UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

Project Title: "**Technical Assessment of Green PV mini-grids for Rural Electrification in Rwanda**".

Case Study RWISIRABO Village

Project no**: ACEESD/REE/21/09**

A Thesis submitted to the African Center of Excellence in Energy studies for sustainable development (ACE-ESD)

In partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN RENEWABLE ENERGY

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2021

Kigali-Rwanda

DECLARATION

I, the undersigned, declare that this Project proposal is my original work, and has not been presented for a degree at the University of Rwanda or any other universities. All sources of materials that will be used for the thesis work will have been fully acknowledged.

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APPROVAL

Date of Submission: **25th October 2021**

This Thesis proposal has been submitted for examination with my approval as a university advisor.

Dr. Dalson Athanase GACE

Thesis Advisor

Signature

DEDICATION

This work is truly dedicated to my beloved Partner Mrs. **Honorine MUTAZINDA**

ACKNOWLEDGMENTS

In everyday life, people get struggle to achieve the desired target. Keeping in mind that some enormous challenges and obstacles might hinder any achievement we have to fight endlessly.

Following the above, I would like to take this great opportunity to express my sincere appreciations to both my supervisor Dr. GACE Athanase Dalson, and co-supervisor Mr. Geoffrey GASORE for their precious guidance to reach this great step. Many thanks go to the entire ACEESD staff especially lecturers among others for their sacrifices to deliver knowledge to us especially during the period whereby the Covid-19 pandemic has stopped many activities including face-to-face teaching.

My profound appreciation goes to my partner for her grateful support during thesis writing. I cannot forget my relatives, workmates, and classmates for their encouragement towards my studies.

Thanks go to the Rwanda Energy Group and typically management of Energy Development Corporation Ltd for their support in getting key information related to the energy sector and the government projections in terms of electricity access.

"God Bless you all!"

ABSTRACT

Having access to clean energy is very essential for everyone's health, education, and social welfare enhancements. Most countries especially sub-Saharan Africa suffer from low electrification rates and with the majority of the population living in off-grid areas, whereby the productive uses do not have access to electricity to grow up. This fact doesn't allow the use of basic or modern technology among the population. In Rwanda, Photovoltaic microgrids are used to provide free renewable energy solutions following the National Electrification Plan (NEP) that has demarcated off-grid villages by the year 2024.

In the present Thesis, different components such as PV modules, inverter, charge controller, and Batteries have been sized, simulated, and optimized for the off-grid village namely Rwisirabo located in Kayonza District, eastern province of Rwanda. The designed power plant was considered to have fixed components and the tracking systems were put in my recommendations for future work. Principally AC load within the village was 158.29 kWh/day with a peak load of 21.6 kW, with COE $0.444/kWh was found as an optimum of the power plant. HOMER was chosen as the best simulating software in the present thesis. Electrical energy from the SPV power plant supplies power directly to the Ac load and the storage battery gets charged in any case there is excess energy produced and are discharged so that load remains connected to the power electricity. The load has been suggested for households, small businesses, secondary schools, health posts, police posts, community churches, and deferrable loads as water pumping. While designing and sizing of the microgrid, the simulation and optimization were carried out based on the daily consumption, weather parameters like solar irradiance and temperature, the economics of integrated system elements, and other parameters in which the total Net Present Cost and Levelized COE have to be minimized to select economically feasible and technically capable solar PV power plant. The data from design is used for simulation as input of HOMER software to figure out the total energy production per year.

Keywords: PV power plant; Modelling of SPV system; load estimation; solar photovoltaic; rural electrification, mini-grids

ABBREVIATIONS & ACRONYMS

ACEESD: African Center of Excellence in Energy for Sustainable Development

BE: Battery Efficiency

DoA: Days of Autonomy

DoD: Depth of Discharge

EC: Energy Categories

EDCL: Energy Development Corporation Limited

Endev: Energizing Development

EPD: Energy Private Developers

GMG: Green Mini-Grid

IEA: International Energy Agency

IED: Innovation Energie Development

MININFRA: Ministry of Infrastructures

NEP: National Electrification Plan

NEZ: Net Zero Emissions

OSC: Off-grid Solar Company

PSH: Peak Sun Hours

PV: Photo Voltaic

RE: Renewable Energy

REF: Renewable Energy Fund

REG: Rwanda Energy Group

RES: Rural Electrification Strategy

SHS: Solar Home Systems

SL: Solar Lighting

SPV: Solar Photo Voltaic

UR: University of Rwanda

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CHAPTER1. INTRODUCTION

1.0.Background

The population having access to electricity in Africa was highly increased up to 20 million connections between 2014 and 2018[1]. Therefore, the number of households with no access to electricity declined slowly to around 595 million in that period. However, according to the Africa Energy outlook 2019 by the IEA, the African sub-Saharan region's electrification rate was at only 45% in 2018. This shows that it remains very low compared with other regions all over the world [1].
In the year 2018 Africa counted only 50 Gigawatts of renewable energy capacity, frequently from hydro. Mini-grids and solar home systems are playing great importance to bring clean energy services and attract productive uses and employment to remote populations.

