THE DESIGN AND FINANCIAL VIABILITY OF SOLAR PV PLANTS IN RWANDA.

THESIS BY

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In Partial Fulfillment of the Requirements for the Degree of DOCTOR OF PHILOSOPHY

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DEDICATION

This work is dedicated to my beloved late Father Munyampeta Leo and my Mother Melanie Numukobwa.

TABLE OF CONTENTS

1. Contents

ABSTRACT

This thesis encapsulates a study on designing optimally sized photovoltaic (PV) plants for rural villages in Rwanda. The initial phase focused on assessing solar energy potential and energy requirements to determine the ideal model for these villages, estimating the daily energy supply needs of different sites, and observing minimal variation in electrical loads throughout the year. The major factor contributing to energy loss in PV plants was found to be heat-induced losses in solar panels. Despite the high initial costs, investing in such energy systems is deemed worthwhile, with a projected break-even point of around 10 years for a plant lifetime of 25 years and a potential 29% drop in energy costs.

The research also delved into the impact of incentives and subsidies on the cost of PV energy in rural areas, emphasizing the need for a deeper assessment of these factors to optimize the technical and economic aspects of PV plants. It is to be noted that a significant return on investment and increased renewable energy share with the application of incentives and subsidies. Additionally, the study addresses the growing energy demands in rural Rwanda, proposing that solar PV plants could achieve full electrification, especially with the support of subsidies and incentives.

A key contribution of this study lies in its unique design and sizing of PV plants capable of meeting the diverse energy needs of households, businesses, and agriculture in off-grid regions of Rwanda. The findings hold substantial implications for potential developers, communities, and the Rwandan government, providing insights into potential financial gains and broader benefits. The study acknowledges limitations related to standalone PV plants and suggests avenues for future research, including exploring grid-connected PV plants and hybrid solar-hydro PV systems tailored to Rwanda's climate and economic conditions.

DECLARATION

I hereby declare that the dissertation entitled “**The Design of Solar PV plants in Rwanda and their Financial Viability** ” to be submitted for the Degree of Doctor of Philosophy is my original work and the dissertation has not formed the basis for the award of any degree, diploma, associateship or fellowship of similar other titles. It has not been submitted to any other University or Institution for the award of any degree or diploma.

Place: Kigali, Signature of the Scholar: Date: 20/06/2024,
Names: Morris Kayitare

APPROVAL SHEET

I, Sendegeya AlMas (PhD), the Supervisor of this work entitled “**The Design of Solar PV Plants in Rwanda and their Financial Viability**”, prepared and submitted by Morris Kayitare in accordance with the specifications for the award of Doctor of Philosophy, I certify that this thesis has been examined and approved.

Supervisor
Name: AlMas Sendegeya, PhD

Signature:
Date: 20/06/2024

1. SECTION 1: INTRODUCTION SUMMARY

1.1. Background

The increasing global energy demand, driven by population and economic growth, presents a critical challenge, particularly in developing nations where energy access is limited [1]–[4]. This study aims to address the urgent need for sustainable and efficient energy solutions in developing countries, with a specific focus on Rwanda. The motivation arises from the fact that over 1.3 billion people lack electricity access [5], and the reliance on conventional energy sources leads to environmental degradation [6], [7]. To achieve economic growth while minimizing harm to the environment, there is a demand for supplementary energy sources, particularly renewable ones like solar energy. The potential of solar photovoltaic (PV) systems is recognized due to their technological advancement, decreasing costs, and environmental benefits [8], [9]. However, there is a gap in understanding the cost-effective and optimal design and sizing of these systems to meet the complex energy demands of rural electrification and e-farming, especially in Rwanda. This study aims to bridge this gap by conducting a comprehensive assessment of energy requirements and modelling PV systems for rural electrification and agricultural activities in Rwanda.

1.2. Statement of the Research Problem

The research problem addressed by this study is the lack of location-specific analyses for the design and optimization of solar photovoltaic (PV) systems to fulfill the energy demand for rural electrification and e-farming in Rwanda. While there have been some prior studies on PV systems [10], [11], they often lack applicability due to variations in solar resources and electrical load profiles across different geographical locations. Additionally, the integration of energy requirements for agricultural activities has been overlooked in existing studies. Moreover, the impact of subsidies and incentives on the profitability and feasibility of PV projects in Rwanda remains understudied. This study aims to address these gaps by conducting detailed analyses to optimize PV system designs, considering actual and forecasted energy consumption, agricultural needs, and the influence of subsidies and incentives on project viability.

1.3. Objectives

1.3.1. General Objective:

The main objective of the studies is to develop and optimize cost-effective and sustainable solar photovoltaic (PV) systems models for rural electrification and e-farming in off-grid regions in Rwanda, addressing the unique energy demands and environmental challenges of the region.

1.3.2. Specific Objectives:

- To conduct a comprehensive assessment of current and projected energy consumption in rural areas and agricultural activities in Rwanda.
- To analyze the variations in solar resources and electrical load profiles across different geographical locations within Rwanda.
- To develop PV system designs tailored to the specific energy needs of rural electrification and e-farming.
- To incorporate technological advancements and cost-reducing strategies in PV system designs to enhance efficiency and affordability.
- To assess the economic viability of PV systems, considering the cost of implementation, maintenance, and potential savings.
- To integrate the energy requirements of agricultural activities into the PV system designs to ensure a holistic approach to rural energy solutions.
- To investigate the impact of government subsidies and incentives on the feasibility and profitability of PV projects in Rwanda.

By achieving these objectives, the study potentially can contribute to the development of sustainable and efficient energy solutions in Rwanda, promoting economic growth and environmental sustainability.

1.4. Significance of the study

The research is envisaged to have a potential impact on the improvement of energy access and sustainability in Rwanda. Like many other developing nations, Rwanda faces significant challenges in providing reliable and affordable electricity, especially in rural areas. By exploring the design and implementation of photovoltaic (PV) mini-grid plants, this research contributes to the broader goal of enhancing energy access. Solar PV technology offers a sustainable and renewable energy source that reduces dependency on fossil fuels, thereby aiding environmental conservation and combating climate change.

Electrification is a crucial driver of economic development and poverty alleviation. For rural communities, access to electricity can transform livelihoods by enabling the use of modern farming equipment, improving productivity, and fostering small businesses. This study’s techno-economic analysis provides insights into the financial viability of solar PV systems, demonstrating their potential as a cost-effective solution for rural electrification. By identifying challenges and opportunities, the research offers practical recommendations for policymakers and stakeholders to promote economic development and poverty alleviation.

This research advances the understanding of PV technology in the context of Rwanda. The detailed characterization of PV mini-grid plants and the analysis of their technical and economic aspects contribute significantly to the knowledge base necessary for optimizing these systems. The findings can guide engineers, researchers, and practitioners in enhancing the design and efficiency of PV installations, fostering innovation in the renewable energy sector.

One of the critical aspects of this study is its focus on the role of subsidies and incentives in the adoption of solar PV power generation. By examining the impact of these financial mechanisms, the research provides valuable insights for policymakers. The recommendations derived from this analysis can help shape effective policies that support renewable energy adoption, encourage investment in solar infrastructure, and create a conducive environment for sustainable energy development.

The study’s findings have direct implications for Rwanda's rural electrification strategies. By highlighting the technical and economic feasibility of PV mini-grids, the research supports the deployment of these systems as a viable solution for off-grid communities. The case-specific insights ensure that the proposed solutions are tailored to the unique socio-economic and geographical context of Rwanda, increasing the likelihood of successful implementation. Additionally, it is crucial for Rwanda to invest in base-load power plants that produce bulk electricity using three-phase synchronous generators and continue to expand the national grid. This investment is essential to meet the core power requirements needed for industrialization and to effectively serve industrial loads. Such infrastructure will complement the PV mini-grids by providing a stable and reliable energy supply necessary for economic growth and industrial development.

On a broader scale, this study contributes to global efforts to promote renewable energy and achieve sustainable development goals (SDGs). By focusing on Rwanda, it provides a model that can be adapted and replicated in other developing countries with similar energy challenges. The research underscores the importance of local context in designing renewable energy solutions, adding valuable perspectives to the global discourse on sustainable energy transitions.

Finally, the study identifies gaps and areas for future research, paving the way for ongoing exploration and development in the field of renewable energy. By outlining the challenges and opportunities of PV mini-grid systems in Rwanda, it sets the stage for further studies that can build on its findings and continue to advance the field. This ensures that the research remains relevant and contributes to the continuous improvement of renewable energy technologies and strategies.

1.5. Methodology

The summary of the methodology for our three papers that constitute this thesis are as follow: The study conducted a physical assessment at 32 locations, selecting eight for detailed load evaluation. Total load demand was estimated by inventorying equipment, recording power ratings, and usage hours. A techno-economic analysis using PVSyst was performed on the eight sites based on solar potential and needs. The PV plant was modeled mathematically to determine power output, efficiency, and economic feasibility. The design involved using 370 Wp PV panels, lithium-ion batteries, and a bidirectional converter. Data on solar irradiation, load demands, and equipment were collected for accurate site representation and future load predictions. Technical and economic analyses were supported by PVSyst software.

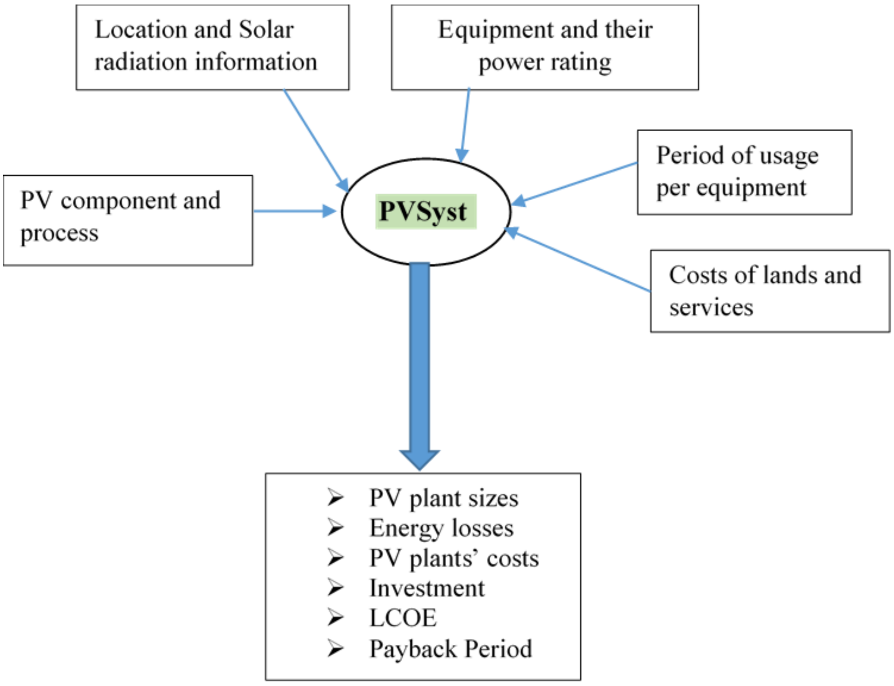

Figure 1. Methodology

The methodologies used for the three papers, while distinct, are complementary in their approach to evaluating photovoltaic (PV) systems. The first methodology provides a comprehensive analysis, integrating both technical and economic aspects, including detailed modeling of power output, efficiency, and battery performance using PVSyst software. It emphasizes site-specific technical assessments and performance simulations. In contrast, the second methodology focuses primarily on the economic side, offering in-depth financial evaluations such as Net Present Cost (NPC), Levelized Cost of Energy

(LCOE), and detailed cost modeling of system components. This methodology prioritizes financial feasibility over technical design details. Together, they offer a holistic view of PV systems, combining robust technical analysis with thorough economic evaluation to ensure both technical performance and financial viability.

1.6. Organization Structure of the Thesis

This thesis is organized into 5 sections that aim to collectively explore the design, characterization, and economic implications of photovoltaic (PV) mini-grid plants and solar PV power generation in Rwanda, with a focus on modern farming and rural electrification. It is composed of a general introduction, two papers published in peer-reviewed international journals, one paper published in a peer-reviewed international conference as well and a general conclusion. is composed of five main chapters, each serving a distinct purpose in presenting the research comprehensively.

The first section, General Introduction, provides a foundational understanding of the research. It includes a background that sets the context, a statement of the research problem identifying the gap this study aims to fill, and the objectives guiding the research.

Section 2 consists of the first paper published in a peer-reviewed international journal. The paper delved into: "Design and Characterization of PV Mini-Grid Plants for Modern Farming and Rural Electrification in Rwanda." It begins with an abstract summarizing the study, followed by an introduction that outlines the research purpose and scope. A case study is then presented, detailing the practical application of the research. The methodology section explains the techno-economic analysis conducted, which leads into the findings section, divided into technical and economic studies, along with the challenges and opportunities of implementing PV mini-grid systems in Rwanda. The main findings of the paper are that solar resources can reliably meet community energy demands. However, factors like heating due to rising temperatures cause significant energy losses, with up to 9.46% lost. Solar radiation exceeds 1800 kW/m²/year. Financial benefits for investors are projected for 10 out of 25 years, with energy prices dropping from 0.252 EUR/kWh to 0.180 EUR/kWh.

Section 3 covers the second paper peer-reviewed and published in the international journal: "A Techno-Economical Characterization of Solar PV Power Generation in Rwanda: The Role of Subsidies and Incentives." This paper has a similar structure to paper 1, starting with an abstract and keywords, followed by an introduction. The methodology section is detailed, including the overall study procedure, mathematical framework, and technical specifications. The results and discussion section presents the findings, leading to the conclusion and recommendations. The key findings presented in paper 2 indicated that with 20% incentives and subsidies, the Levelized Cost of Energy for solar PV systems decreases from 0.098 Euro to 0.072 Euro, the payback period shortens from 7.5 to 6.0 years, and the return on investment ranges from 425.72% to 615.32% over 25 years. These findings highlight the critical role of government subsidies in making solar PV projects highly profitable.

Section 4 presents the third paper: "A Study on the Design and Financial Viability of Solar PV Plants in Rwanda." It includes an introduction, methodology, and results and discussion sections, similar to the previous chapters. This paper is a summarized analysis of Paper 1 and Paper 2. It confirmed that

despite temperature-related energy losses, the regions have sufficient solar resources to meet village energy demands. Economic analysis shows that solar PV plants can be profitable for investors, with a significant reduction in energy costs benefiting consumers.

Finally, section 5, presents the general conclusion and recommendations, which synthesizes the findings. Furthermore, the section aims to encapsulate the insights gained and propose directions for future research and practical implementation in Rwanda's solar energy sector.

