frac{OMP_{BES}}{(1+d_r)^y} - RC_{BES}.\left(\frac{T_{BES,rem}}{T_{BES}}\right)\right] \end{aligned} \tag{25}$$

In Eq. (25), N_{BES}, IC_{BES}, RC_{BES}, OMC_{BES} and SC_{BES} are the number of batteries, the initial cost of batteries, the replacement cost of batteries, the operation, and maintenance cost for the batteries, and the salvage value of the batteries respectively. Also, respectively, IPR_{BES}, RPR_{BES}, OMP_{BES} stand initial price per battery, replacement price per battery, and operation and maintenance price per battery while T_{BES}, $T_{BES,rem}$ are the battery's lifetime and remaining battery life at a given time respectively too.

The PV facility has a converter to convert direct current to alternating current. Using Eqs. (26) and (27) from reference [27], the NPC of the system converter and its power are computed.

$$P_{INV}(t) = \eta_{INV}.[P_{PV,o}(t) + P_{BES}(t)] \tag{26}$$

The price of an inverter is obtained

$$\begin{aligned} NPC_{INV} &= P_{INV}.\,[IC_{INV} + RC_{INV} + OMC_{INV} - SC_{INV}] \\ &= P_{INV}.\left[IPR_{INV} + \frac{RPR_{INV}}{(1+d_r)^{15}} + \sum_{y=1}^{25}\frac{OMP_{INV}}{(1+d_r)^{y}} - RC_{BDC}.\left(\frac{T_{INV,rem}}{T_{INV}}\right)\right] \end{aligned} \quad (27)$$

As in the previous case, P_{INV}, η_{INV}, IC_{INV}, RC_{INV}, OMC_{INV}, SC_{INV} are the power of the inverter, efficiency of the inverter, initial cost of the inverter, replacement cost of the inverter, operation and maintenance cost for the inverter, and the salvage value of the inverter, respectively. Likewise, IPR_{INV}, RPR_{INV}, OMP_{INV} stand for initial price per inverter, replacement price per inverter, and operation and maintenance price per inverter while T_{INV}, $T_{INV,rem}$ are the inverter's lifetime and remaining inverter life at a given time, respectively.

2.3 Technical Specifications and Inputs

Having collected the solar irradiation intensities at the selected sites presented in Fig. 2 and evaluated the load at each site, the design, and sizing of the standalone PV power systems have been carried out. Table 1 presents the technical specifications of the main components for designed PV plants' models. The Monocrystalline-Silicon PV module with nominal power of 370 Wp was used. The reference operating temperature was considered ambient, 25°C. For energy storage, the lithium-ion battery with a capacity of 252 Ah and a nominal voltage of 51.8 V was used. The battery minimum state of charge (SOC) was maintained at 10% while the maximum charge was kept at 95%. The operating temperature for the batteries was set at 20°C. For the conversion of DC power from the PV panels to AC power for consumption by equipment, a Universal controller was used. The used universal Controller was coupled with an MPPT converter to maintain the battery's state of charge (SOC) between the allowable minimum and maximum limits.

Table 1: Technical specifications for the PV plant's components

PV module		Battery	
Model	EGE 166-M-60-HC 370 Wp	Model	EM048252P3BA 252 Ah
Technology	Si-Mono	Technology	Lithium-ion, NMC
Unit Nom. Power	370 Wp	Discharging min SOC	10.0%
Temperature (Ref)	25°C	Charging	0.95
Controller		Discharging	0.10
Universal controller	Nom. Voltage	51.8 V	
Technology	MPPT converter	Temperature	Fixed at 20°C
Temp. Coeff.	−5.0 mV/°C/Elem		
Converter			
Efficiencies	97.0%/95.0%		

In addition to technical specifications of the PV plant components, the economic study on the eight standalone PV plants under this study considered input parameters such as site locations, solar irradiances, load, system power for each plant as well as the number of PV panels and storage batteries were determined. Table 2 summarises the values of solar radiation intensity, energy requirement, desired plant power as well as the number of panels and batteries needed to design an optimal PV plant at each site. According to the table, the minimum global horizontal irradiation (GHI) observed was at 1678.6 (kW/m^2/year) in Burera. This irradiance is however high enough to sustain enough solar energy production by a PV power plant. One may notice that the number of solar panels of 3818, and batteries of as many as 1535 is too high. However, such an investment is worth it given that these are to serve a load of more than 4000 kWh/day.

Table 2: Input parameters

Sites description	Sites coordinates		Global horizontal irradiation (kW/m^2/year)	User's needs (kWh/Day)	System power (kWp)	PV modules (Number of units)	Batteries (Number of units)
	Latitude	Longitude					
Site (1)—Nyagatare	−1.29°	30.18°	1831.4	3959	1322	3572	1410
Site (2)—Bugesera	−2.14°	30.24°	1850.3	4354	1400	3784	1535
Site (3)—Kayonza	−1.83°	30.71°	1826.7	4125	1413	3818	1455
Site (4)—Kirehe	−2.27°	30.71°	1816.2	3892	1314	3552	1375
Site (5)—Musanze	−1.54°	29.51°	1684.4	2278	746	2016	735
Site (6)—Burera	−1.45°	29.71°	1678.6	2701	826	2688	950
Site (7)—Nyaruguru	−2.70°	29.56°	1700.5	2476	870	2352	875
Site (8)—Gisagara	−2.62°	29.85°	1791.2	2127	728	1968	710