Rwanda's target is to reach universal access (100%) electricity access by the year 2024 (48% off-grid and 52% on-grid). Currently, the country counts only 62.3% of the total population having access to electricity with 46% to the main grid and **16.3% via off-grid**. Mini-grids contribute to only 3.5% and the rest is being electrified through solar home systems[2]. Following the above-stated figures; there is still a long journey to reach 100% access to electricity by 2024. Consequently, and in line with the above-mentioned off-grid electrification target, efforts need to be put in the development of mini-grids in line with the national electrification plan (NEP).

The solar irradiation in Rwanda is good enough whereby the peak sun time per day is expected to be 5 hours, even in the rainy seasons, and the average solar potential is 4.5 kWh/m^2/day [3]. Therefore, Rwanda has a great opportunity to shift towards clean energy technologies while ensuring power access to rural areas through solar green mini-grids.

1.1. Problem Statement

Having access to electricity is very important for every citizen's life. However, a great number of Africans especially in the Sub-Saharan regions are still living with no electricity and most of those people live in remote areas whereby the cost of central grid extension is very high. On the other hand, the people having access habitually rely on unreliable, polluting, and even costly diesel-powered generators.

Implementation of PV green mini-grid within African regions has been very slow, considering the growth of the development of solar energy in between the year 2010 and 2018, only about 4 Gigawatts from new solar power plants (PV) have been developed. Most of this capacity was developed in only sub-Saharan regions including Rwanda. One of the key threats/barriers that most countries face consists of limited capacity, no scale and competition, more transaction cost, and the alleged high risk of such projects [2].

According to the Rwanda Energy Group (REG), currently Rwanda counts 235.6MW of the installed capacity, and 62.3% of the population has access to electricity. Nevertheless, the electrification level mostly replicates grid-connected customers in the urban zones with insignificant coverage in rural villages. To date, only 16.3 % of the total households are connected to the off-grid while mini-grids contribute to only 3.5%. However, the country's target is to reach universal access by the year 2024 whereby 48% of the population will have access to the off-grid including such mini-grids. Unfortunately, Literature research related to the deployment of green mini-grids is still insignificant and needs more emphasis to contribute to the national target which requires to be achieved three (3) years ahead of now.

1.2. Research Objectives

1.2.1. Major Objective

The major objective of this research is to deeply conduct a feasibility study of PV green mini-grids about their contribution to rural electrification in Rwanda.

1.2.2. The Specific Objectives

This research is aiming at achieving the below specific objectives among others:

i. To gather information about potential areas and needs assessment of a given locality for green mini-grids solar development in Rwanda.
ii. To estimate the PV Plant capacity in terms of power output and storage among other parameters,
iii. To propose the PV plant configuration for efficient energy provision,
iv. To predict the Operations and Maintenance plan and relevant costs for the PV plant.

1.3. Research Questions

- Why solar energy is most preferable while intermittent?
- What are the parameters to consider while designing a solar mini-grid system?
- How much evolution of energy demand in year 4 concerning year 1?
- What are the most attractive productive uses in the given locality?
- Are there the Key Indicators of the potential customer's ability to pay?

1.4. Research Justification

As there are still many households living far from the national grid, and in need of access to electrical energy to improve the living condition, the solar mini-grid is more important to reduce the cost of electricity in terms of access. Since solar energy is clean and solar is a free source of energy, **this minimizes the cost of energy provided to the people in need**.

The more the mini-grid is reliable, the more growth in businesses in rural communities accessing electricity from such power plants. Here I can say that the living condition for the rural community will be changed from good to the best. Mini-grid allows developers to stimulate deep knowledge about rural households' electricity needs and develop great milestones to provide energy from the local mini-grid.

1.5. Scope of the study

This research will gather and analyze solar PV plant data useful for rural electrification in Kayonza District, Mwiri sector, Kageyo cell, Rwisirabo village (off-grid village with the potential of solar PV Plant).

Different data used were collected through numerous approaches including consultation of Solar Atlas, Meteo Rwanda.

During the simulation of the collected data, HOMER was used, and the results obtained were governed by the license purchased. However, the data utilized were following the satellite-based, not a quantifiable base instrument.

During the design of the plant, deferrable loads such as water pumping for home water usage were also considered.

1.6. Conceptual framework

Going through different and similar research, several approaches have been applied to deal with the target objective. This work has been conducted firstly through identification of site for the project development, clearly defining the problems among the community living within the village, collecting relevant data for analysis, consulting related literature and identifying the gaps, using software to simulate the collected data and come up with findings that might be applicable to satisfy the population's needs in terms of electricity access facing out the issues encountered among the community.