1.7. Key findings

The three papers collectively highlight the significant potential of solar PV systems in providing reliable, eco-friendly energy to remote villages in Rwanda. They emphasize the importance of accurate load demand assessment, including energy requirements for farming activities, for optimal sizing and utilization of PV plants.

The key findings from our first paper show that Rwanda has ample solar resources, with solar radiation intensity exceeding 1800 kW/m²/year, capable of meeting the energy needs of rural communities. However, energy losses, particularly due to temperature-induced heating of the panels, can reach up to 9.46%. The techno-economic analysis using PVSyst software indicates that, despite these losses, PV plants can offer substantial financial benefits, reducing the energy price from 0.252 EUR/kWh to 0.180 EUR/kWh, with an ROI of 10 out of 25 years.

The second paper underscored the critical role of government subsidies and incentives. With a 20% subsidy, the Levelized Cost of Energy (LCOE) could decrease from 0.098 EUR/kWh to 0.072 EUR/kWh, reducing the payback period from 7.5 to 6 years, and increasing the return on investment to between 425.72% and 615.32% over the system's lifetime.

The third paper confirmed the findings of the first and second papers and drew the observation that our findings are essential for planners and investors, providing them with the necessary data to make informed decisions about solar PV investments in Rwanda.

The findings from the three published papers align closely with the specific objectives outlined for the study on solar PV systems in Rwanda.

Our objective, to conduct a comprehensive assessment of current and projected energy consumption in rural areas and agricultural activities in Rwanda, is addressed by the emphasis on accurate load demand assessment, including energy needs for farming activities, as highlighted in all three papers. The first paper, in particular, provides detailed insights into the energy consumption patterns and the adequacy of solar resources.

The second objective, to analyze the variations in solar resources and electrical load profiles across different geographical locations within Rwanda, is supported by the first paper's findings, which report ample steady solar resources with radiation intensity exceeding 1800 kW/m^2/year, and the second paper's analysis of optimal sizing using varied data from different sites.

The third objective, to develop PV system designs tailored to the specific energy needs of rural electrification and e-farming, is directly linked to the studies' focus on integrating farming energy requirements into the PV system designs, ensuring that these systems are well-suited to the specific needs of rural communities.

The fourth objective, to incorporate technological advancements and cost-reducing strategies in PV system designs to enhance efficiency and affordability, is reflected in the papers' discussions on factors affecting energy efficiency, such as temperature-induced losses, and the importance of cost-reducing strategies like government subsidies.

The fifth objective, to assess the economic viability of PV systems, considering the cost of implementation, maintenance, and potential savings, is thoroughly addressed in the second and third papers, which analyze the financial benefits, including reduced energy prices and favorable ROI, confirming the economic potential of solar PV systems in Rwanda.

The sixth objective, to integrate the energy requirements of agricultural activities into the PV system designs to ensure a holistic approach to rural energy solutions, is achieved through the detailed consideration of e-farming energy needs, as evidenced by the comprehensive assessments and system designs tailored for such activities in the first paper.

The seventh objective, to investigate the impact of government subsidies and incentives on the feasibility and profitability of PV projects in Rwanda, is directly supported by the second paper's findings on how subsidies can significantly reduce the Levelized Cost of Energy (LCOE), shorten payback periods, and boost returns on investment.

In summary, the studies provide a robust foundation for planners and investors, offering critical data that align with the outlined objectives, ensuring that solar PV investments in Rwanda are informed, economically viable, and effectively tailored to the specific energy needs of rural and agricultural communities.

PUBLICATIONS

1. K. Morris, G. A. Dalson, and S. Al-Mas, “Design and Characterization of PV Minigrid Plants for Modern Farming and Rural Electrification in Rwanda,” Int. J. Photoenergy, vol. 2023, p. 2570325, 2023, doi: 10.1155/2023/2570325.
2. M. Kayitare, G. A. Dalson, and A.-M. Sendegeyad, “A Techno-Economical Characterization of Solar PV Power Generation in Rwanda: The Role of Subsidies and Incentives,” Energy Engineering, vol. 120, no. 9. 2023, doi: 10.32604/ee.2023.028559.
3. M. Kayitare, G. A. Dalson, and A. M. Sendegeyad, “A Study on the Design and Financial Viability of Solar PV Plants in Rwanda,” IEEE Explor., 2023, doi: 10.1109/ICECCME57830.2023.10252327.

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2. SECTION 2: DESIGN AND CHARACTERIZATION OF PV MINI-GRID PLANTS FOR MODERN FARMING AND RURAL ELECTRIFICATION IN RWANDA.

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2.1 Abstract

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.

2.2 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 subSaharan 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 nitrogenbased 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.

2.3 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.

2.4 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:

$$\boldsymbol{P_{PV} = P_{STC} DF \left(\frac{IR}{IR_{STC}}\right)\left[1 + a_p\left(T_{mod} - T_{mod,STC}\right)\right]} \tag{1}$$

In the equation (1) $\boldsymbol{P_{STC}}$ is the power of PV plant when $\boldsymbol{IR_{STC} = 1000\, {}^{W}/_{m^2}}$ and $\boldsymbol{T_{mod,STC} = 25^0 C}$, and wind speed = 0 m/s. IR stands for solar irradiation intensity, while $\boldsymbol{IR_{STC}}$ 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 $T_{mod,STC}$ stands for temperature of the PV panels under STC (standard test conditions) which are $IR_{STC} = 1000\, {}^{W}/_{m^2}$, $T_{mod,STC} = 25^0C$ and wind speed = 0 m/s.

The power of the Solar PV modules under standards test conditions is given by equation (2)

$$P_{STC} = (N_{series} x N_{string\,parallel}) \cdot P_{m,\ STC} \qquad (2)$$

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

The efficiency of the plant can be calculated as by equation (3).

$$\eta_{m,\ STC} = \frac{P_{m,\ STC}}{A_{PV} IR_{STC}} \qquad (3)$$

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

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

$$S_oC(t) = S_oC(0) + \eta_c \sum_{k=0}^{t} P_{CB}(k) + \eta_d \sum_{k=0}^{t} P_{DB}(k) s \qquad (4)$$

In equation *(4)* S_oC(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 equation (5).

$$\begin{cases} \mathrm{B}_{min} \le S_o\mathrm{C} \le \mathrm{B}_{max} \\ \mathrm{B}_{min} = (1 - D_oD)\mathrm{B}_{max} \end{cases} \qquad (5)$$

where B_{min}, B_{max} are minimum and maximum capacities while D_oD 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 equation (6).

$$0 \le \mathrm{P}_{DB}(k) \le \mathrm{P}_{max} \qquad (6)$$

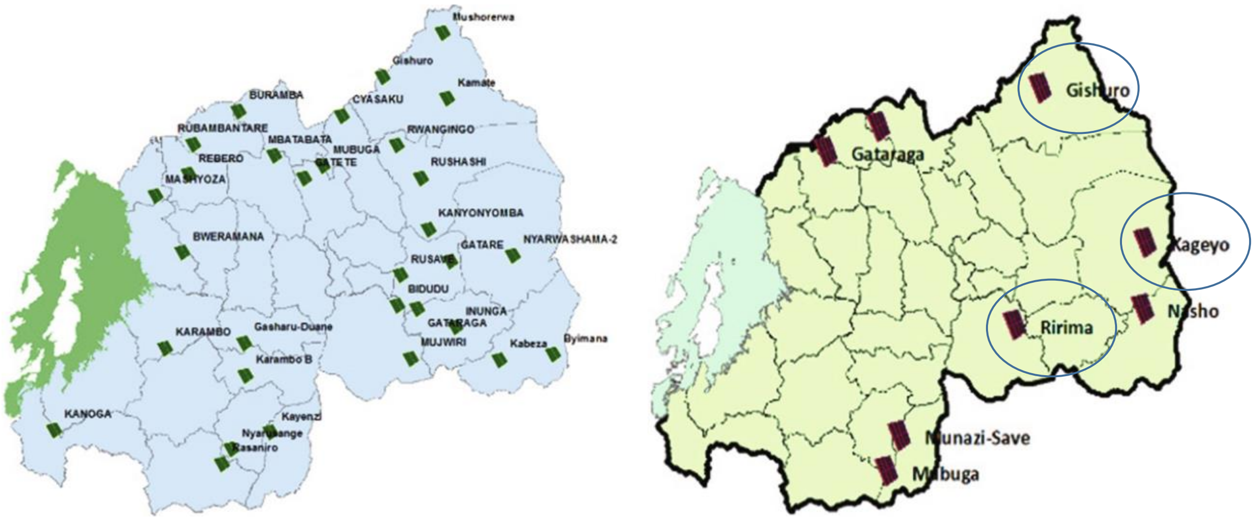
P_{max} is the maximum value of the battery's power discharge per hour.

The mathematical representation of conversion for the converter connected between the DC and AC busses for DC to AC conversion is as per Equation (7).

$$\mathbf{P}_{\boldsymbol{InvOut}} = \mathbf{P}_{\boldsymbol{InvIn}}\boldsymbol{\eta}_{\boldsymbol{Inv}} \tag{7}$$

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

The total load requirement includes the energy consumption by the eTractor, 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, the load should correspond to the sum in equation (8) while for standalone 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
	Latitude	Longitude	(kW/m^2/year)
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).

$$\mathbf{P}_{\boldsymbol{L}}(\boldsymbol{k}) = \mathbf{P}_{\boldsymbol{PV}}(\boldsymbol{k}) + \boldsymbol{P}_{\boldsymbol{DB}}(\boldsymbol{k}) \tag{8}$$

$$\mathbf{P}_{L}(\boldsymbol{k}) = \mathbf{P}_{PV}(\boldsymbol{k}) + \boldsymbol{P}_{Grid}(\boldsymbol{k}) \tag{9}$$

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 370W 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.

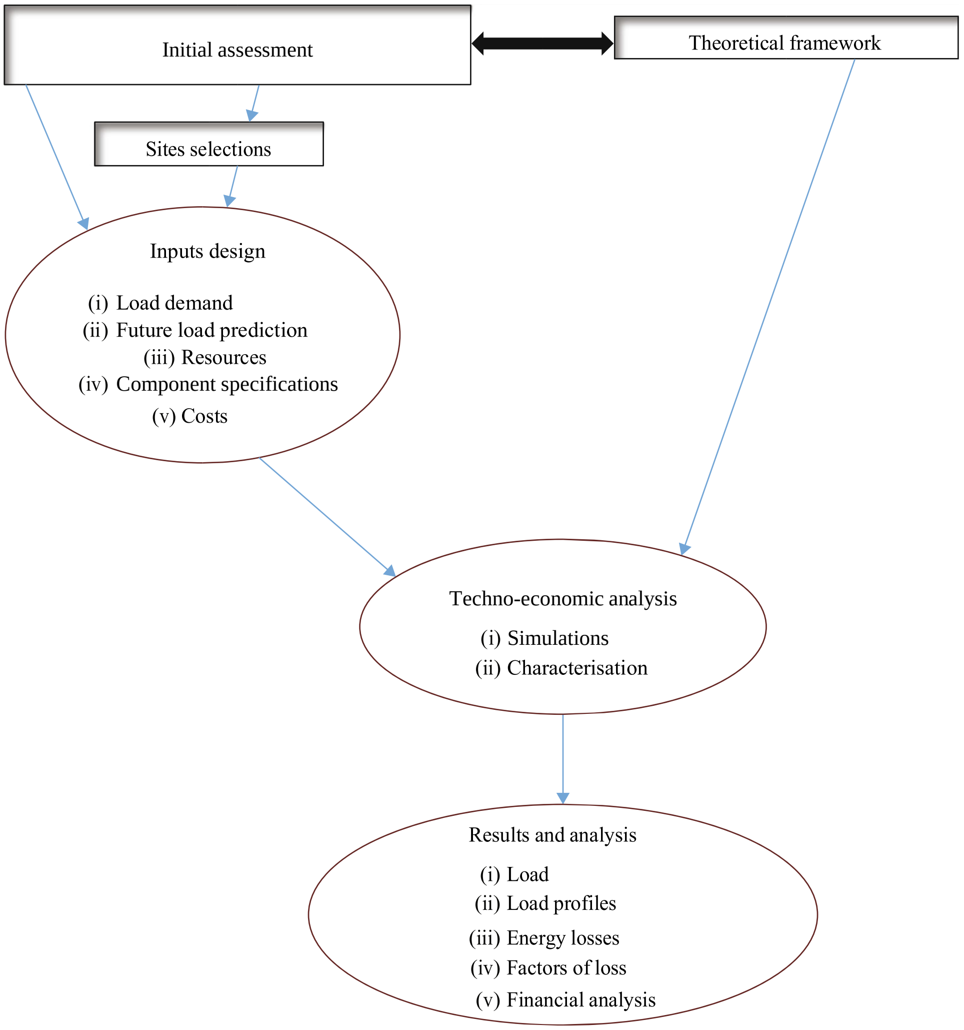


Figure 2: Study framework.

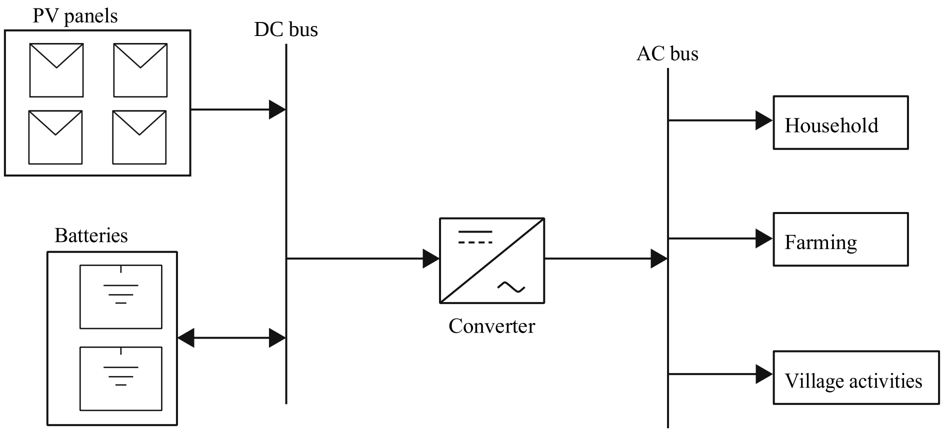


Figure 3: Solar PV minigrid design.

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 64Ah are used when an off-grid case is considered. Their maximum power output is 92.5 kWh at the voltage of 51.8V, and a maximum charge of 58AMPs 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.

2.5 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 3,997,214.80Wh/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 0.5kWh/m^2/day while at Kageyo, the plant generated the energy at a minimum threshold sunshine intensity of 1.5kWh/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 370Wp solar panels were used, while at the Kageyo site, the Eco Green Energy EGE 156-M-60 270Wp solar panels were used. One may note that the panel used at Gishuro and Gashanga bear a higher power rating 370Wp 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 3.8kWh/m^2/day and 4.2kWh/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 5.1kWh/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					(b) Gashanga					(c) Kageyo				
		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)
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.