3 Results and Discussion

The study evaluated the energy requirements at eight different sites throughout the country presented in Fig. 2. Table 3 presents the energy requirement per site. The required total load was obtained as a sum of daily energy consumption per equipment. Home activities, farm activities, office activities and small businesses were considered in the load requirement estimation. As can be seen from the table, among the eight selected sites in Rwandan territory, the SITE (2)—BUGESERA (Gashanga village) has the highest value in total energy demand at approximately 4.4 MWh per day to serve 320 community households. On the other hand, the SITE (8)—GISAGARA (Zihare village) has the smallest value in total energy demand. It is about half of the load requirement at Bugesera, precisely around 2.2 MWh per day. At Gisagara a community with only 128 households need to be served. It is worthwhile to note that domestic appliances (fridges, ACs, washing machines, and resistive loads) would mainly contribute to energy consumption in villages. Nevertheless, it is to be noted that this study took into consideration the projected additional loads in the next five (5) years in line with the government of Rwanda's ambitions for sustainable development as National Strategies for Transformation (NST1) stipulates.

Table 3: Load estimates per site

		a) SITE (1)—NYAGATARE					b) SITE (2)—BUGESERA					c) SITE (3)—KAYONZA				
SN	Equipment	Qty	Tot	Unit power (Wat)	Time/day (Hr)	Tot energy/day (Wh/day)	Qty	Tot	Unit power (Watt)	Time/day (Hr)	Tot energy/day (Wh/day)	Qty	Tot	Unit power (Watt)	Time/day (Hr)	Total energy/day (Wh/day)
	Lamps															
1	For inside	6	1398	15	5	104850	5	1600	12	5	96000	5	1500	12	5	90000
2	For outside	2	466	18	10	83880	2	640	15	10	96000	2	600	15	10	90000
3	T.V screen	1	233	100	6	139800	1	160	100	6	96000	1	150	100	6	90000
4	Radios	1	233	50	4	46600	1	320	50	4	64000	1	300	50	4	60000
5	Printers	1	20	20	0.5	200	1	10	20	0.5	100	1	10	20	0.5	100
6	Scanners	1	20	40	0.5	400	1	10	40	0.5	200	1	10	40	0.5	200
7	LAPTOPS	1	233	25	12	69900	1	160	25	12	48000	1	150	25	12	45000
8	Phone chargers	2	466	5	1	2330	2	640	5	1	3200	2	600	5	1	3000
9	Ceiling fans	2	466	100	2	93200	2	640	100	2	128000	2	600	100	2	120000
10	Kettles	1	233	1000	0.25	58250	1	320	1000	0.25	80000	1	300	1000	0.25	75000
11	Irons	1	233	1100	0.25	64075	1	320	1100	0.25	88000	1	300	1100	0.25	82500
12	Fridges	1	233	150	18	629100	1	320	150	18	864000	1	300	150	18	810000
13	Microwaves	1	233	1000	0.5	116500	1	160	1000	0.5	80000	1	150	1000	0.5	75000
14	Cooking stoves	2	466	3000	0.5	699000	2	640	3000	0.5	960000	2	600	3000	0.5	900000
15	Washing machines	1	233	2400	0.5	279600	1	320	2400	0.5	384000	1	300	2400	0.5	360000
16	Air conditioners	1	233	3500	1	815500	1	160	3500	1	560000	1	150	3500	1	525000
17	Juicer machine	1	233	200	0.25	11650	1	320	200	0.25	16000	1	300	200	0.25	15000
18	Blender machine	1	233	300	0.25	17475	1	320	300	0.25	24000	1	300	300	0.25	22500
19	Batteries for E-tractors	24	24	4,800	1	115200	24	24	4,800	1	115200	24	24	4,800	1	115200
20	Common market	1	1	1620	6	9720	1	1	1620	6	9720	1	1	1620	6	9720
21	Bar and restaurants	1	1	6910	5.86	40492.6	1	1	6910	5.86	40492.6	1	1	6910	5.86	40492.6
22	Hairdressing salons	3	3	4410	6.4	84672	3	3	4410	6.40	84672	3	3	4410	6.40	84672
23	Community workshop	1	1	37,000	3.15	116550	1	1	37,000	3.15	116550	1	1	37,000	3.15	116550
24	Food storages	1	1	4600	13.33	61318	1	1	4600	13.33	61318	1	1	4600	13.33	61318
25	Butchers	1	1	2765	2.82	7797.3	1	1	2765	2.82	7797.3	1	1	2765	2.82	7797.3
26	MCCs	1	1	25500	11.41	290955	1	1	25500	11.41	290955	1	1	25500	11.41	290955
27	Farming activities						1	1	11160	1.00	11160	1	1	11160	1.00	11160
28	Irrigation system energy						1	1	28,100	1.00	28100	1	1	23,400	1.00	23400
	Total load					**3,959,014.9**					**4,353,465**					**4,124,564.90**

		d) SITE (4)—KIREHE					e) SITE (5)—MUSANZE					f) SITE (6)—BURERA				
SN	Equipment	Qty	Tot	Unit power (Watt)	Time/day (Hour)	Tot energy/day (Wh/day)	Qty	Tot	Unit power (Watt)	Time/day (Hr)	Tot energy/day (Wh/day)	Qty	Tot	Unit power (Watt)	Time/day (Hr)	Total energy/day (Wh/day)
	Lamps															
1	For inside	5	1400	12	5	84000	5	700	12	5	42000	5	900	12	5	54000
2	For outside	2	560	15	12	100800	2	280	15	12	50400	2	360	15	12	64800
3	T.V screen	1	140	100	6	84000	1	70	100	6	42000	1	90	100	6	54000