Below is the summary of the research conceptual framework:

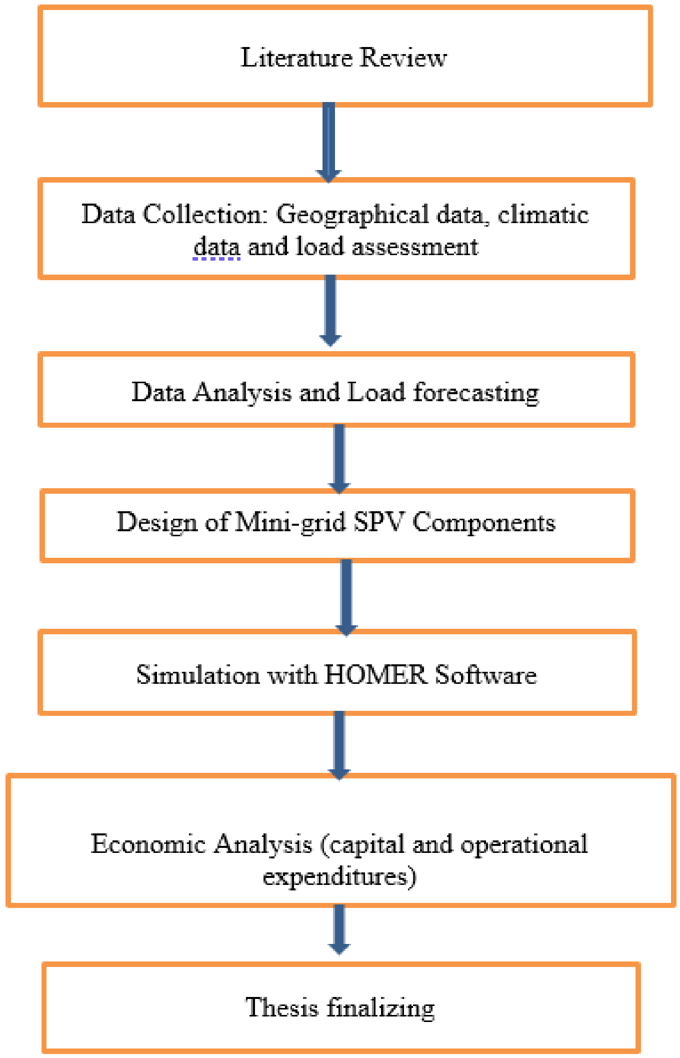

Figure 1: Conceptual framework of the research

1.7. Thesis organization

As per the tile of the work "Technical assessment of solar mini-grid in Rwanda" highlights, this work was carried out systematically focusing on the designing a solar power plant in Rwisirabo village, from the eastern province of Rwanda. To develop the work, about six main chapters were covered as follow:

The first chapter covers the general introduction of the research work, clearly defining the background of the research, highlighting the existing problem, and identifying research gaps, then comes up with the research objectives and their relevancy, finally the expected outcomes of the work and methodology approach.

Chapter two summarizes the contents that were consulted from numerous literature and some key terms that were used in the project development about designing solar mini-grid PV systems.

Chapter three describes the materials and methods that were mainly utilized to conduct the research work, such as simulation tools that might be potential in developing this work, resources assessment, and approaches that might be useful to reach the set objectives. The assessment was based on both primary and secondary data. Estimation of AC primary daily load and energy forecasting requirement in four (4) years were presented in this thesis.

Chapter four discusses the system design analysis of the different mini-grid solar PV components such as PV modules, battery banks, inverters, and accessories.

Chapter five consists of a general conclusion and recommendations about the thesis work.

1.8. Expected Outcomes and Significance of the Study

1.8.1. Expected Outcome of the Study

Following are the expected outcomes after this research:

i. Reliable electricity to users will be provided,

ii. PV plant designed based on accurate data collected and precision tools utilized, thus the plant will operate efficiently than ever,

iii. Good design leads to a sustainable PV plant and requires little Operation and Maintenance costs.

iv. Proven feasibility of solar PV plants for rural development in Rwanda, will attract both private sector and development partners with this type of clean and sustainable energy sector.

v. Increased number of households and productive uses connected to sustainable electricity.

1.8.2. Significance of the Study

This research will contribute to the development of PV green mini-grids in Rwanda thus will be a good reference to the mini-grid developers having the intention to participate in off-grid electrification. Potential villages with enough solar radiation and fit for GMG will be easily identified and complete the national electrification plan, especially through solar mini-grids.

This research is flexible to be implemented in many rural villages in Rwanda. Shall this project proposal be implemented; it will help the Government of Rwanda to reach its target of universal electricity access by the year 2024.

The country (Rwanda) will become one among the countries that have access to green energy and thus a proven resilience to climate change.

Any solar PV plant can be easily designed and implemented following the accuracy of the collected data among all other parameters within this research.

CHAPTER 2. LITERATURE REVIEW

2.0. Introduction

The drive of this research literature review is to show up the brief of the global energy sector and the status of electrification rate in the African sub-Saharan regions including Rwanda. It will also highlight the mini-grid technologies as one of the areas that need to be developed to make the country have access to reliable, sustainable, clean, and green power in the near future.