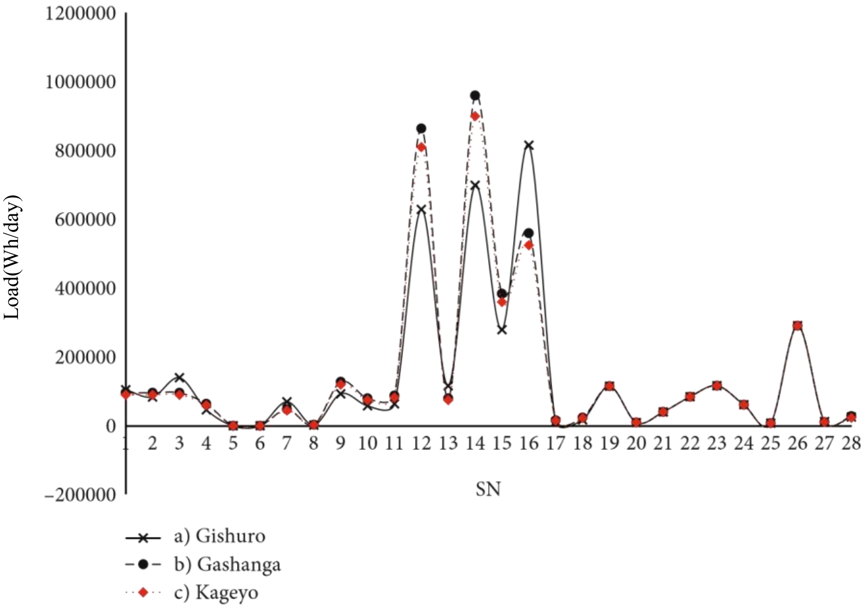


Figure 4: Energy load for different pieces of equipment.

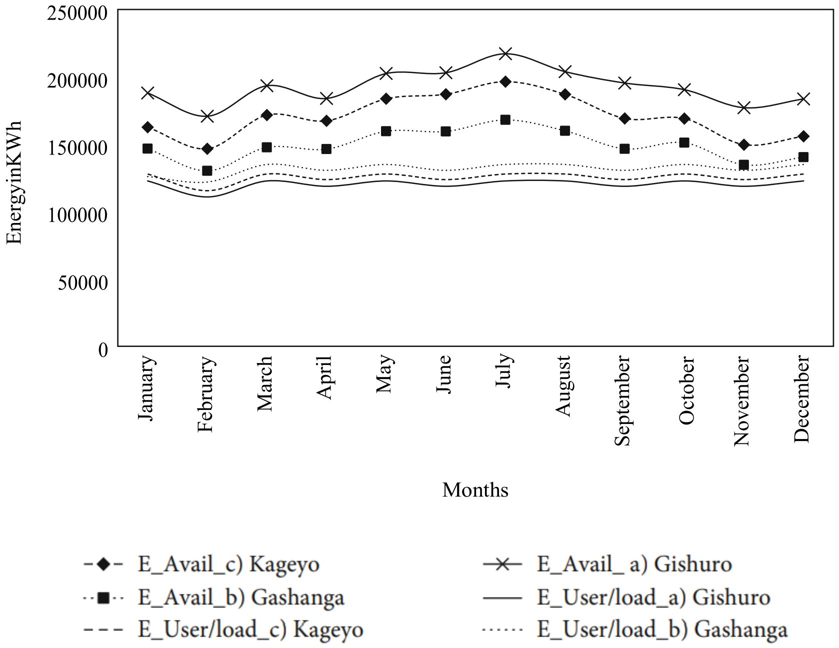
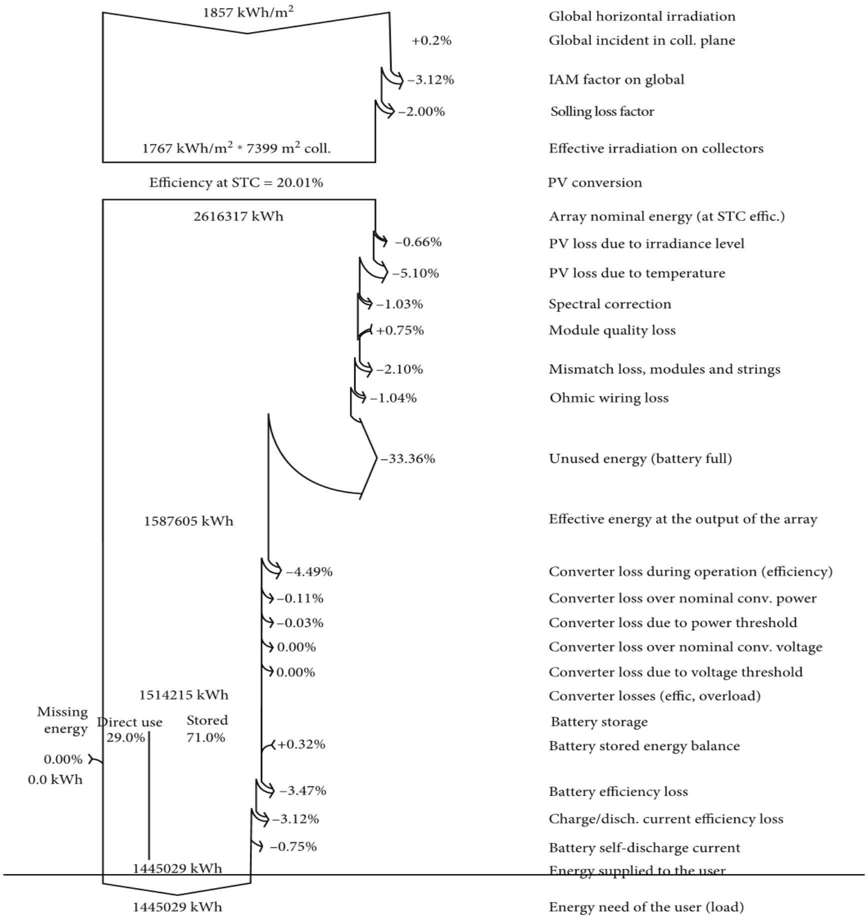


Figure 5: Temporal variation of solar energy and electrical energy requirement.

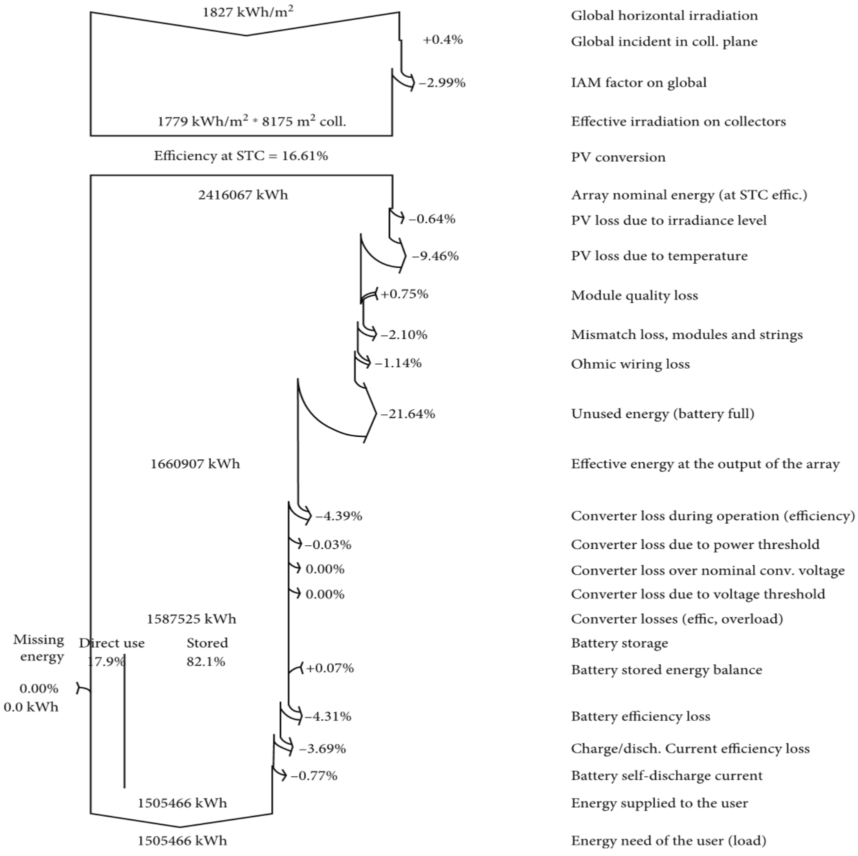
panels, hence impeding the panels' conversion efficiency. A portion of solar energy gets lost during the heating process. For example, much of the energy loss,9.46%, was associated with the panels' heating at one of the plants' sites (Gashanga) as can be seen from Figure 6(b).

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

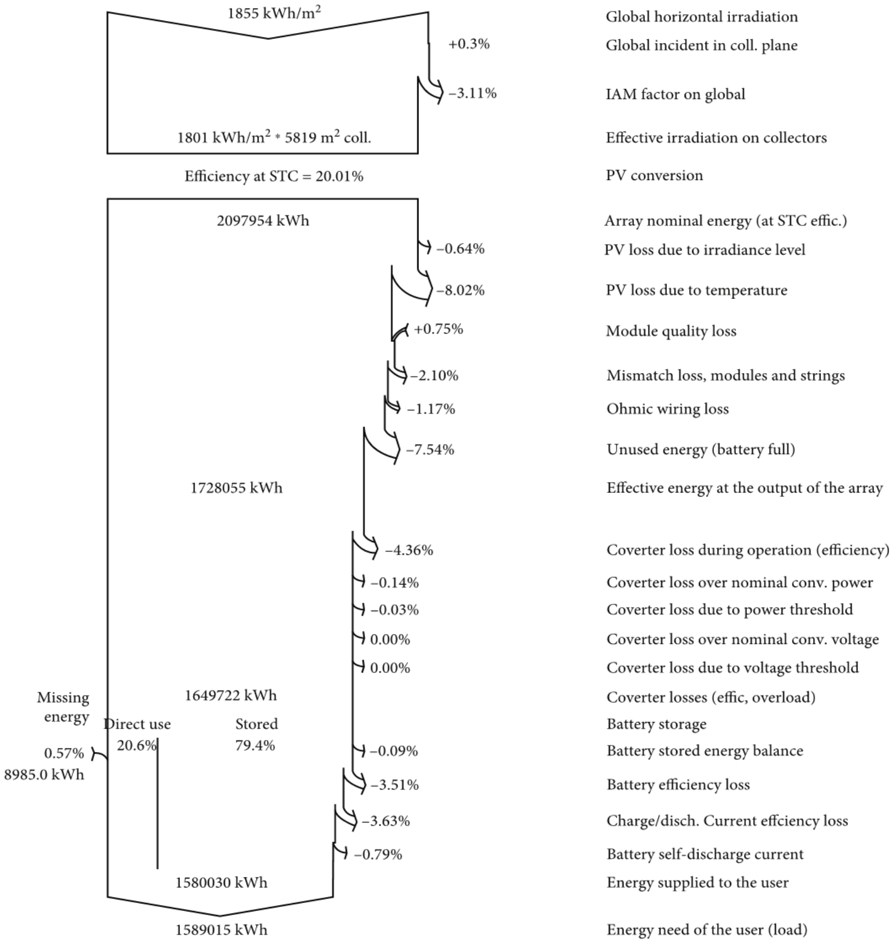

1857 kWh/m²
Global horizontal irradiation
+0.2%
Global incident in coll. plane
−3.12%
IAM factor on global
−2.00%
Solling loss factor
1767 kWh/m² * 7399 m² coll.
Effective irradiation on collectors
Efficiency at STC = 20.01%
PV conversion
2616317 kWh
Array nominal energy (at STC effic.)
−0.66%
PV loss due to irradiance level
−5.10%
PV loss due to temperature
−1.03%
Spectral correction
+0.75%
Module quality loss
−2.10%
Mismatch loss, modules and strings
−1.04%
Ohmic wiring loss
−33.36%
Unused energy (battery full)
1587605 kWh
Effective energy at the output of the array
−4.49%
Converter loss during operation (efficiency)
−0.11%
Converter loss over nominal conv. power
−0.03%
Converter loss due to power threshold
0.00%
Converter loss over nominal conv. voltage
0.00%
Converter loss due to voltage threshold
1514215 kWh
Converter losses (effic, overload)
Missing energy
Direct use 29.0%
Stored 71.0%
Battery storage
+0.32%
Battery stored energy balance
0.00%
0.0 kWh
−3.47%
Battery efficiency loss
−3.12%
Charge/disch. current efficiency loss
−0.75%
Battery self-discharge current
1445029 kWh
Energy supplied to the user
1445029 kWh
Energy need of the user (load)

(a)


1827 kWh/m²
Global horizontal irradiation
+0.4%
Global incident in coll. plane
−2.99%
IAM factor on global
1779 kWh/m² * 8175 m² coll.
Effective irradiation on collectors
Efficiency at STC = 16.61%
PV conversion
2416067 kWh
Array nominal energy (at STC effic.)
−0.64%
PV loss due to irradiance level
−9.46%
PV loss due to temperature
+0.75%
Module quality loss
−2.10%
Mismatch loss, modules and strings
−1.14%
Ohmic wiring loss
−21.64%
Unused energy (battery full)
1660907 kWh
Effective energy at the output of the array
−4.39%
Converter loss during operation (efficiency)
−0.03%
Converter loss due to power threshold
0.00%
Converter loss over nominal conv. voltage
0.00%
Converter loss due to voltage threshold
1587525 kWh
Converter losses (effic, overload)
Missing energy
Direct use 17.9%
Stored 82.1%
Battery storage
+0.07%
Battery stored energy balance
0.00%
0.0 kWh
−4.31%
Battery efficiency loss
−3.69%
Charge/disch. Current efficiency loss
−0.77%
Battery self-discharge current
1505466 kWh
Energy supplied to the user
1505466 kWh
Energy need of the user (load)

(b)

Figure 6: Continued.