(Continued)

Table 3 (continued)

4	Radios	1	140	50	4	28000	1	70	50	4	14000	1	90	50	4	18000
5	Printers	1	10	20	0.5	100	1	8	20	0.5	80	1	10	20	0.5	100
6	Scanners	1	10	40	0.5	200	1	8	40	0.5	160	1	10	40	0.5	200
7	LAPTOPS	1	140	25	12	42000	1	70	25	12	21000	1	90	25	12	27000
8	Phone chargers	2	560	5	1	2800	2	280	5	1	1400	2	360	5	1	1800
9	Ceiling fans	2	560	100	2	112000	2	280	100	2	56000	2	360	100	2	72000
10	Kettles	1	280	1000	0.25	70000	1	140	1000	0.25	35000	1	180	1000	0.25	45000
11	Irons	1	280	1100	0.25	77000	1	140	1100	0.25	38500	1	180	1100	0.25	49500
12	Fridges	1	280	150	18	756000	1	140	150	18	378000	1	180	150	18	486000
13	Microwaves	1	140	1000	0.5	70000	1	70	1000	0.5	35000	1	90	1000	0.5	45000
14	Cooking stoves	2	560	3000	0.5	840000	2	280	3000	0.5	420000	2	360	3000	0.5	540000
15	Washing machines	1	280	2400	0.5	336000	1	70	2400	0.5	84000	1	90	2400	0.5	108000
16	Air conditioners	1	140	3500	1	490000	1	70	3500	1	245000	1	90	3500	1	315000
17	Juicer machine	1	280	200	0.25	14000	1	140	200	0.25	7000	1	180	200	0.25	9000
18	Blender machine	1	280	300	0.25	21000	1	140	300	0.25	10500	1	180	300	0.25	13500
19	Batteries for E-tractors	24	24	4,800	1	115200	24	24	4,800	1	115200	24	24	4,800	1	115200
20	Common market	1	1	1620	6	9720	1	1	1620	6	9720	1	1	1620	6	9720
21	Bar and restaurants	1	1	6910	5.86	40492.6	1	1	6910	5.86	40492.6	1	1	6910	5.86	40492.6
22	Hairdressing salons	3	3	4410	6.40	84672	3	3	4410	6.40	84672	3	3	4410	6.40	84672
23	Community workshop	1	1	37,080	3.15	116802	1	1	37,080	3.15	116802	1	1	37,080	3.15	116802
24	Food storages	1	1	4600	13.33	61318	1	1	4600	13.33	61318	1	1	4600	13.33	61318
25	Butchers	1	1	2765	2.82	7797.3	1	1	2765	2.82	7797.3	1	1	2765	2.82	7797.3
26	MCCs	1	1	25500	11.41	290955	1	1	25500	11.41	290955	1	1	25500	11.41	290955
27	Farming activities	1	1	11730	1.00	11730	1	1	19320	1.00	19320	1	1	19320	1.00	19320
28	Irrigation system energy	1	1	25,750	1.00	25750	1	1	51,500	1.00	51500	1	1	51,500	1.00	51500
	Total load					**3,892,337**					**2,277,817**					**2,700,677**

		g) SITE (7)—NYARUGURU					h) SITE (8)—GISAGARA				
SN	Equipment	Qty	Tot	Unit power (Watt)	Time/ day (Hr)	Tot energy/day (Wh/day)	Qty	Tot	Unit power (Watt)	Time/ day (Hr)	Tot energy/day (Wh/day)
	Lamps										
1	For inside	5	800	12	5	48000	5	640	12	5	38400
2	For outside	2	320	15	12	57600	2	256	15	12	46080
3	T.V screen	1	80	100	6	48000	1	64	100	6	38400
4	Radios	1	80	50	4	16000	1	64	50	4	12800
5	Printers	1	6	20	0.5	60	1	8	20	0.5	80
6	Scanners	1	6	40	0.5	120	1	8	40	0.5	160
7	LAPTOPS	1	80	25	12	24000	1	64	25	12	19200
8	Phone chargers	2	320	5	1	1600	2	256	5	1	1280
9	Ceiling fans	2	320	100	2	64000	2	256	100	2	51200
10	Kettles	1	160	1000	0.25	40000	1	128	1000	0.25	32000
11	Irons	1	160	1100	0.25	44000	1	128	1100	0.25	35200
12	Fridges	1	160	150	18	432000	1	128	150	18	345600

(Continued)

Table 3 (continued)