2.1. Literature review

2.1.1. Electricity access

More than two-thirds of the population worldwide live with no access to electricity are in sub-Saharan Africa. In 2018, Northern Africa reached roughly universal electricity access while the electrification rate in sub-Saharan Africa was 45% in the above-mentioned year. Nowadays electrification rate within sub-Saharan Africa is still very low compared to the levels in other developing areas of the world. Unavailability of electricity often pushes citizens, small and medium businesses, or community services that can manage to pay for it to use inefficient, spoiling, and expensive alternative energy solutions for essential services. In remote villages that are not connected to the main grid, finding reasonable off-grid solutions and business models is important. However, many households are living in informal neighborhoods nearby the grid lines, but not connected at all [1].

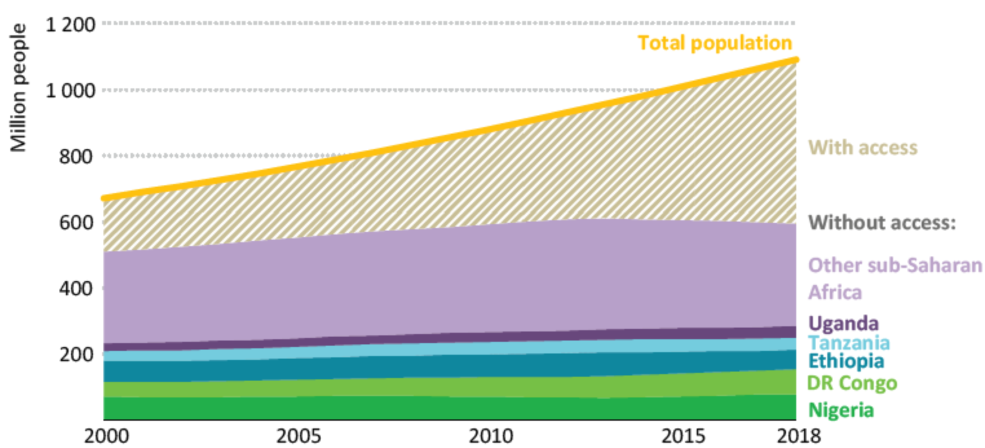

Figure 2:Electricity access by country in sub-Saharan Africa, 2000-2018 [5]

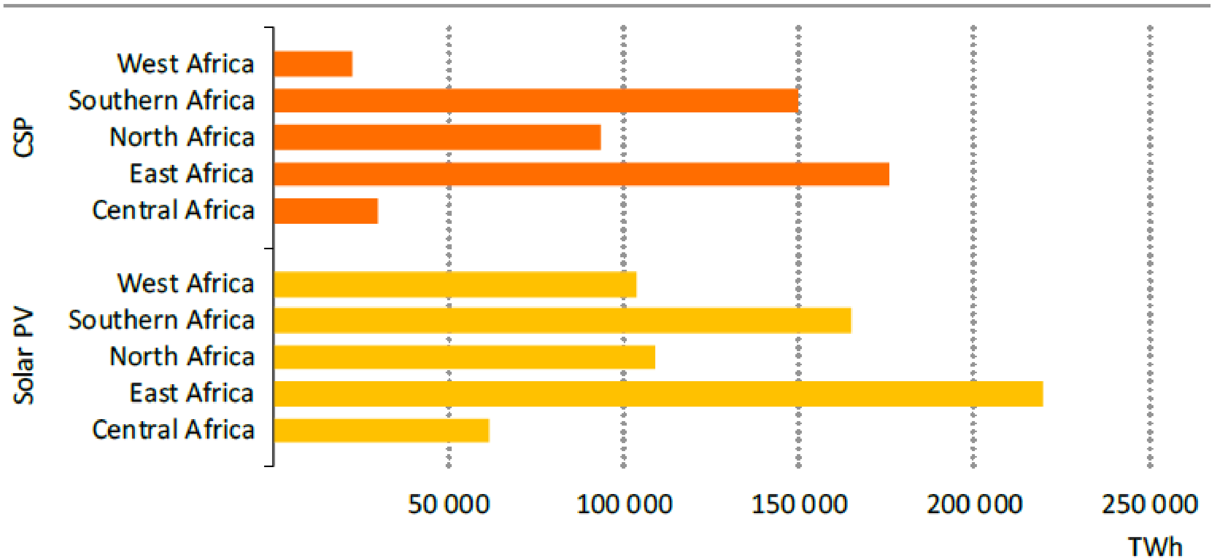

Figure 3:Solar energy resource potential per year in Africa [5]

Following the figure mentioned above from the Africa Energy outlook as of 2019, it could be found that East Africa, the region from which Rwanda is located, is the one with the highest solar resource potential [1].

As of September 2021, the cumulative connectivity rate is 66.8% of Rwandan households including 48.4% connected to the national grid and 18.4% accessing through off-grid systems (mainly solar) [4].

2.1.2. Net Zero Emission

The nonexistence of access to electricity not only delays economic development but also causes serious impairment to health and hinders the progress on gender equality and education [5].