(c)

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

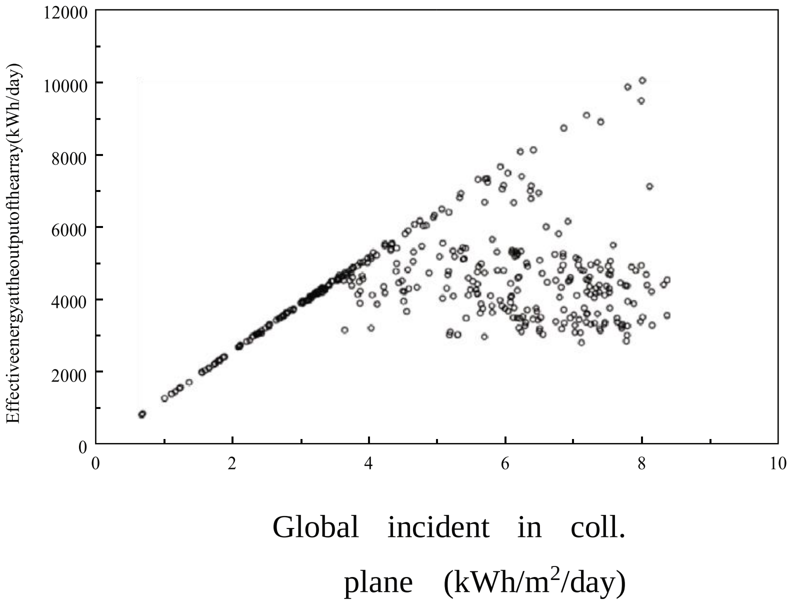
losses can arise from the installation, maintenance, operating conditions, and ambient conditions. The reduction of radiations reaching the solar cells due to changes in incidence angle (IAM factor on global), losses due to solar spectrum variation, losses due to variation irradiance levels, and soiling 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.

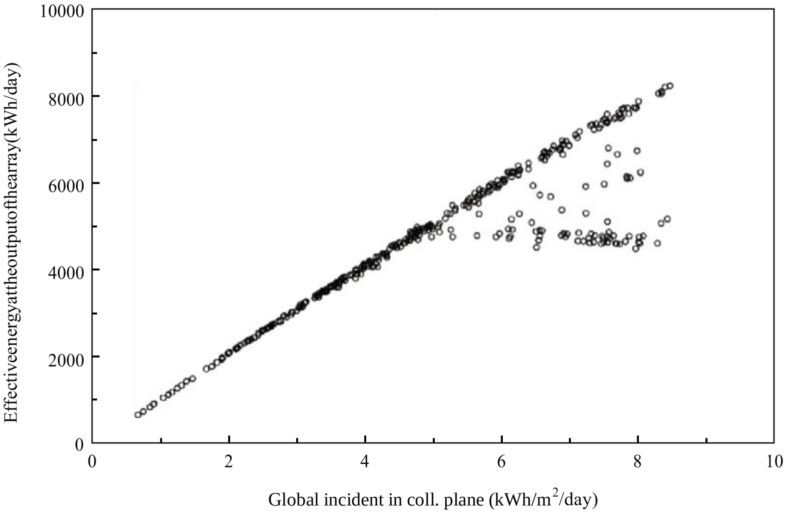
4.2. Economic Analysis. The preliminary financial analysis summarized in Table 3 shows that on average, the designed PV plants can cost from 2,338,823 EUR up to 4,322,260 EUR. These amounts may look huge, but noting that they will be used to supply energy for a village with more than 300 households powering 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.

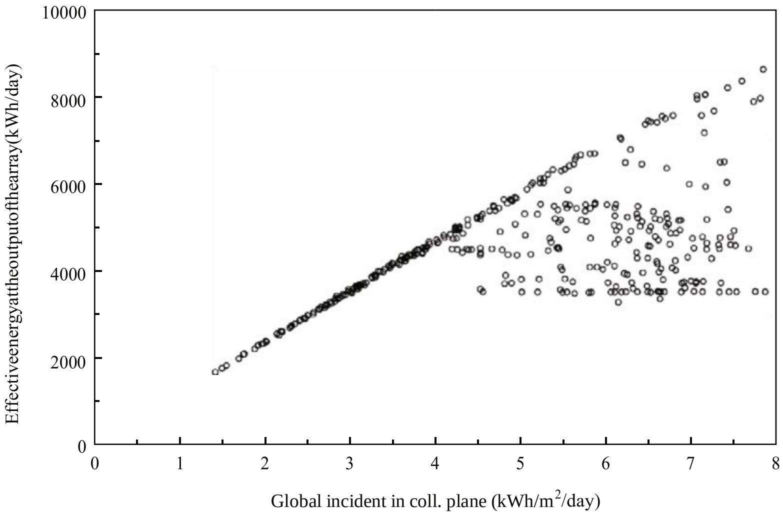
4.3. Challenges and Opportunities of Photovoltaic Minigrid Systems in Rwanda. The biggest challenge, as our results indicate, is the need for relatively large initial investments and running costs in the initial stages of the PV plants' operation. In addition to significant upfront capital costs, it 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.

2.6 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 4MWh/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.

2.7 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.

2.8 Conflicts of Interest

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

2.9 References

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3. SECTION 3: A TECHNO-ECONOMICAL CHARACTERIZATION OF SOLAR PV POWER GENERATION IN RWANDA: THE ROLE OF SUBSIDIES AND INCENTIVES.

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3.1 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

3.2 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] supports 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.

3.3 Methodology

3.1.1. *Overall study procedure*

Error! Reference source not found. 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 Figure 3 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.

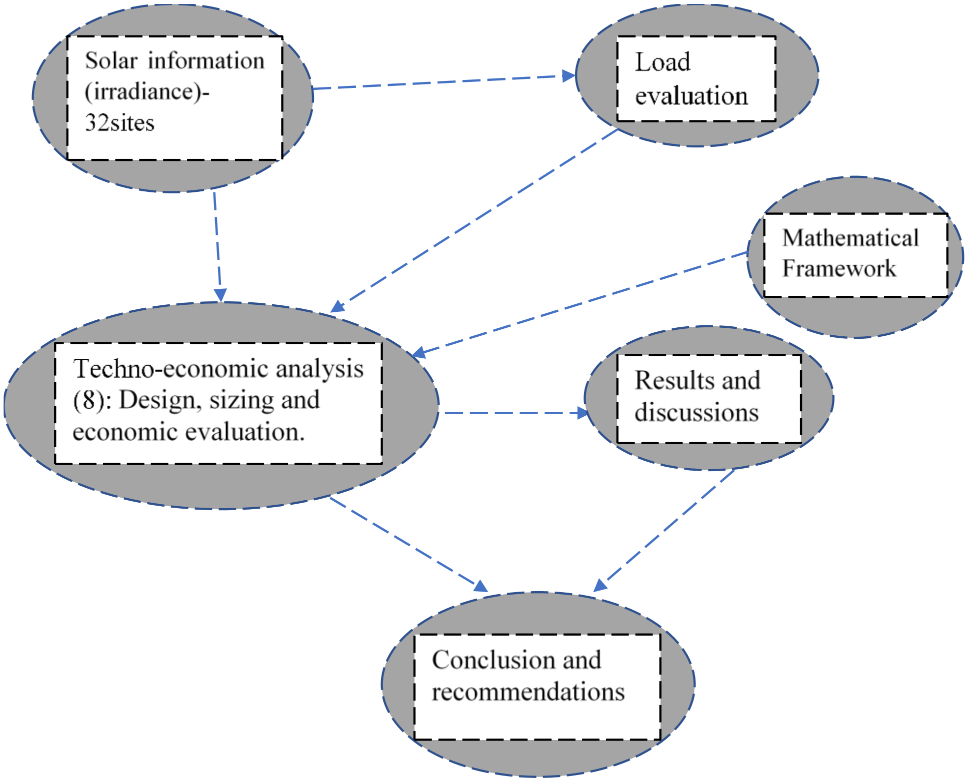


Figure 2: Analysis Framework

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 Figure 3. 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.

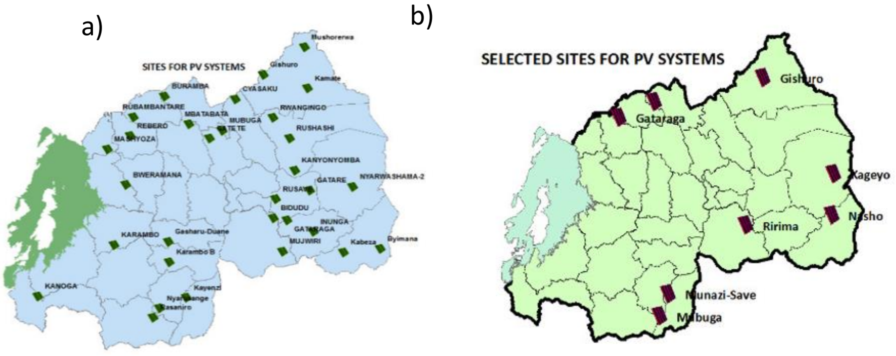


Figure 3: a) Sites at Which a Preliminary-physical Study was done and b) Sites Selected for Detailed Techno-economic Study on Solar PV Plants

3.1.2. 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 $\mathrm{NPC_s}$ of all system components using Eq. (10), where k is one of the considered components.

$$\mathrm{NPC} = \sum_{\mathrm{k=PV.Bater\_storage,Inv}} \mathrm{NPC_k} \qquad (10)$$

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. (11).

$$\mathrm{NPC_k} = \mathrm{IC_k} + \mathrm{RC_k} + \mathrm{OMC_k} - \mathrm{SC_k} \qquad (11)$$

In Eq. (11) $\mathrm{IC_k}$ stands for the sum of initial costs for the component k, $\mathrm{RC_k}$is the sum of replacement cost for a component k; $\mathrm{OMC_k}$ is the sum of operation and maintenance for the item k while $\mathrm{SC_k}$ 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, $\mathrm{IPR_k}$, and the number of used items of type k, $\mathrm{N_k}$ as per Eq. (12).

$$\mathrm{IC_k = N_k . IPR_k} \tag{12}$$

The total replacement cost for given components $\mathrm{RC_k}$ is determined by Eq. (13).

$$\mathrm{RC_k = N_k . DF(d_r, T_k) . RPR_k} \tag{13}$$

Where DF is the discount factor, $\mathrm{d_r}$ is the discount rate, $\mathrm{RPR_k}$ is the price for the replacement for item k and $\mathrm{T_k}$ 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, $\mathrm{OMC_k}$, over 25 years can be found by using the Eq. (14).

$$\mathrm{OMC_k = N_k . \sum_{y=1}^{25} DF(d_r, y) . OMPR_k} \tag{14}$$

In Eq. (14), $\mathrm{OMPR_k}$ stands for the cost of operation and maintenance for a given component k.

The salvage value of the plants' components, $\mathrm{SC_k}$, is determined as per Eq. (15) where $\mathrm{T_k}$, rem is its remaining life for a particular item k.

$$\mathrm{SC_k = RC_k . \left(\frac{T_k, rem}{T_k}\right)} \tag{15}$$

The remaining lifetime for the components, k, depends on both the lifetime of that component and the project lifetime, see Eq. (16), $\mathrm{T_{Proj}}$ being the project lifetime.

$$\mathrm{T_k . rem = T_k - \left[T_{Proj} - T_k . INT\left(\frac{T_{Proj}}{T_k}\right)\right]} \tag{16}$$

The discount factor used in Eqs. (13) and (14) is calculated using Eq. (17).

$$\mathrm{DF(d_r, y) = \frac{1}{(1 + d_r)^y}} \tag{17}$$

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 ($\mathrm{C_{tot,ann}}$) divided by the system's total usable yearly electricity output,$\mathrm{E_{gen}}$, see Eq. (18).

$$\mathrm{LCOE} = \frac{\mathrm{C_{tot,ann}}}{\mathrm{E_{gen}}} \tag{18}$$

The yearly cost of the plant is determined from Eq. (19) based on the capital recovery factor, (CRF) and the total net present cost (TNPC) for the plant system.

$$\mathrm{C_{tot,ann}} = \mathrm{CRF}\left(\mathrm{d_r}, \mathrm{T_{proj}}\right)\mathrm{TNPC} \tag{19}$$

Where the capital recovery factor is calculated using Eq. (20).

$$\mathrm{CRF}\left(\mathrm{d_r}, \mathrm{T_{porj}}\right) = \frac{\mathrm{d_r}.\,(1+\mathrm{d_r})^{\mathrm{T_{proj}}}}{(1+\mathrm{d_r})^{\mathrm{p}} - 1} \tag{20}$$

In Eq. (20), the capacity recovery factor is dependent on the discount rate, which in turn is calculated from Eq. (21).

$$\mathrm{d_r} = \frac{\mathrm{d_n} - \mathrm{f_r}}{1 + \mathrm{f_r}} \tag{21}$$

Where dn is the nominal discount rate while $\mathrm{f_r}$ is the inflation rate.

For solar panels, the power output, efficiency, and cost are modelled by Eq. (22) through Eq. (26). The power output is determined by Eq. (22)

$$\mathrm{P_{PV,o}}(\mathrm{t}) = \mathrm{P_{PV,n}}..\,\mathrm{F_{PV}}..\left(\frac{\lambda(\mathrm{t})}{\lambda_{\mathrm{STC}}}\right).\left[1 + \beta_{\mathrm{t}}.\left(\mathrm{T_C}(\mathrm{t}) - \mathrm{T_{c,STC}}\right)\right] \tag{22}$$

Here, $\mathrm{P_{PV,o}}$ stands for power output, $\mathrm{P_{PV,n}}$is the nominal power, $\mathrm{F_{PV}}$ 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 $\mathrm{T_{c,STC}} = 25^{0}\mathrm{C}$, and speed of wind = 0 m/s. $\mathrm{T_C}$ is the temperature of the solar cell and β_{t} is the temperature coefficient.