13	Microwaves	1	80	1000	0.5	40000	1	64	1000	0.5	32000
14	Cooking stoves	2	320	3000	0.5	480000	2	256	3000	0.5	384000
15	Washing machines	1	80	2400	0.5	96000	1	64	2400	0.5	76800
16	Air conditioners	1	80	3500	1	280000	1	64	3500	1	224000
17	Juicer machine	1	160	200	0.25	8000	1	128	200	0.25	6400
18	Blender machine	1	160	300	0.25	12000	1	128	300	0.25	9600
19	Batteries for E-tractors	24	24	4,800	1	115200	24	24	4,800	1	115200
20	Common market	1	1	1620	6	9720	1	1	1620	6	9720
21	Bar and restaurants	1	1	6910	5.86	40492.6	1	1	6910	5.86	40492.6
22	Hairdressing salons	3	3	4410	6.40	84672	3	3	4410	6.40	84672
23	Community workshop	1	1	37,080	3.15	116802	1	1	37,080	3.15	116802
24	Food storages	1	1	4600	13.33	61318	1	1	4600	13.33	61318
25	Butchers	1	1	2765	2.82	7797.3	1	1	2765	2.82	7797.3
26	MCCs	1	1	25500	11.41	290955	1	1	25500	11.41	290955
27	Farming activities	1	1	16740	1.00	16740	1	1	11160	1.00	11160
28	Irrigation system energy	1	1	40,800	1.00	40800	1	1	36,100	1.00	36100
	Total load					**2475877**					**2127417**

One can note, however, that it is important to describe the variation of power consumption with the hours of the day. This is due to the fact that the daily distribution of load influences both the size, the required plant performance, and hence the cost of the plant in general. In fact, when high consumptions do not coincide with hours with high irradiation intensities, large storage capacity or more efficient panels are required, thence the cost of the PV plant raise. The consumption distribution over 24 h of the day at four sites is captured in Fig. 3. As can be seen from the figure, at three sites out of four (Burera, Nyaruguru, and Kayonza) more power is consumed in the evening hours, precisely between 6 and 9 PM. Moreover, the major daily energy consumption is predicted to remain between these hours as people return home and do many activities at home during these hours. For the site at Kirehe, the consumption was almost evenly distributed from 6 to 9 PM. At Kirehe and other districts that are likely to depend on mechanized agriculture as Rwanda's economy grows, the even distribution from morning hours to evening can be explained by the fact that the farmer will make use of energy from morning to sun-set in agriculture activities and keep using power for home activities in evening hours.