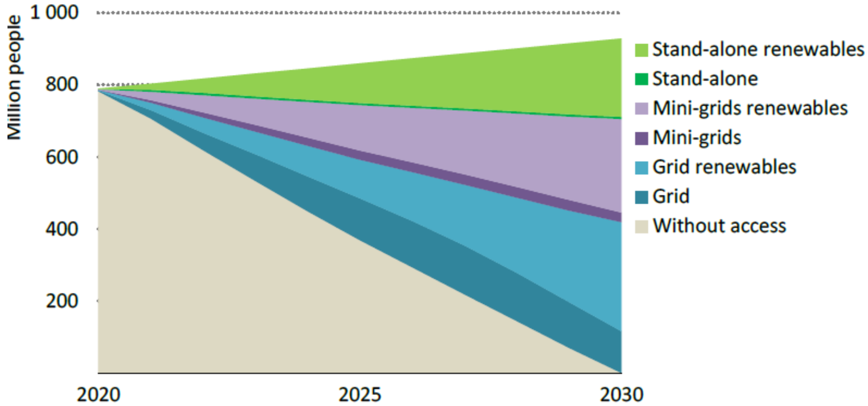

Figure 4: Electricity access by type of connection in emerging market and developing economies in the NZE [5]

In Rwanda, the estimated emissions reduction potential in 2030 for all mitigation measures evaluated from different mitigation measures can be shown below. The total mitigation potential is estimated at around 4.6 million tCO_2e in 2030. As per the analysis, mitigation measures identified within the energy (34% of total), increased use of renewables to meet increasing energy demand dominates the mitigation potential. the use of solar energy for water heating, pumping for agricultural irrigation, and off-grid electricity will contribute more.

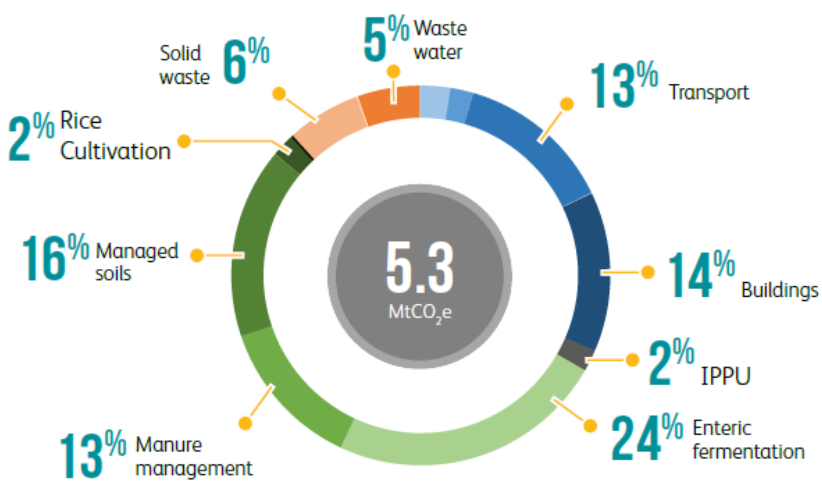

Figure 5: Estimated GHG mitigation potential in 2030 from energy use[5]

2.1.3. Electricity Accessibility in Rwanda

Rwanda is currently estimating around 238.67 MW of the installed capacity which serves electricity to around 66.7% of the total population for both ON and OFF the grid [4]. Thinking about the nationwide target to reach 100% electricity access, an electrification plan demarcating all the villages of Rwanda has been developed considering that such target will have to be met by the year 2024. Subsequently, Households far away from the planned national grid coverage have been encouraged to use alternatively cheaper connections such as Mini-grids and Solar Photovoltaics (PVs) to reduce the cost of access to electricity whilst relieving constraints on historical government subsidies.

The current access targets stipulate 100% of households' access to electricity by the year 2024 while productive users will be all connected before the end of the year 2022. To achieve this target, REG intends to increase the number of new connections by 500,000 every year, including 200,000 on-grid and 300,000 off-grid.

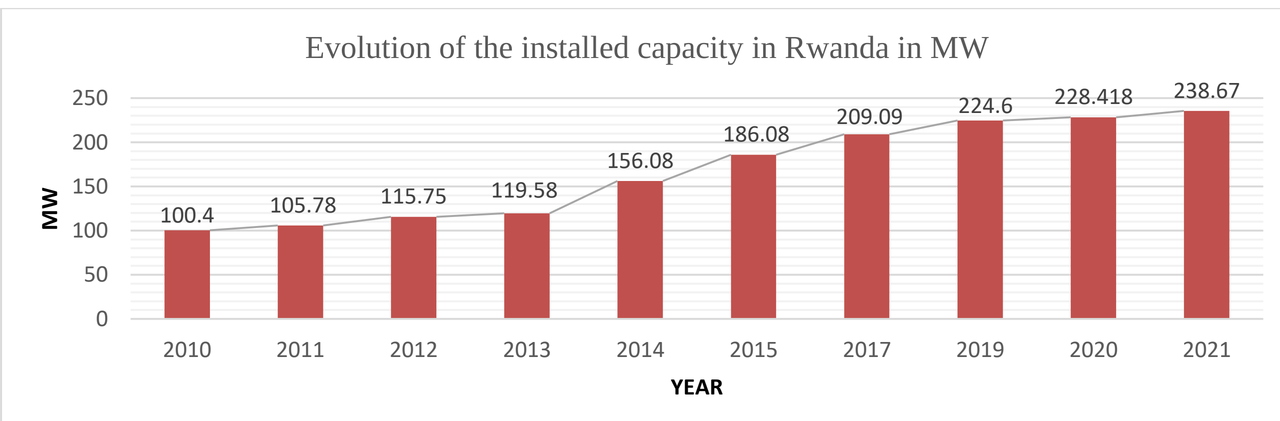

Figure 6: Evolution of the installed capacity in Rwanda in MW[8]