The efficiency of the PV module is determined by Eq. (23) where η_{STC} is the module efficiency under standard operating conditions.

$$\eta_{\mathrm{PV}}(\mathrm{t}) = \eta_{\mathrm{STC}}.\left[1 + \beta_{\mathrm{P}}.\left(\mathrm{T_C}(\mathrm{t}) - \mathrm{T_{c,STC}}\right)\right] \tag{23}$$

The efficiency of the PV module under standard η_{STC} conditions can be calculated from Eq. (24). In Eq. (24), $\mathrm{A_{PV}}$ represents the surface area of the PV module.

$$\eta_{\mathrm{STC}} = \frac{\mathrm{P_{PV,n}}}{\mathrm{A_{PV}}.\,\lambda_{\mathrm{STC}}} \tag{24}$$

The temperature of the solar cell is determined by Eq. (25). 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 $0.8kW/m^2$.

$$T_C(t) = T_a(t) + \lambda(t).\left[\frac{T_{c,NOCT} - T_{a,NOCT}}{\lambda_{NOCT}}\right] \tag{25}$$

The cost estimation (NPV_{PV}) of PV panels is calculated over the plant's lifetime by Eq. (26).

$$NPV_{PV} = P_{PV,n}\left[IC_{PV} + OMC_{PV} = IPR_{PV} + \sum_{y=1}^{25}\frac{OMPR_{PV}}{(1 + d_r)^y}\right] \tag{26}$$

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. (27), (28), and Eq. (29), respectively.

$$E_{BES} = \frac{E_{load,d}.\,DA}{\eta_{INV}.\,\eta_{BES}.\,DOD} \tag{27}$$

Eq. (27) 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.

$$E_{BES,ch}(t) = E_{BES}(t - 1).\,(1 - \mu) + \eta_{BES}.\left[E_{gen}(t)\eta_{INV} - \frac{E_{load}(t)}{\eta_{INV}}\right] \tag{28}$$

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

$$\mathrm{E_{BES,disch}(t) = E_{BES}(t-1).(1-\mu) + \left[\frac{E_{load}(t)}{\eta_{INV}} - E_{gen}(t).\eta_{INV}\right] / \eta_{BES}} \tag{29}$$

In Eq. (29), $\mathrm{E_{BES,disch}}$ is the energy discharged from the battery storage system.

$$\mathrm{SOC_{BES}(t) = \frac{E_{BES,st}(t)}{C_{BES}}} \tag{30}$$

In Eq. (30), the state of charge of a battery equals the energy stored in the battery, $\mathrm{E_{BES,st}}$, divided by the storage capacity available, $\mathrm{C_{BES}}$. It should remain bound between the maximum and minimum acceptable values namely $\mathrm{SOC_{max}}$ and $\mathrm{SOC_{min}}$, Eq. (31).

$$\mathrm{SOC_{min} \leq SOC_{BES}(t) \leq SOC_{max}} \tag{31}$$

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. (32).

$$\mathrm{E_{BES,min} \leq SOC_{BES}(t) \leq E_{BES,max}} \tag{32}$$

The maximum energy storage one could expect can be calculated from Eq. (33).

$$\mathrm{E_{BES,max} = (1 - DOD).E_{BES}} \tag{33}$$

The cost estimate ($\mathrm{NPV_{BES}}$) of energy storage batteries is calculated over the plant's lifetime by Eq. (34) [27].

$$\begin{aligned}\mathrm{NPC_{BES}} &= \mathrm{N_{BES}.[IC_{BES} + RC_{BES} + OMC_{BES} - SC_{BES}]} \\ &= \mathrm{N_{BES}.\left[IPR_{BES} + \frac{RPR_{BES}}{(1+d_r)^{10}} + \sum_{y=1}^{25}\frac{OMP_{BES}}{(1+d_r)^{y}} - RC_{BES}.\left(\frac{T_{BES,rem}}{T_{BES}}\right)\right]}\end{aligned} \tag{34}$$

In Eq. (34), $\mathrm{N_{BES}}$, $\mathrm{IC_{BES}}$, $\mathrm{RC_{BES}}$, $\mathrm{OMC_{BES}}$ and $\mathrm{SC_{BES}}$ 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, $\mathrm{IPR_{BES}}$, $\mathrm{RPR_{BES}}$, $\mathrm{OMP_{BES}}$ stand initial price per battery, replacement price per battery, and operation and maintenance price per battery while $\mathrm{T_{BES}}$, $\mathrm{T_{BES,rem}}$ 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 Eq. (35) and Eq. (36) from ref [27], the NPC of the system converter and its power are computed.

$$\mathrm{P_{INV}(t) = \eta_{INV}.\left[P_{PV,o}(t) + P_{BES}(t)\right]} \tag{35}$$

The price of an inverter is obtained

$$\begin{aligned}\mathrm{NPC_{INV}} &= \mathrm{P_{INV}.\,[IC_{INV} + RC_{INV} + OMC_{INV} - SC_{INV}]} \\ &= \mathrm{P_{INV}.}\left[\mathrm{IPR_{INV}} + \frac{\mathrm{RPR_{INV}}}{(1+\mathrm{d_r})^{15}}\right. \\ &\left.+\sum_{y=1}^{25}\frac{\mathrm{OMP_{INV}}}{(1+\mathrm{d_r})^{y}} - \mathrm{RC_{BDC}}.\left(\frac{\mathrm{T_{INV,rem}}}{\mathrm{T_{INV}}}\right)\right]\end{aligned} \tag{36}$$

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

3.1.3. *Technical specifications and inputs*

Having collected the solar irradiation intensities at the selected sites presented in Figure 3 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 370Wp was used. The reference operating temperature was considered ambient, 25oC. For energy storage, the lithium-ion battery with a capacity of 252Ah 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 20oC. 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 252Ah
Technology	Si-Mono	Technology	Lithium-ion, NMC
Unit Nom. Power	370 Wp	Discharging min SOC	10.0 %
Temperature (Ref)	250C	Charging	0.95
Controller		Discharging	0.10
Universal controller		Nom. Voltage	51.8 V
Technology	MPPT converter	Temperature	Fixed at 20 0C
Temp. Coeff.	-5.0 mV/0C/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. load of more than 4000kWh/day.

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/m2/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 4000kWh/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 ^{0}	30.18 ^{0}	1831.4	3959	1322	3572	1410
Site (2) – Bugesera	-2.14 ^{0}	30.24 ^{0}	1850.3	4354	1400	3784	1535
Site (3) – Kayonza	-1.83 ^{0}	30.71 ^{0}	1826.7	4125	1413	3818	1455
Site (4) – Kirehe	-2.27 ^{0}	30.71 ^{0}	1816.2	3892	1314	3552	1375
Site (5) – Musanze	-1.54 ^{0}	29.51 ^{0}	1684.4	2278	746	2016	735
Site (6) – Burera	-1.45 ^{0}	29.71 ^{0}	1678.6	2701	826	2688	950
Site (7) – Nyaruguru	-2.70 ^{0}	29.56 ^{0}	1700.5	2476	870	2352	875
Site (8) – Gisagara	-2.62 ^{0}	29.85 ^{0}	1791.2	2127	728	1968	710

3.1.4. Results and Discussion

The study evaluated the energy requirements at eight different sites throughout the country presented in Figure 3. 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

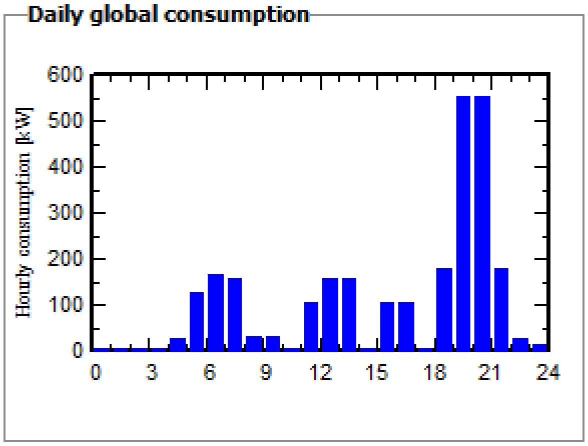
27	Farming activities		1	1	11160	1.00	11160	1	1	11160	1.00	11160
28	Irrigation system energy		1	1	28,100	1.00	28100	1	1	23,400	1.00	23400
	Total Load	3,959,014.9					4,353,465					24,564.90

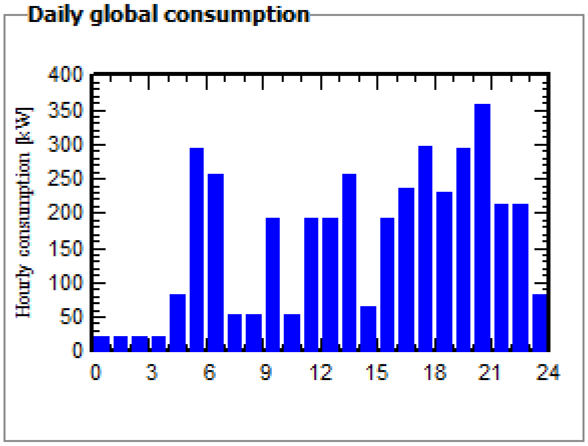
		d) SITE (4) – KIREHE					e) SITE (5) – MUSANZE					f) SITE (6) – BURERA				
SN	Equipment	Qty	Tot	Unit Power (Watt)	Time/ day (Hour)	Tot Energy/day (Wh/day)	Qty	Tot	Unit Power (Watt)	Time/day (Hr)	Tot Energy/ day (Wh/day)	Qty	Tot	Unit Power (Watt)	Time/day (Hr)	Total Energy/day(Wh/day)
	Lamps															
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
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

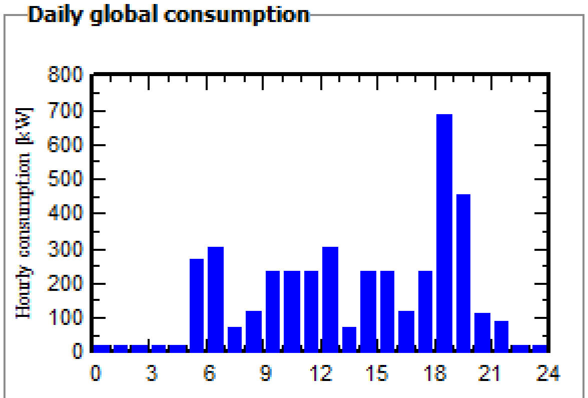
		g) SITE (7) - NYARUGURU					h) SITE (8) – GISAGARA				
SN	Equipment	Qty	Tot	Unit Power (Watt)	Time/ day (Hr)	Tot Energy/day (Wh/day)	Qty	Tot	Unit Power (Watt)	Time/day (Hr)	Tot Energy/ day (Wh/day)
	Lamps										
1	For inside	5	800	12	5	48000	5	640	12	5	38400
2	For outside	2	320	15	12	57600	2	256	15	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
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 hours of the day at four sites is captured in Figure 4. 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 PM 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 AM 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.







Kayonza site (Kageyo village)

Nyaruguru site (Ngarulira village)

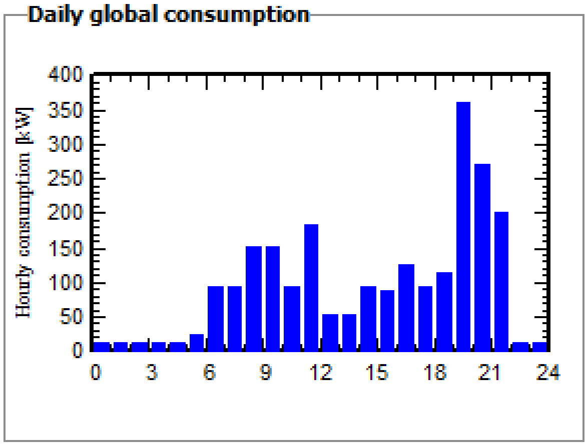


Figure 4: Daily Power Consumption

For the technical analysis of the PV plants' system power, a model has been developed for the energy load up to 4400kWh/day. The model was developed considering the average solar radiation intensity in Rwanda at 5kWh/m2/day and the peak period approximated at 5 hours/day. Moreover, the model was validated by the results of detailed studies conducted at the eight selected sites throughout the country, see Figure 3. Figure 5 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.

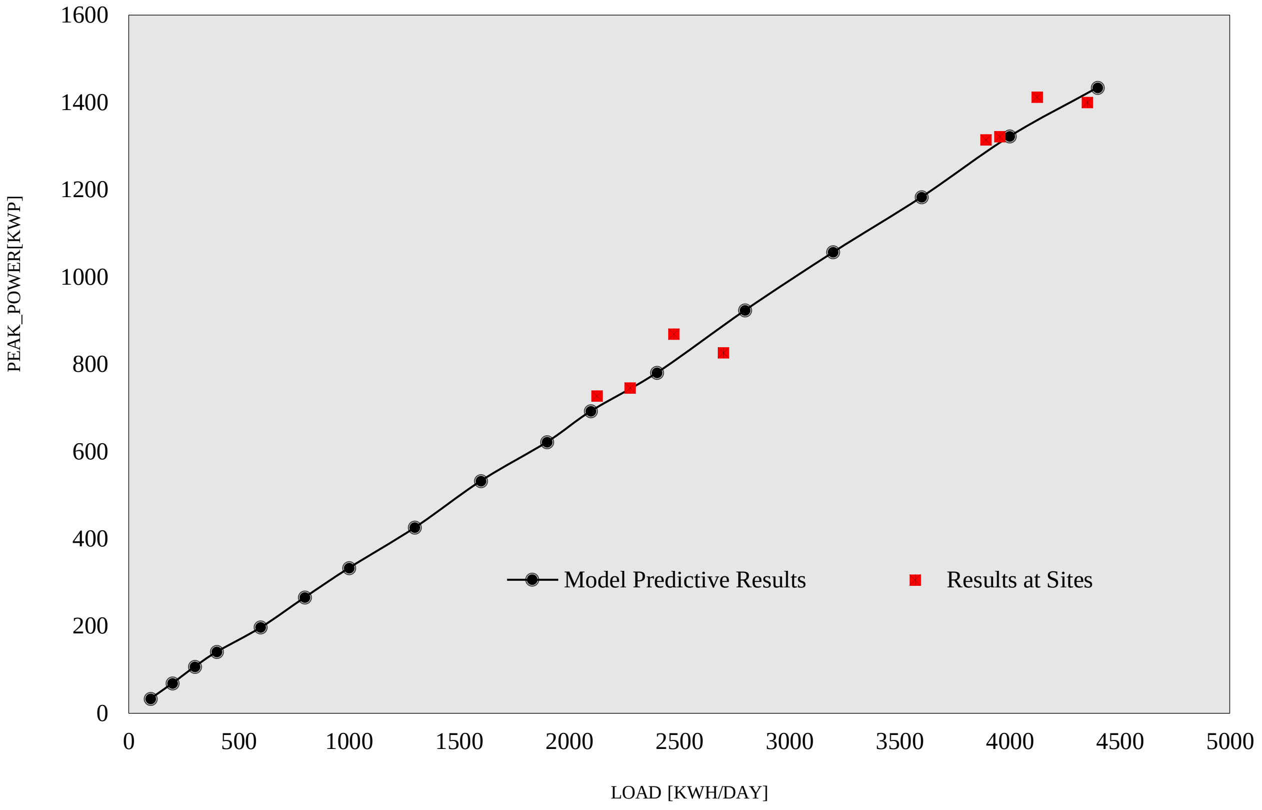


Figure 5: Peak Power of the PV Plants as vs Load

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. Figure 6 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

2000kWh/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 2000kWh 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.