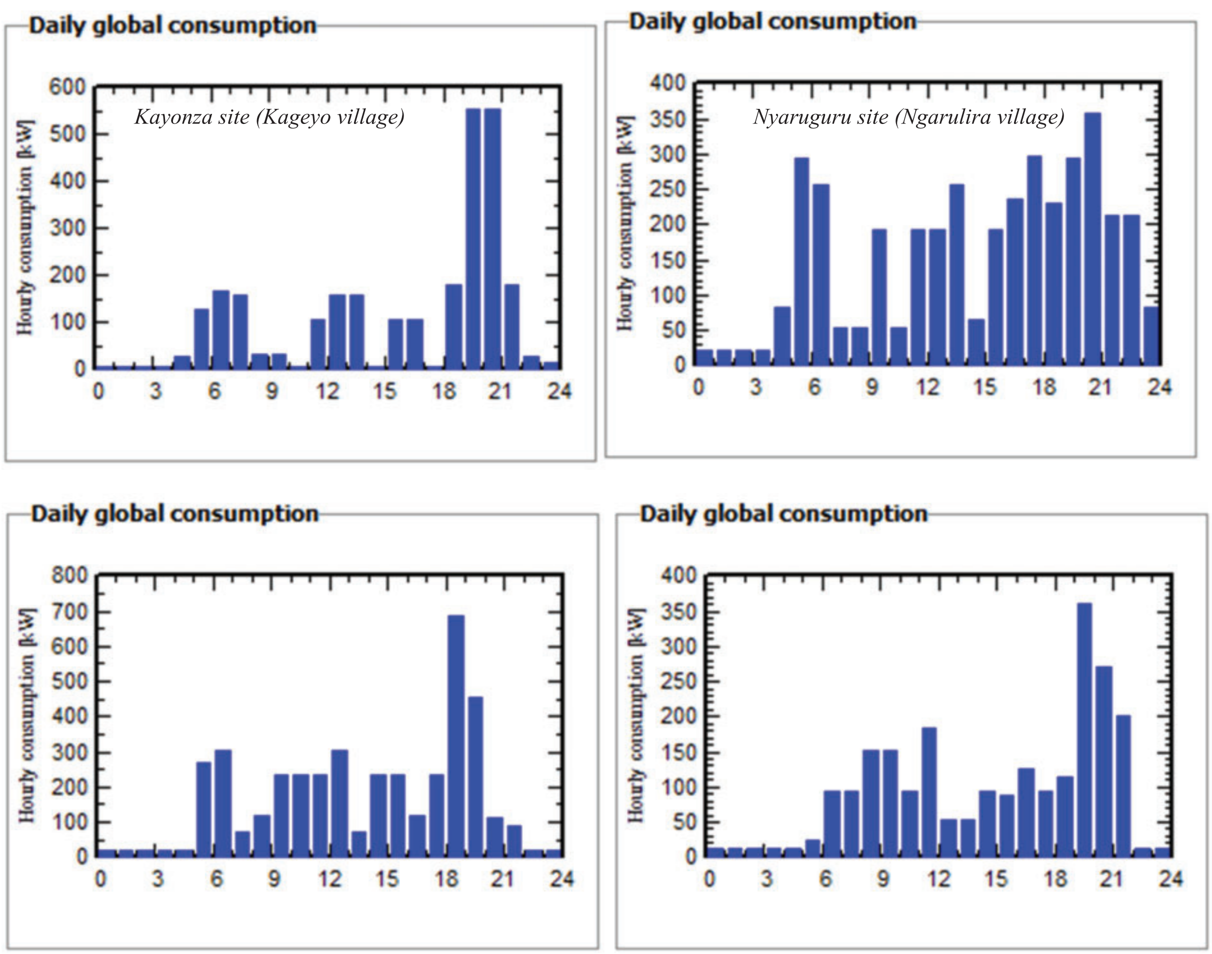

Figure 3: Daily power consumption

For the technical analysis of the PV plants' system power, a model has been developed for the energy load up to 4400 kWh/day. The model was developed considering the average solar radiation intensity in Rwanda at 5 kWh/m^2/day and the peak period approximated at 5 h/day. Moreover, the model was validated by the results of detailed studies conducted at the eight selected sites throughout the country, see Fig. 2. Fig. 4 presents the predicted peak power/system for PV plants of various sizes at sites with different daily energy consumption profiles in rural villages in Rwanda. It also shows the results of detailed studies on the sites priorly specified. One can see from the figure that the model has been able to replicate the results of the field study fairly well. Therefore one can note that such a validated model is significantly important as it can serve as a reference for further studies. Particularly, in this research, it was further used for economic analyses including the evaluation of the impact of incentives and subsidies on the PV plants' profitability at the chosen eight sites.

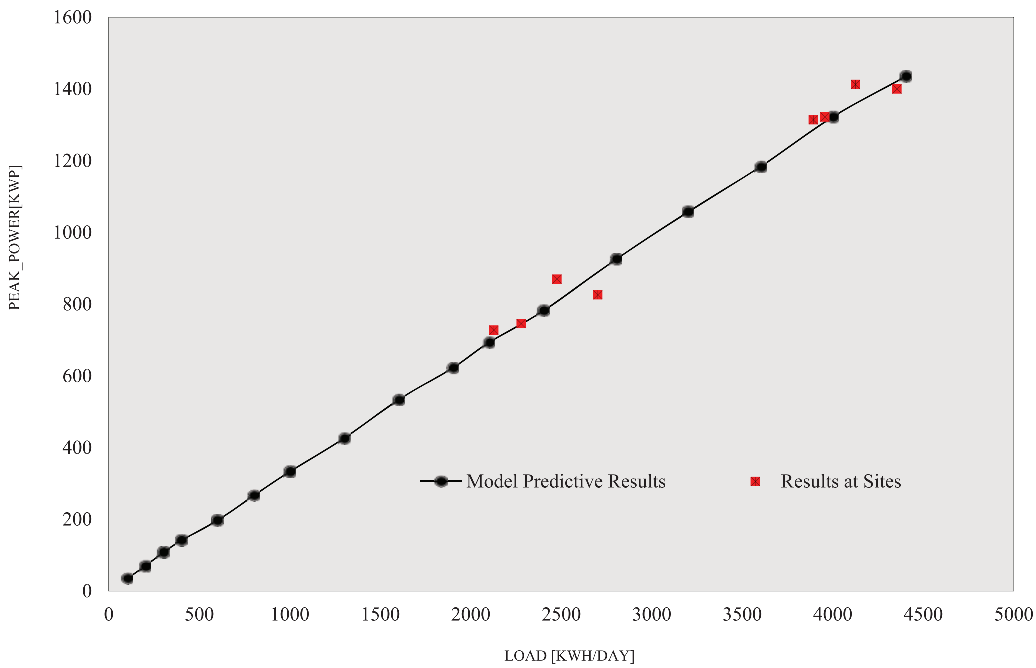

Figure 4: Peak power of the PV plants as *vs*. load

Likewise, an economic model was designed on basis of which the cost of the PV plants can be estimated depending on energy requirements for a given site. Fig. 5 shows the total costs required to construct PV plants of various sizes (load). It comprises the cost estimations carried out under general conditions in terms of solar radiation availability and intensity, the inclination of solar rays, and the daily energy load profile in the country. It also contains the deep cost evaluation carried out at eight different sites that were selected among thirty-two sites based on the need for energy in these locations and on the suitability of solar PV plants in these given regions. It can be seen from the figure that the predicted costs by our model match the field-study-based costs. The similarities between the results obtained through the two-different approaches confirm that the developed model can be used for the estimation of PV plants' costs at any other locations even with slightly different physical conditions. One might think that the validation of model results by comparison with field data would have been carried out for small loads to increase the reliably of the model for locations with total energy requirements below 2000 kWh/day. However, it is worth noting that for all off-grid regions given the current population and needs for machinery in agriculture activities, needs of community workshops, and use of technology facilities and tools, it is rare for even a small region that communities will keep their energy requirement at less than 2000 kWh the whole day even in the near future. The energy demand is expected to keep growing sharply and the expected increase in load demand was accommodated in this study for only 5 years even though the PV plants are expected to last for 25 years. This makes the validation at only high loads reasonable.