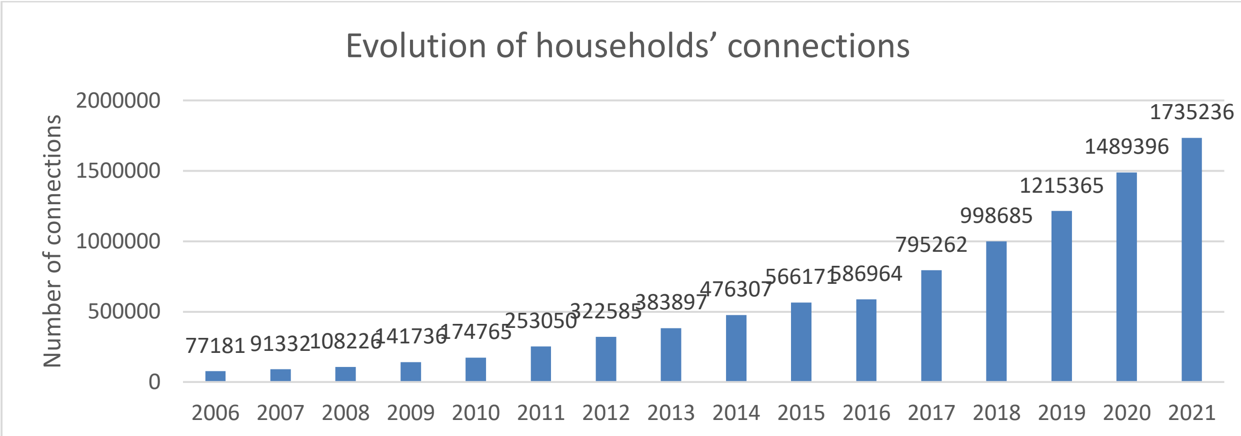

Figure 7: Evolution of households' connections [8]

2.1.4. Mini grids

In remote villages, decentralized energy systems (mini-grids and/or stand-alone systems) are found more cost-effective compared to the national grid extension.

Like the central grid, mini-grids need a stable power flow to work properly and often use a backup system (either a diesel generator or battery bank). Mini-grids can be scaled up in line with rising demand, and eventually be connected to the main grid. Mini-grids may be developed either from Hydro or solar energy technology depending on the feasibility study done at a given locality[5,6].

Solar mini-grids are a perfect alternative solution to central grid electricity in rural isolated areas. And because such mini-grids are independent units, these can also be controlled and managed without many challenges to the conventional grid [8].

Figure 8: Rushonga 30kW AC Mini-grid constructed in Kirehe District[8]

Decentralized mini-grids.

As per the investment necessity of such mini-grids, the regionalized mini-grids sometimes use diesel generators in remote villages generating electricity for the customers.

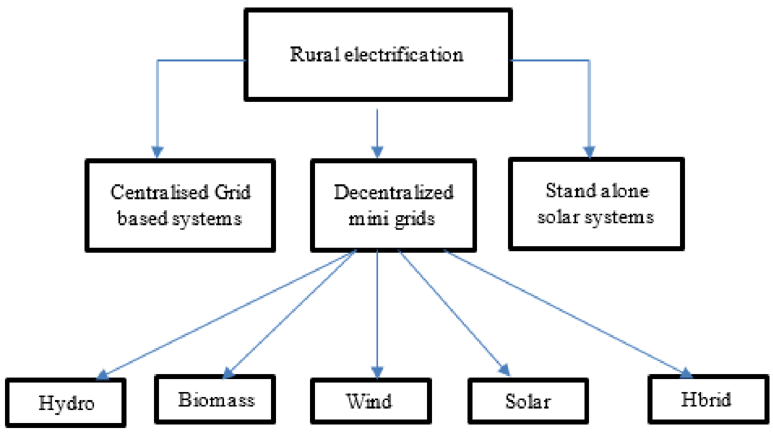

Figure 9:Rural Electrification Approaches

Table 1:Main risks and their fundamental causes in installing Mini-grids

Revenue Risk for mini-grid	
• Low demand	• Inability or delay recovering the upfront investment because of low electricity demand than expected. (this is the results of an over-sized mini-grid) • Mini-grid customers have very low incomes.
• Low affordability • Tariff level and subsidies	• Dependence or uncertainty regarding subsidies when it comes to setting the tariff by the national level; difficult to maintain support for and collect cost-recovery tariffs which are somehow higher than the grid tariff.
Regulatory Risk for mini-grid	
• Registration and licensing	• Unclear rules on licensing and registrations and sometimes delays in obtaining the permits.
• Tariff setting	• Uncomplete tariff setting methodology.
• Interaction with the national grid	• Weak specifications of what happens when the national grid arrives in the area where the mini-grid operates.