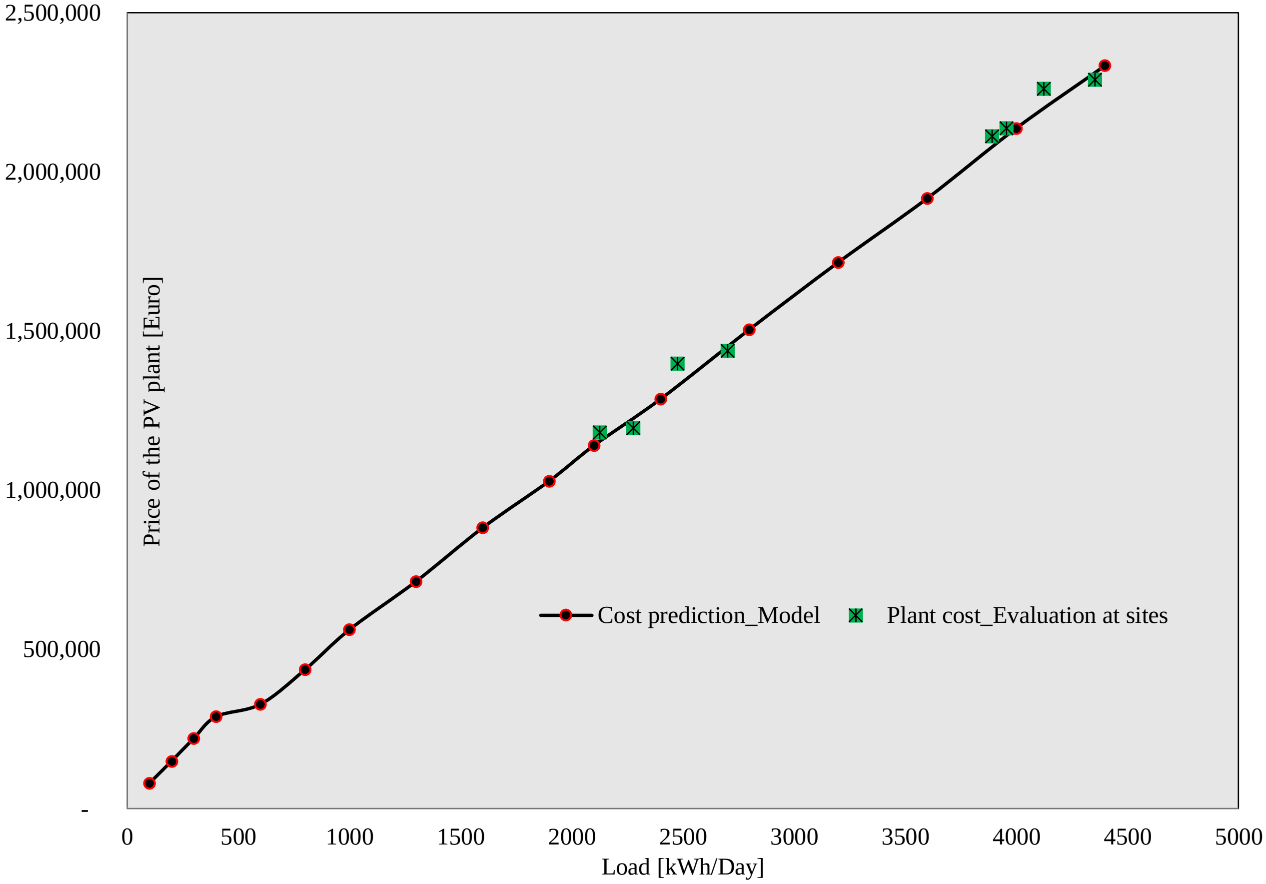


Figure 6: Installation Cost per PV Plant Size (Load)

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 Figure 7, 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.

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
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%			

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.

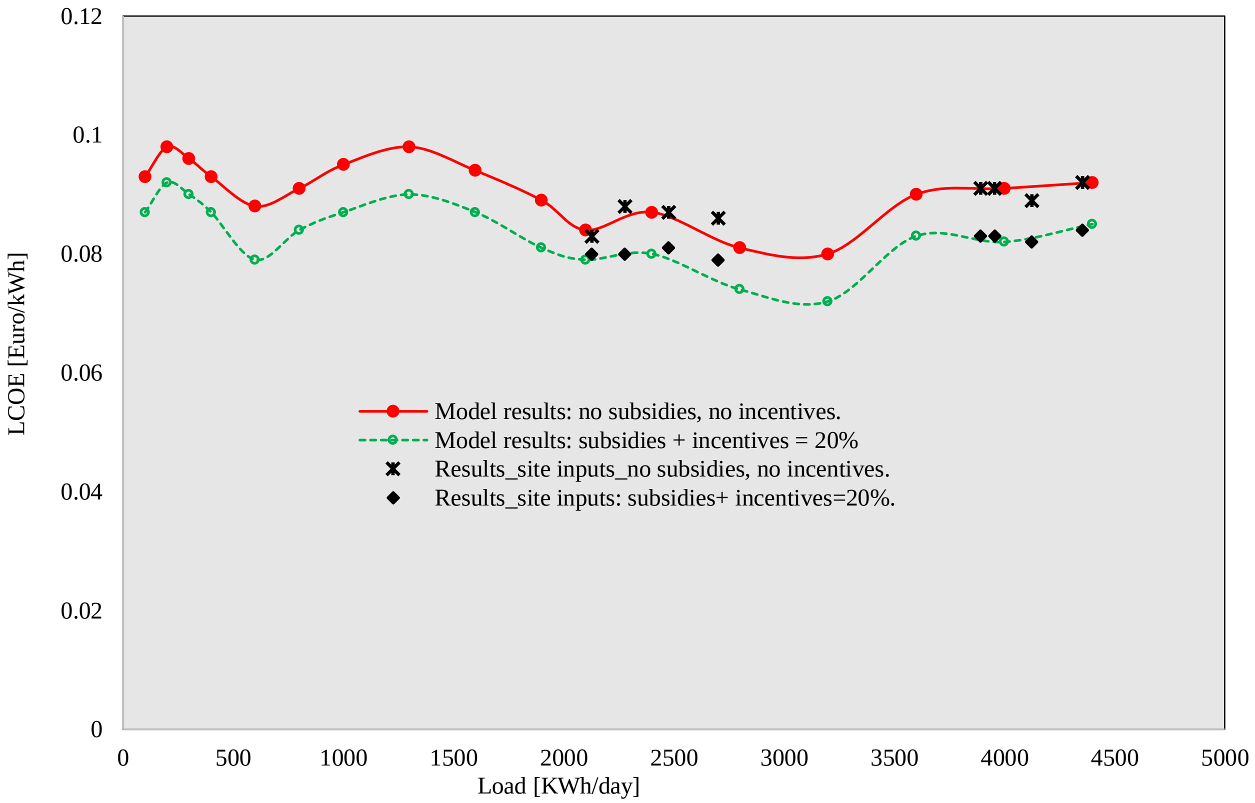


Figure 7: Levelised Cost of Energy

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.

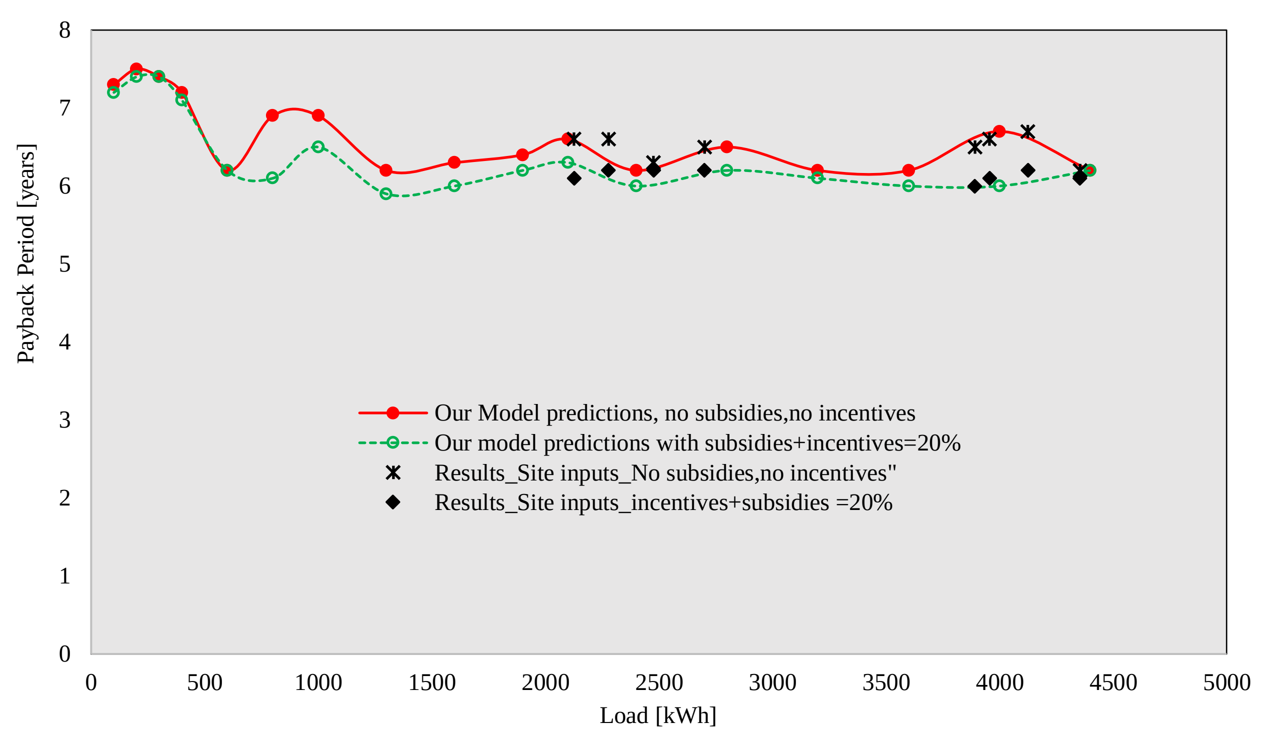


Figure 8: Payback Periods

Figure 8 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 years 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.

Table 5: Return on Investments (ROI)

S/N	Energy-Kwh/d	kWp	Total initial Cost (EUR)	NPV(EUR)	ROI
	100	34	79,810.50	570897.88	615.32
	200	69.6	149,456.00	980001.57	555.71
	300	107	221,112.00	1428242.78	545.94
	400	141	288,905.00	1987232.12	587.85
	600	197	327,878.00	2040848.76	522.44
	800	266	436,340.00	2747807.95	529.74
	1000	333	562,025.00	3,017,775.43	436.95
	1300	426	713,938.00	4,238,379.77	493.66
	1600	533	882,375.00	4,638,864.13	425.72
	1900	622	1,029,530.00	6,149,076.43	497.27
	2100	693	1,140,498.00	6,636,751.80	481.92
	2400	781	1,286,553.00	8,083,483.51	528.31
	2800	924	1,505,059.00	9,130,520.01	506.66
	3200	1051	1,716,104.00	11,137,957.69	549.03
	3600	1183	1,916,934.00	11,837,221.73	517.51
	4000	1322	2,136,968.00	13,307,660.35	522.74
	4400	1434	2,333,814.00	13,718,221.75	487.80

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.

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 15kWh per month and 0.180 Euro/kWh for consumers that uses more than 15kWh 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 1600kWh/day.

Table 6: Financial Benefit for Customers (end users/consumers)

				0-15 kWh/Month		>15 kWh/Month	
N	Energy-Kwh/d	kWp	LCOE [EURO]	REG Price [EURO]	Diff[%]	REG Price [EUR]	Diff [%]
	100	34	0.087	0.086	-1.163	0.180	51.667
	200	69.6	0.092	0.086	-6.977	0.180	48.889
	300	107	0.09	0.086	-4.651	0.180	50.000
	400	141	0.087	0.086	-1.163	0.180	51.667
	600	197	0.079	0.086	8.140	0.180	56.111
	800	266	0.084	0.086	2.326	0.180	53.333
	1000	333	0.087	0.086	-1.163	0.180	51.667
	1300	426	0.09	0.086	-4.651	0.180	50.000
	1600	533	0.087	0.086	-1.163	0.180	51.667
	1900	622	0.081	0.086	5.814	0.180	55.000
	2100	693	0.079	0.086	8.140	0.180	56.111
	2400	781	0.08	0.086	6.977	0.180	55.556
	2800	924	0.074	0.086	13.953	0.180	58.889
	3200	1051	0.072	0.086	16.279	0.180	60.000
	3600	1183	0.083	0.086	3.488	0.180	53.889
	4000	1322	0.082	0.086	4.651	0.180	54.444
	4400	1434	0.085	0.086	1.163	0.180	52.778
	3956	1322	0.083	0.086	3.488	0.180	53.889
	4354	1400	0.084	0.086	2.326	0.180	53.333
	2278	746	0.080	0.086	6.977	0.180	55.556
	2476	870	0.081	0.086	5.814	0.180	55.000
	4125	1413	0.082	0.086	4.651	0.180	54.444
	3892	1314	0.083	0.086	3.488	0.180	53.889
	2127	728	0.080	0.086	6.977	0.180	55.556
	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 15KWh/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 8.927MW 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 276.068MW. 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.

3.4. Conclusion and recommendations

This study aimed to characterize 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 8.927MW 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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Conception and design of the study:; acquisition of data:; analysis and/or interpretation of data:; drafting the manuscript: M. Kayitare; revising the manuscript critically for important intellectual content. All authors reviewed the results and approved the final version of the manuscript

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.

Conflict of interest: The authors declare that they know of no conflict of interest associated with the publication of this manuscript.

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4. SECTION 4: THE DESIGN AND FINANCIAL VIABILITY OF SOLAR PV PLANTS IN RWANDA

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Abstract— Solar PV systems are believed vital to provide reliable and eco-friendly energy to remote villages. However, a lack of information on the load demands, lack of information on factors of energy loss, and scarcity of information on the potential financial benefits of PV plants in rural areas hinder the optimal development of PV plants and investments in PV plant development. This study addresses these issues by assessing the load requirements for electrification and farming activities in remote areas in Rwanda, identifying energy loss factors for PV plants, and estimating the financial gains from such systems. The study shows that despite factors such as temperature-induced energy losses, the regions have enough solar resources to meet the villages' load demands. The economic evaluation reveals that solar PV plants can be beneficial to investors, with the cost of energy dropping significantly and benefiting consumers.

Keywords— Stand-alone photovoltaic (SAPV plants), energy losses, Agrivoltaic, Optimal sizing, Solar Solar-energy Economy, Energy in Rwanda

4.1. Introduction

Due to population and economic growth, global energy consumption is anticipated to double by the middle of the century [1], [2]. According to the International Energy Agency (IEA) [5], more than 1.3 billion people in developing countries do not have access to electricity due to grid problems and other problems. Meanwhile, much more quickly than developed nations, emerging nations are increasing their energy use. To meet their energy needs, developing nations, the majority of which are in Sub-Saharan Africa, must significantly and quickly grow their installed producing capacity [13], [14], [56].