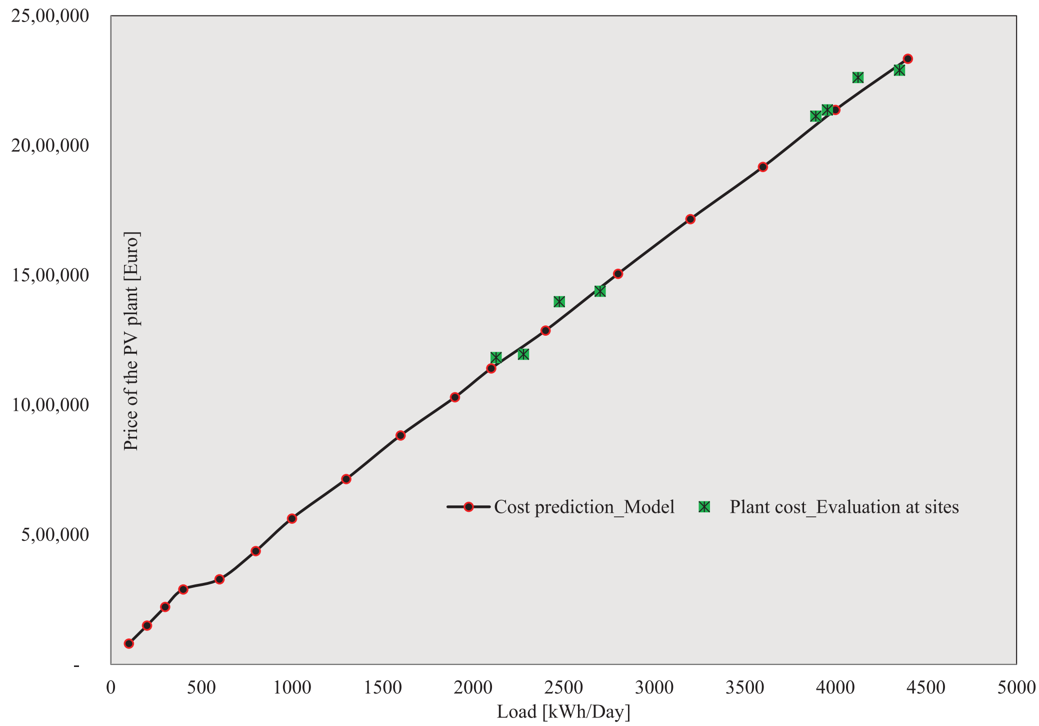

Figure 5: Installation cost per PV plant size (Load)

The financial performance of the developed PV plant models was characterised by both the Leviterised Cost Energy (LCOE) or cost of useful energy at production and the payback period. The LCOEs and the payback periods are presented in Figs. 6 and 7, respectively. As can be seen from Fig. 6, the LCOEs calculated using the developed model under different nominal load sizes and generalized conditions over the country were benchmarked to LCOEs calculated with site-specific data as inputs. Two cases were considered. In the first case, the LCOEs were estimated without considering incentives and subsidies that could be provided by both the government of Rwanda and the beneficial local administrative entities as well as the contribution from the community in the villages. While the second case considered incentives, subsidies, and community contributions equal to 20% of each plant's total cost, see Table 4.

The available incentives and subsidies estimated are constituted by the exoneration of taxes, land costs, permitting and administrative fees and other contributions from the local administration. In addition, the local community's contribution to land preparation and assuring the security of the plants were valued among factors influencing the drop in the total plants' costs.

Likewise, the evaluation of the payback periods of the PV plants of different sizes showed that the subsidies and incentives are potentially significant as they can assist the investors to recover their capital in reduced periods.