2.1.5. Solar Irradiation in Rwanda

Literature research was conducted at the international airport of Kigali using the daily recording of temperature, pressure, and relative humidity; precipitation, wind speed, and its direction with also taking into consideration peak sun hours.

On the other hand, some data were provided by the Meteorology department. below are the observations from such a survey [9].

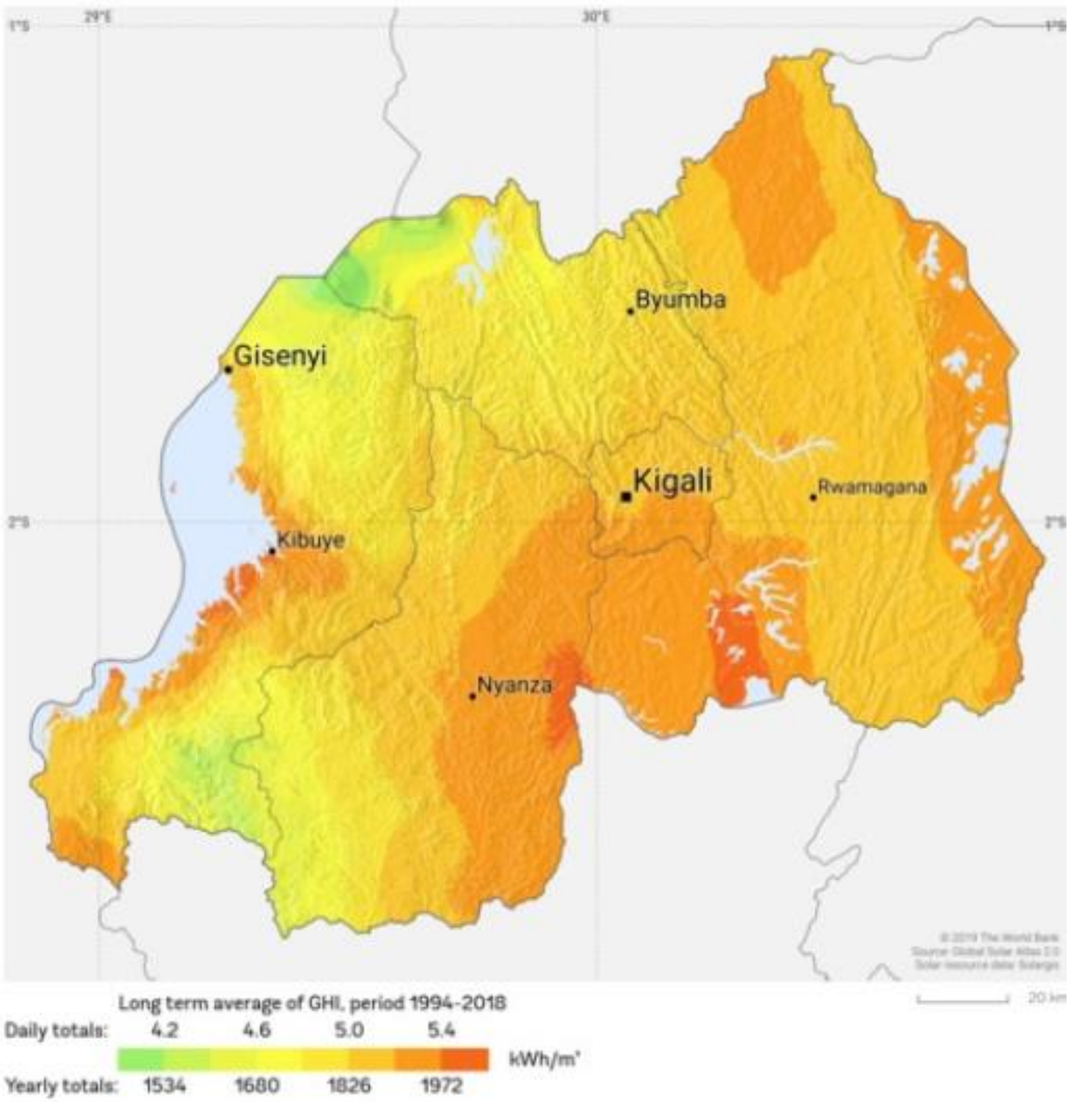

Photo 1:Global Horizontal Irradiation (GHI)

The results give the annual solar radiation value of 5269Wh/m^2/day for Rwanda while the commonly given value in literature or website is 5.15 Wh/m^2/day. The monthly value was obtained using nonlinear meteorological radiation models (MRM) with satellite data was varied between 4.3 and 5.2 Wh/m^2/day[10].