Rural areas, where the bulk of people in developing countries reside, continue to rely on non-renewable energy sources to meet their daily energy demands [6], [57]. For instance, the majority of people utilize wood for cooking and house heating, whereas paraffin is most frequently used for indoor lighting while the physical energy of animals and humans is used for agricultural tasks [15].

However, it is acknowledged that reliance on renewable energy sources is necessary to meet the aforementioned rising energy demands [58]. Solar PV systems are therefore considered to be a technologically, economically, and environmentally viable long-term solution to the rapidly increasing energy demand [59], [60], especially in emerging nations [8], like Rwanda. Firstly, solar radiation is a plentiful and accessible source of renewable energy [61]. Furthermore, PV components are now more affordable than they were thirty years ago. For example, solar panel prices have been falling year over year while their output has been rising by roughly 30% annually. In addition to that, there have been numerous research efforts to improve the PV system technologies [62], [63]. Thus, solar energy is currently less expensive than coal and the majority of other fuels [10].

Numerous measures have been taken to encourage the integration of renewable energy [43], and photovoltaic (PV) technology has emerged as one of the most promising REs globally [44], [45]. According to A. Goldthau [46], a systemic change towards more efficient resources necessitates a tactical plan in order to encourage investment in the construction of PV Plants. These facilities, however, require systematic assessment of solar energy resources available, identification of factors influencing the performance of PV systems as well as estimates of potential benefits of PV power plants. This information is lacking as no studies have been done on such topics in Rwanda. The lack of such information discourages investments in developing PV energy systems and may contribute to the low degree of private sector engagement. This study explores and quantifies the available solar resources, factors influencing the loss of energy during the energy production process by PV plants, and the potential financial benefit of the PV plants in Rwanda.

4.2. Methodology

5.3.1 Techno-economic analysis

Designing and sizing PV plants that can power both agriculture and homes was done by using the PVSyst software. Additionally, it is used to evaluate how well and sensitively the proposed PV plants respond to variables affecting energy losses. Data from several places around the country were gathered in different communities to ensure the correctness of the energy requirements. The sizing and analysis included the following solar PV plant components in the models of standalone solar plants: the PV panels, battery, and converter as may be seen in figure 9.

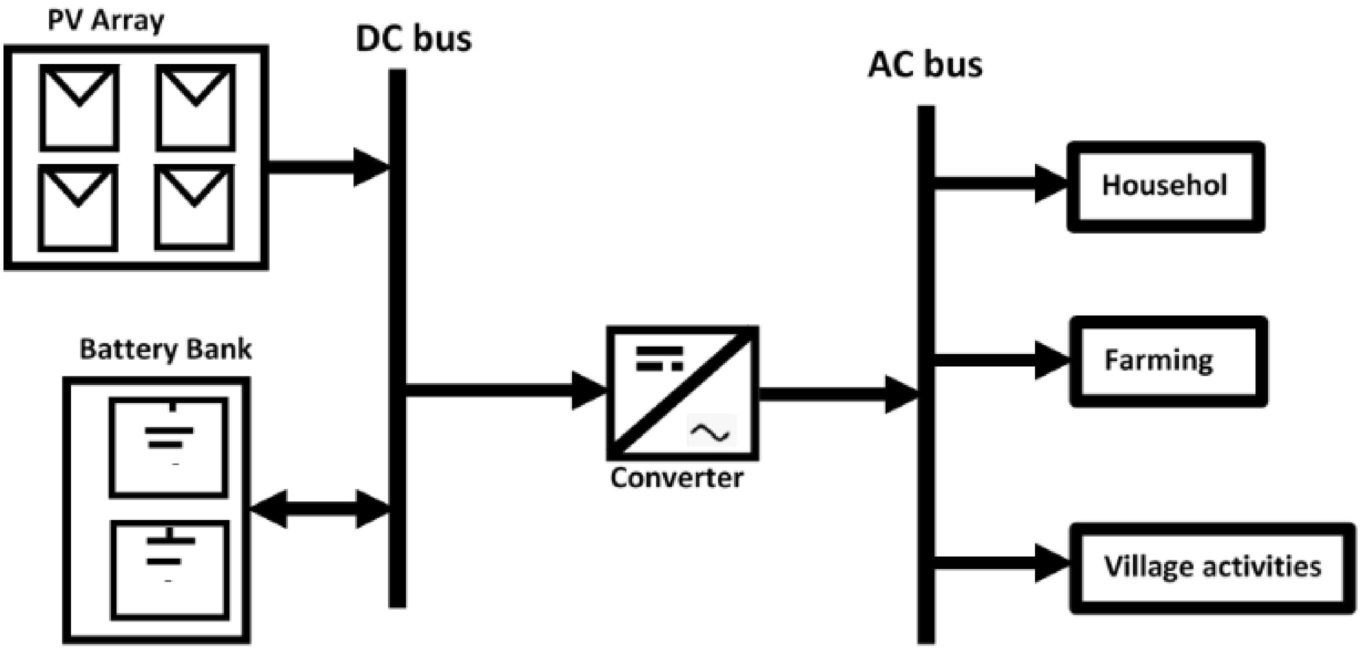


FIGURE 9: THE ARCHITECTURE OF THE DESIGNED SOLAR PV MINI-GRID.

A flat PV solar panel with an efficiency of 22.39 percent and a maximum power output of 370 W was used for this study. Working temperatures range between 25°C to -0.33%/oC, and temperature coefficients. The 92% DF from Equation (1) was taken into account. The PV system has an initial investment cost of $400 per panel, and the total number of panels needed for the plants varies depending on the load requirement. As plant size changed, so did the expense of running and maintaining the plants. A solar photovoltaic (PV) system can last for 25 years. The DC electricity is converted into AC power using a 98 percent efficient bidirectional converter.

The 1000 W universal controller with an MPPT converter was employed. It has a EUR 800 total capital cost and no replacement cost because a 25-year lifetime is anticipated. When an off-grid scenario is taken into account, LG Chem M4860P2S Lithium-ion batteries with a 64 Ah capacity were used for energy storage. 92.5 kWh of electricity may be generated at a nominal voltage of 51.8 V. 58 AMPs is the maximum charge. When the battery is entirely discharged, it is at least 40% charged. The battery has a 10-year life expectancy, but because it costs EUR 450 and EUR 900 to replace it, it would need to be changed twice over 25 years.

5.3.2 Theoretical Framework

The proposed PV plant was modeled by the equations obtained from the literature [27], [37] as follows. Its power is given by the equation (1).

$$\boldsymbol{P_{PV} = P_{STC}DF\left(\frac{IR}{IR_{STC}}\right)[1 + a_p(T_{mod} - T_{mod,STC})]} \quad (37)$$

here $\boldsymbol{P_{STC}}$ stands for PV power under standard conditions i.e. the solar irradiance $\boldsymbol{IR_{STC} = 1000 \, {}^{W}/_{m^2}}$ and $\boldsymbol{T_{mod,STC} = 25^0 C}$, and speed of wind = 0 m/s. In the formula, the solar radiation intensity is denoted by IR, while $\boldsymbol{IR_{STC}}$ denotes the solar irradiance at STC, and DF denotes the power loss caused by dust accumulation on solar panels. The temperature of the PV panels is denoted by $\boldsymbol{T_{mod}}$ and the power-temperature coefficient is denoted by $\boldsymbol{a_p}$. $\boldsymbol{T_{mod,STC}}$ is the temperature of the photovoltaic panel when subjected to standard test conditions.

The storage can be modeled by considering both the battery charge by the solar panels and the discharge from the battery to different electrical loads. Thus, at a given time the battery state can be estimated by the use of equation (4).

$$\boldsymbol{S_o}\mathrm{C}(t) = \boldsymbol{S_o}\mathrm{C}(0) + \boldsymbol{\eta_c \sum_{k=0}^{t} P_{CB}(k) + \eta_d \sum_{k=0}^{t} P_{DB}(k) s} \quad (38)$$

In equation *(4)* $\boldsymbol{S_o}$C(0) is the initial state of charge, $\boldsymbol{P_{DB}}$, and $\boldsymbol{P_{CB}}$ are the power discharge from the battery and charge to the battery respectively. $\boldsymbol{\eta_d}$ and $\boldsymbol{\eta_c}$ are efficiencies of the battery for discharging and charging processes respectively.

The load requirement for the off-grid PV plant the total load is determined from equation (9).

$$\mathbf{P}_{\boldsymbol{L}}(\boldsymbol{k}) = \mathbf{P}_{\boldsymbol{PV}}(\boldsymbol{k}) + \boldsymbol{P_{Grid}(k)} \quad (39)$$

The economic modeling of PV plants in this study was adapted from ref.[55]. It consists of the determination Net Present Cost (NPC) of the plant and the cost of energy based on the PV plant components. It is determined as the sum of NPCs of all system components using Equation (10), where k is one of the considered components.

$$\mathrm{NPC} = \sum_{\mathrm{k=PV.Bater\_storage,Inv}} \mathrm{NPC_k} \quad (40)$$

For each component, $\mathrm{NPC_k}$ is the sum of the initial capital, operation cost, maintenance cost, and cost replacement minus salvage costs.

4.3. Results and Discussion

The energy need for each site is shown in the study's evaluation of the energy needs at three distinct locations in Rwanda. The total load was calculated as a sum of the daily energy used by each piece of equipment. The load calculation took into account activities conducted at homes, on farms, in offices, and by small businesses. The SITE (3) - KAGEYO (IN Kayonza District) has the highest energy consumption among the three sites chosen (selected among 32) where the study was conducted, as shown in table (T), with an estimated 4.125 MWh per day to service 320 community houses. It is important to note that home appliances (fridges, air conditioners, washers, and resistive loads) consume a large portion of the energy used in villages.

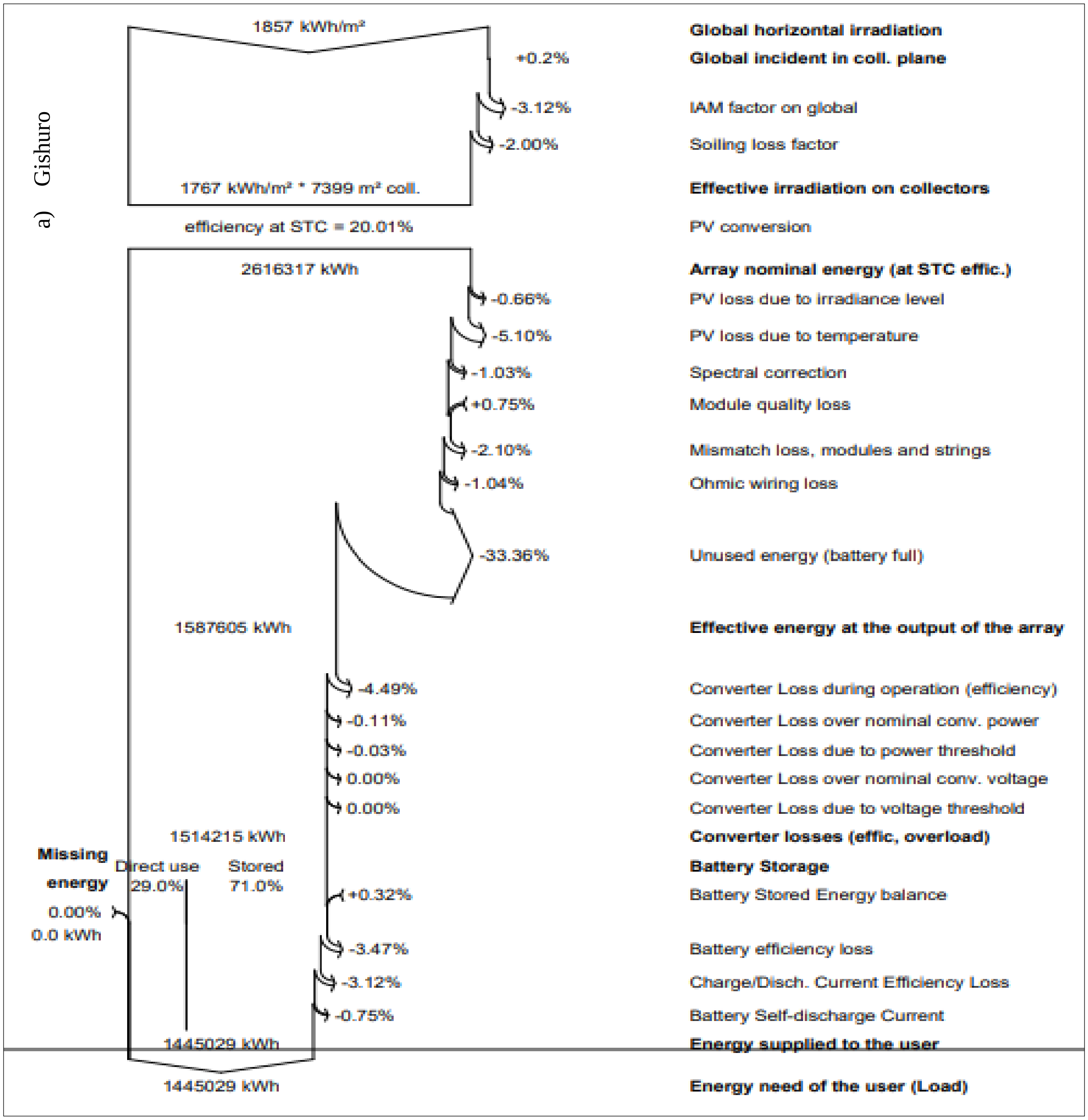
It is to be noted that this analysis included the anticipated increases in loads over the next five (5) years in accordance with the government of Rwanda's goals for sustainable development as outlined in National Strategies for Transformation (NST1).

Table 1. Load estimates for each site.