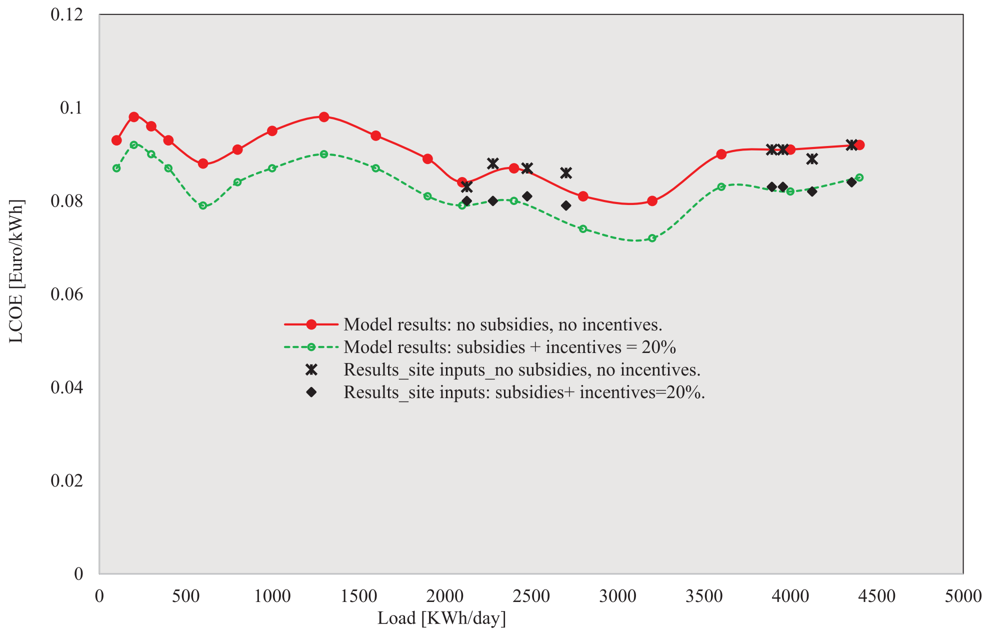

Figure 6: Levelised cost of energy

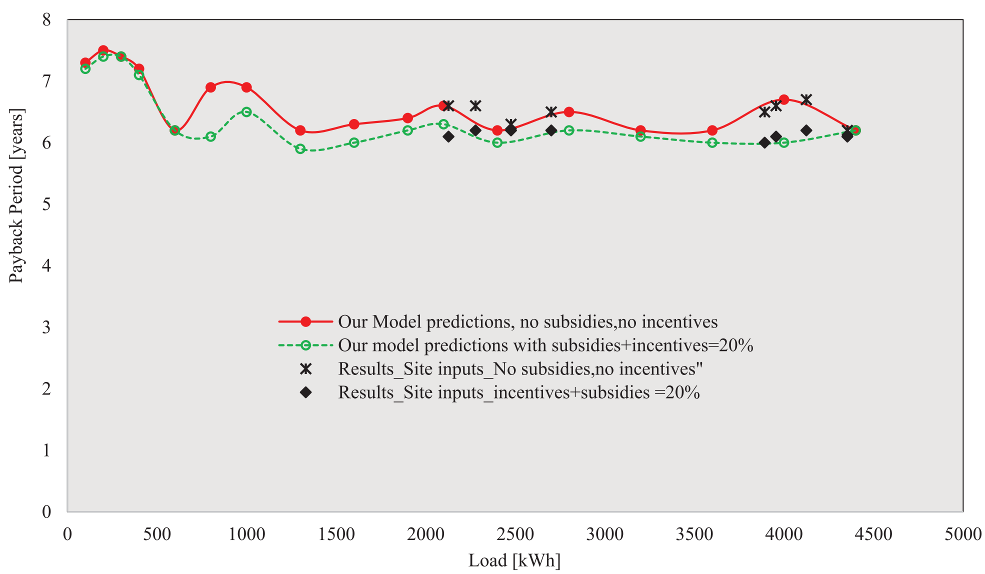

Figure 7: Payback periods

Table 4: The estimated value of incentives and subsidies available in districts

Site	Total cost of the PV plant (Euro).	Incentives and subsidies (Euro).	Incent. and Subs. Ratio (%).
Nyagatare	2136968	428000	20.028
Bugesera	2290111	449400	19.624

(Continued)

Table 4 (continued)

Site	Total cost of the PV plant (Euro).	Incentives and subsidies (Euro).	Incent. and Subs. Ratio (%).
Musanze	1195089	240750	20.145
Nyaruguru	1397833	281400	20.131
Kayonza	2261752	452825	20.021
Kirehe	2113093	422700	20.004
Gisagara	1182582	236500	19.999
Burera	1438222	288000	20.025
			Average: 19.997%≅20%

Fig. 7 recapitulates the payback periods for the designed PV plants at different sites. The figure compares the values of these payback periods obtained using sites-specific-inputs to the ones from our extended predictive model developed for the PV plants to serve varied loads. As can be seen from the figure, the results of detailed field studies also match our model results. Also, it shows that incentivizing and subsiding the production of solar energy will alleviate the burden on investors as they considerably reduced the payback periods on the PV plants. As one can see, in some cases these periods to recoup the investments in the PV plants were reduced from 6.9 to 6.1 years. Another important remark that one can make is that the observed maximum payback period was 7.5 years. Noting that the lifetime of PV plants is 25 years, one can obviously confirm that the investors in development will be able to obtain financial gains for more than a decade.

Moreover, to quantify further the potential financial interests for such big investments, it is necessary to determine the return on investments (ROI) for plants of various sizes. These estimates of return on investments are presented in Table 5. According to the findings in the table, the investments in the PV plants could lead to net profits between 425.72 and 615.32 per cent of the total investments over the plants' lifetime of 25 years. In most cases, such profits are above 500% which justifies that such investments are worth making. However, such profits can only be achieved only if the consumers' price is set at least equal to the LCOE.

Table 5: Return on investments (ROI)

S/N	Energy-kWh/d	kWp	Total initial cost (EUR)	NPV(EUR)	ROI
1	100	34	79,810.50	570897.88	615.32
2	200	69.6	149,456.00	980001.57	555.71
3	300	107	221,112.00	1428242.78	545.94
4	400	141	288,905.00	1987232.12	587.85
5	600	197	327,878.00	2040848.76	522.44
6	800	266	436,340.00	2747807.95	529.74
7	1000	333	562,025.00	3,017,775.43	436.95
8	1300	426	713,938.00	4,238,379.77	493.66
9	1600	533	882,375.00	4,638,864.13	425.72

(Continued)

Table 5 (continued)

S/N	Energy-kWh/d	kWp	Total initial cost (EUR)	NPV(EUR)	ROI
10	1900	622	1,029,530.00	6,149,076.43	497.27
11	2100	693	1,140,498.00	6,636,751.80	481.92
12	2400	781	1,286,553.00	8,083,483.51	528.31
13	2800	924	1,505,059.00	9,130,520.01	506.66
14	3200	1051	1,716,104.00	11,137,957.69	549.03
15	3600	1183	1,916,934.00	11,837,221.73	517.51
16	4000	1322	2,136,968.00	13,307,660.35	522.74
17	4400	1434	2,333,814.00	13,718,221.75	487.80

The costs of susceptible to reduce below the Levelised Cost of Energy for the PV plants' energy to be competitive on the national market. That is since the current price of electricity for consumers is set to 0.086 Euro/kWh for consumers that use less than 15 kWh per month and 0.180 Euro/kWh for consumers that uses more than 15 kWh per month. In Table 6, the financial benefits for customers were calculated considering the current cost of energy as per regulations. As can be seen from the table, small PV plants are not likely to make profits if they are only used by small consumers. The results indicate that the PV plants' energy price can only be lower than the current energy price in Rwanda if a given community can consume more than 1600 kWh/day.