		SITE (1) – GISHURO					*SITE (2) – KIREHE*					*SITE (3) – KAGEYO*				
S/N	***Equipment's***	***Qty***	***Tot***	***Unit Power (Wat)***	***Time/ day (Hour)***	***Tot Energy/ day (Wh/day)***	***Qty***	***Tot***	***Unit Power (Watt)***	***Time /day (Hour)***	***Tot Energy/ day (Wh/day)***	***Qty***	***Tot***	***Unit Power (Watt)***	***Time/ day (Hour)***	***Total Energy/day(Wh/day)***
	Lamps															
1	For inside	6	1398	15	5	104850	5	1400	12	5	84000	5	1500	12	5	90000
2	For outside	2	466	18	10	83880	2	560	15	12	100800	2	600	15	10	90000
3	T.V Screen	1	233	100	6	139800	1	140	100	6	84000	1	150	100	6	90000
4	Radios	1	233	50	4	46600	1	140	50	4	28000	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	140	25	12	42000	1	150	25	12	45000
8	Phone Chargers	2	466	5	1	2330	2	560	5	1	2800	2	600	5	1	3000
9	Ceiling Fans	2	466	100	2	93200	2	560	100	2	112000	2	600	100	2	120000
10	Kettles	1	233	1000	0.25	58250	1	280	1000	0.25	70000	1	300	1000	0.25	75000
11	Irons	1	233	1100	0.25	64075	1	280	1100	0.25	77000	1	300	1100	0.25	82500
12	Fridges	1	233	150	18	629100	1	280	150	18	756000	1	300	150	18	810000
13	Microwaves	1	233	1000	0.5	116500	1	140	1000	0.5	70000	1	150	1000	0.5	75000
14	Cooking Stoves	2	466	3000	0.5	699000	2	560	3000	0.5	840000	2	600	3000	0.5	900000
15	Washing Machines	1	233	2400	0.5	279600	1	280	2400	0.5	336000	1	300	2400	0.5	360000
16	Air conditioners	1	233	3500	1	815500	1	140	3500	1	490000	1	150	3500	1	525000
17	Juicer Machine	1	233	200	0.25	11650	1	280	200	0.25	14000	1	300	200	0.25	15000
18	Blender Machine	1	233	300	0.25	17475	1	280	300	0.25	21000	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	37,080	3.15	116802	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	11730	1.00	11730	1	1	11160	1.00	11160
28	Irrigation system energy						1	1	25,750	1.00	25750	1	1	23,400	1.00	23400
	Total Load					**3,959,015**					**3,892,337**					**4,124,565**

Numerous factors have influences on energy loss as can be seen from **Error! Reference source not found.**. The figure shows that temperature is a key contributor to energy loss. In fact, when the intensity of the solar radiation is very high, the temperature of the panels rises noticeably and causes heating at the surface of the panels, which forces the panels to convert solar energy into electricity at a slower rate while losing another portion during the heating process. It may be clear that the unused energy that remains in the batteries should be counted on during the design. According to the findings, the plant built in Kageyo had the least amount of unused energy that remains in the battery was -7.54% while Gishuro had the most at -33.36%. This was due to the fact that some of the batteries have to always remain fully charged for backup purposes.



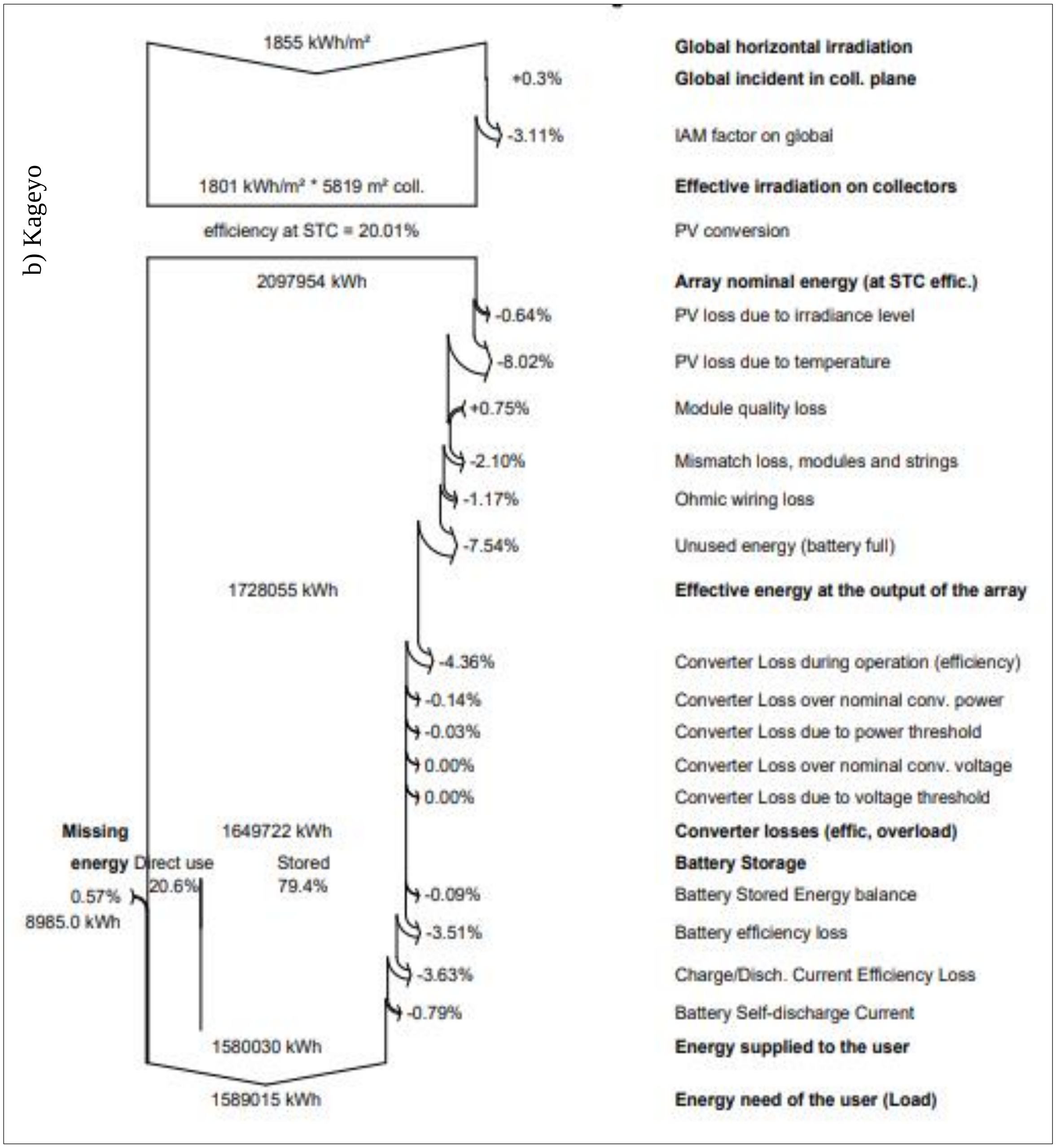


FIGURE 10. LOSS DIAGRAMS FOR A) PLANT AT GISHURO, AND B) PLANT AT KAGEYO.

The Leviterized Cost of Energy (LCOE), also known as the cost of useable energy at production is compared to the current market price of energy in the country to characterise the financial performance of the proposed PV plant models, see. As can be seen from the figure, the positive difference is obtained for large plants, 622kWp which means that small users can save up to 16.279%, and large consumers of energy who use more than 15kWh per month and are expected to get a reduction between 48.889% and 60%. This implies that various types of subsidies and incentives need to be considered for such plants to be more cost-effective for small consumers most of whom live in rural villages.

4.4. Conclusion and Recommendations

In this study, a thorough examination of the performance of PV plants to supply energy for remote areas in Rwanda was carried out. Such a study is significant as it provides information of importance for the development of optimal PV plants. The quantitative analysis of energy requirement, factors influencing energy loss in the PV systems, and the potential financial benefits were characterized. It is observed that such plants can only be of large financial benefit to big developers and users. Thus, further studies might need to examine the impacts of potential subsidies and incentives available for development on the financial viability of such PV plants. Also, future research could focus on analyzing the policy and regulatory framework for solar energy in rural areas, identifying challenges and opportunities for investment, and proposing policy recommendations to encourage and facilitate the development of solar energy in remote villages.

Table 6. FINANCIAL BENEFIT FOR CUSTOMERS (END USERS/CONSUMERS).

				0-15 kWh/Month		*>15 kWh/Month*	
S/N	***Energy-Kwh/d***	***kWp***	***LCOE [EUR]***	***REG Price [EUR]***	***Diff[%]***	***REG Price [EUR]***	***Diff [%]***
	100	34	0.087	0.086	-1.163	0.180	51.667
	200	69.6	0.092	0.086	-6.977	0.180	48.889
	300	107	0.09	0.086	-4.651	0.180	50.000
	400	141	0.087	0.086	-1.163	0.180	51.667
	600	197	0.079	0.086	8.140	0.180	56.111
	800	266	0.084	0.086	2.326	0.180	53.333
	1000	333	0.087	0.086	-1.163	0.180	51.667
	1300	426	0.09	0.086	-4.651	0.180	50.000
	1600	533	0.087	0.086	-1.163	0.180	51.667
	1900	622	0.081	0.086	5.814	0.180	55.000
	2100	693	0.079	0.086	8.140	0.180	56.111
	2400	781	0.08	0.086	6.977	0.180	55.556
	2800	924	0.074	0.086	13.953	0.180	58.889
	3200	1051	0.072	0.086	16.279	0.180	60.000
	3600	1183	0.083	0.086	3.488	0.180	53.889
	4000	1322	0.082	0.086	4.651	0.180	54.444
	4400	1434	0.085	0.086	1.163	0.180	52.778
	3956	1322	0.083	0.086	3.488	0.180	53.889
	4354	1400	0.084	0.086	2.326	0.180	53.333
	2278	746	0.080	0.086	6.977	0.180	55.556
	2476	870	0.081	0.086	5.814	0.180	55.000
	4125	1413	0.082	0.086	4.651	0.180	54.444
	3892	1314	0.083	0.086	3.488	0.180	53.889
	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

4.5. References

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5. SECTION 5. GENERAL CONCLUSION AND RECOMMENDATIONS

This thesis presents a comprehensive analysis of the design, characterization, and financial viability of photovoltaic (PV) mini-grid plants for rural electrification and modern farming in Rwanda. By integrating the findings from three different studies, it offers a multi-faceted understanding of the potential for solar energy to transform rural communities in Rwanda.

5.1. Design and Characterization of PV Mini-Grid Plants (Paper 1)

The first paper focused on designing optimally sized PV mini-grid plants for rural villages in Rwanda. Through an extensive assessment of solar energy potential and energy requirements, it was determined that model villages would need around 4 MWh/day. The energy demands were found to be relatively stable throughout the year. The PV plants, that could be developed based on the findings of this paper, could effectively meet the energy needs in off-grid areas. However, it was identified that energy losses, particularly due to the heating of solar panels, could impact the efficiency of these systems. Despite the high initial development costs, the investment in such energy systems was justified with a break-even point of approximately ten years and an expected cost reduction of about 29% over the plant's 25-year lifespan. This study underscored the need for further research to minimize energy losses and explore the impact of various incentives and subsidies to reduce the cost of PV energy, particularly in rural areas.

5.2. Techno-Economic Characterization of Solar PV Power Generation

The second study provided a techno-economic characterization of PV plants, emphasizing the role of subsidies and incentives in enhancing affordability, profitability, and penetration of solar PV energy. It was found that, despite increasing energy demands due to rising household numbers and farming mechanization, Rwanda's solar resources could support full electrification through PV plants. Subsidies and incentives were shown to significantly boost renewable energy integration and profitability, with a return on investment of 615.32% and an 8.927 MW increase in renewable energy share. However, the study highlighted the high costs associated with battery storage for standalone systems. Future research should investigate the techno-economic benefits of grid-connected solar PV plants and explore the potential of hybrid solar-hydro PV plants under Rwanda's specific conditions.

5.3. Financial Viability of Solar PV Plants

The third paper examined the financial viability of PV plants for supplying energy to remote areas in Rwanda. It is a more of a summarized analysis of the first and second papers findings. It provided crucial insights into the performance of PV systems, highlighting that significant economic benefits would primarily accrue to large developers and users. The paper recommended further investigation into the impact of subsidies and incentives on the financial viability of PV plants. Additionally, it suggested analyzing the policy and regulatory framework for solar energy in rural areas to identify challenges and opportunities for investment, proposing policy recommendations to encourage solar energy development in remote villages.

In summary, these papers collectively highlight the potential of PV mini-grid plants to enhance rural electrification and support modern farming in Rwanda. They also emphasize the critical role of subsidies, incentives, and policy frameworks in maximizing the financial viability and adoption of solar energy systems.

5.4. The socio-economic impacts

The social-economic impact of this study, although indirectly assessed through economic analysis, include several significant aspects:

> **Economic Development and Job Creation**: By evaluating the cost-effectiveness and financial feasibility of PV systems, this study can facilitate investment in renewable energy projects. Such investments can stimulate local economies through job creation in the installation, maintenance, and management of PV systems.
>
> **Energy Access and Equity**: The study focuses on detailed financial evaluations and designs which help in determining the affordability of PV systems for various socio-economic groups. Effective cost management and reduced energy costs can

enhance energy access for underserved communities, contributing to energy equity.

Community Financial Savings: The detailed cost analysis helps in identifying potential savings on energy expenditure. Lower energy costs can improve the financial well-being of households and small businesses, enabling them to allocate resources to other critical needs.

Long-Term Financial Stability: By analyzing long-term costs and savings, the study can demonstrate how PV systems provide a stable energy cost over time. This stability is crucial for long-term financial planning and economic resilience for both communities and individual households.

Informed Policy and Investment Decisions: The economic insights gained from this study can guide policymakers and investors in making informed decisions about funding and implementing PV projects. This can lead to more effective energy policies and targeted investments that support economic growth and social development.

5.5. Recommendations

Based on the findings from the three studies, the following recommendations are proposed:

5.5.1. Minimizing Energy Losses:

- Further research should focus on strategies to reduce energy losses in PV plants, particularly those caused by the heating of solar panels.

5.5.2. Enhancing Financial Viability:

- Future studies should investigate the impact of various national and international subsidies and incentives on the cost of PV energy. This could help identify mechanisms to make solar energy more affordable for rural communities.

- Considering the high costs of standalone PV systems due to battery storage, it is recommended to explore the techno-economic benefits of grid-connected PV plants. This approach could potentially reduce costs and improve the financial viability of solar projects.

5.5.3. Hybrid Energy Systems:

- Research should be conducted on the feasibility and profitability of hybrid solar-hydro PV plants. Such systems could leverage Rwanda's climatic and economic conditions to provide a more reliable and cost-effective energy solution.

5.5.4. Policy and Regulatory Framework:

- A thorough analysis of the existing policy and regulatory framework for solar energy in rural areas should be conducted. This would help identify barriers to investment and propose policy recommendations to facilitate the development of solar energy in remote villages.

5.5.5. Community and Stakeholder Engagement:

- Efforts should be made to raise awareness and educate rural communities about the benefits of solar energy. This includes providing training on the operation and maintenance of PV systems to ensure sustainability and local ownership of energy projects.
- Engaging with policymakers, stakeholders, and communities is crucial to developing supportive policies and incentives that encourage investment in solar energy projects.

5.5.6. Mechanized Farming Support:

- The design and optimization of PV plants should continue to account for the energy requirements of mechanized farming. This includes supporting the use of electric tractors and other farming equipment to enhance agricultural productivity and rural development.

By addressing these recommendations, it is possible to harness the full potential of solar PV energy to drive rural electrification and modern farming in Rwanda, contributing to sustainable development and improved livelihoods in rural communities.