Table 6: Financial benefit for customers (end users/consumers)

S/N	Energy-kWh/d	kWp	LCOE [EURO]	0–15 kWh/month		>15 kWh/month	
				REG price [EURO]	Diff [%]	REG price [EUR]	Diff [%]
1	100	34	0.087	0.086	−1.163	0.180	51.667
2	200	69.6	0.092	0.086	−6.977	0.180	48.889
3	300	107	0.09	0.086	−4.651	0.180	50.000
4	400	141	0.087	0.086	−1.163	0.180	51.667
5	600	197	0.079	0.086	8.140	0.180	56.111
6	800	266	0.084	0.086	2.326	0.180	53.333
7	1000	333	0.087	0.086	−1.163	0.180	51.667
8	1300	426	0.09	0.086	−4.651	0.180	50.000
9	1600	533	0.087	0.086	−1.163	0.180	51.667
10	1900	622	0.081	0.086	5.814	0.180	55.000
11	2100	693	0.079	0.086	8.140	0.180	56.111
12	2400	781	0.08	0.086	6.977	0.180	55.556
13	2800	924	0.074	0.086	13.953	0.180	58.889
14	3200	1051	0.072	0.086	16.279	0.180	60.000
15	3600	1183	0.083	0.086	3.488	0.180	53.889
16	4000	1322	0.082	0.086	4.651	0.180	54.444
17	4400	1434	0.085	0.086	1.163	0.180	52.778

(Continued)

Table 6 (continued)

S/N	Energy-kWh/d	kWp	LCOE [EURO]	0–15 kWh/month REG price [EURO]	0–15 kWh/month Diff [%]	>15 kWh/month REG price [EUR]	>15 kWh/month Diff [%]
18	3956	1322	0.083	0.086	3.488	0.180	53.889
19	4354	1400	0.084	0.086	2.326	0.180	53.333
20	2278	746	0.080	0.086	6.977	0.180	55.556
21	2476	870	0.081	0.086	5.814	0.180	55.000
22	4125	1413	0.082	0.086	4.651	0.180	54.444
23	3892	1314	0.083	0.086	3.488	0.180	53.889
24	2127	728	0.080	0.086	6.977	0.180	55.556
25	2701	826	0.079	0.086	8.140	0.180	56.111

It is however obvious from the table that for the consumers of more 15 kWh/month, any PV plant development project will be financially competitive in the Rwandan energy market. The generated energy is expected to be 48.889% to 60% cheaper compared to the current energy price. The uncompetitive prices of small PV plant energy can be associated with the high price of batteries for energy storage and a large number of subsidies available for other forms of energy on the market.

Nevertheless, one can optimistically predict that PV plants' energy will be very competitive on the market under any circumstances. That is likely to be influenced by two major factors. Firstly, the government and other organs are likely to increase the incentives and subsidies on the PV plants' energy to raise the portion of clean renewable energy in the energy mix in Rwanda. For instance, the total production for eight designed solar PV plants under this study is expected to be 8.927 MW corresponding to an increase of 3.13% in the solar energy portion in the energy mix compared current total installed Capacity to generate in Rwanda 276.068 MW. That increases the total share of clean renewable solar energy to 7.33% from the current 4.2% percentage. That share is considerable and one can affirm that the incentives and subsidies for such considerable energy generation will be increases considerably.

4 Conclusion and Recommendations

This study aimed to characterise both technically and economically the PV plants for the production of solar energy for use by the rural communities in Rwanda. Specifically, describing the impact of the subsidies and incentives put in place on the affordability, profitability, and penetration of renewable solar PV energy was the major objective. The results of the study indicate that even though the energy loads are greatly increasing in rural communities in Rwanda due to the increasing number of households and farming mechanization, the available solar resources and solar distribution can allow for achieving full electrification by the use of solar PV plants.

Both the modelling and the field-data-based characterization agree with the results of many other studies that subsidies and incentives significantly influence renewable energy integration and increase the profitability of solar PV systems. In fact, the study noted a return investment of up to 615.32 percent and an increment of renewable energy share of 8.927 MW equivalent to 3.13% in the energy mix as well as the drop in the payback period and Levelised Cost of Energy when 20% incentives and subsidies are applied.

Such a study is unique as it has designed and sized the PV plant that can serve the energy load for households, community businesses, and agriculture activities in specific off-grid regions in Rwanda. Such a study has never been done. The findings of this study are particularly significant as they can serve to estimate the potential financial profits and other benefits for potential developers of the PV plants, the community, and the government of Rwanda. Noting that the study was limited to standalone solar PV plants; the heavy costs of battery storage are unavoidable to assure the plants' autonomy. Hence, it is recommended that future studies may consider carrying out such a techno-economic characterization on grid-connected solar PV plants in order to check if that could be the most profitable option. It can also be recommended that future study could assess the possibility of developing hybrid solar-hydro PV plants and estimate their profits under Rwanda's climatic and economic situations.

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Availability of Data and Materials: The data used to support the findings of this study are included within the article. Any additional information, data or materials are available and can be provided when requested.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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