Geospatial analysis showed that the best way in terms of cost-effectiveness reach full access while meeting the energy demand from new customers is to develop mini-grids and solar stand-alone systems in parallel with the national grid extension [1].

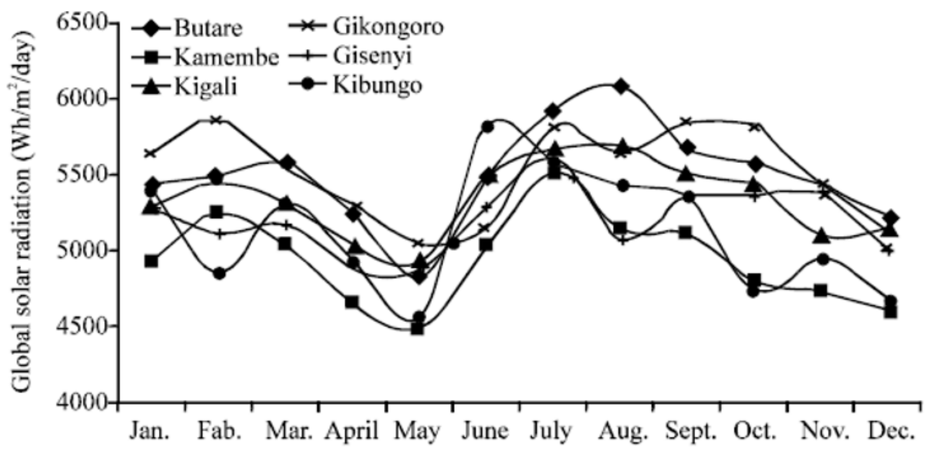

Figure 10: Monthly average of estimated global solar radiation on the sites of Rwanda

2.1.6. Modeling of green PV mini-grid

The term "off-grid customer" refers to any customers who do not have access to the national grid, such users access electricity through either stand-alone PV, mini-grids, or microgrids. To model this, HOMER is mostly helpful to simulate and optimize available sustainable energy needs from a green PV plant. To optimally model a green PV plant, site visits were made to different off-grid villages and interviewing a representative sample residential household.

The electrical equipment, power rating, and hours of use parameters need to be used for analyses. The climatic conditions analysis must also be carried out [10].

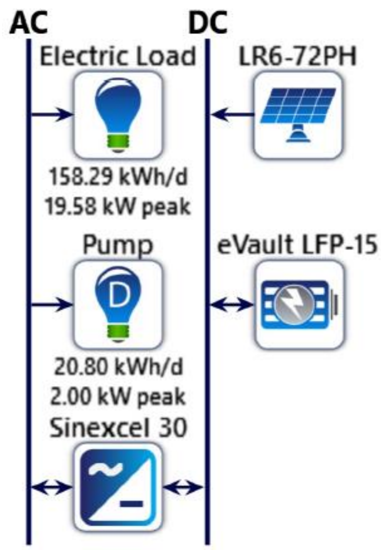

Figure 11:Architecture of the designed solar PV mini-grid with storage

Jean de Dieu, Ahmet, and Turgay [11] in their paper entitled an overview of Renewable Energy Resources in Rwanda have detailed some types of renewable energy available in Rwanda. Following the solar energy pattern, solar radiation is well exploited countrywide, even during the rainy seasons. The average global solar irradiation was approximated to be 4.8 kWh/m^2/day from PVGIS and presented that in Rwanda there are only three (3) grid-tied solar power plants namely Jali, Ndera, and Gigawatt in Rwamagana respectively.

Eustache, Diego, and Umaru [12] engrossed in the current status of renewable energy technologies for electricity generation in Rwanda and their estimated potential, this paper highlights that the daily solar irradiation in Rwanda is high between 4-6 kWh/m^2/day from satellite data and the current average of solar radiation is about 4.5 kWh/m^2/day for most of the country. The work moreover shows that the Government of Rwanda has set a target to reach universal access to electricity (100%) by the year 2024 by promoting the use of renewable energy especially off-grid systems, solar power plants. Households located far away from the planned national grid are encouraged and supported to use solar photovoltaics to reduce the cost of access to electricity [12,13].

Laetitia in her thesis works namely ‘design, simulation, and Evaluation an on-grid Photovoltaic power plant, electricity access and inability of electrifying its people has been shown as one of the challenges that Rwanda is still facing. During her research, she aimed at looking at how generation capacity could be increased to meet the current demand while decreasing fossil fuel dependence. She also highlighted that life of people will be socially and economically improved once this is achieved. Kirehe was chosen as the site to design this on-grid SPV power plant which has 1.3 MW, PVsyst software was being used [11,12].

Jeanine UWIBAMBE [16] was about to design and compare a Solar Home System of 0.2 kW with an off-grid SPV Power Plant of 10 kW capacity for obtaining electricity at a low cost in the Kinazi Cell. The main purpose of the work was achieved by considering the weather parameters and also focusing on the primary daily load for only one household. HOMER Software was utilized for simulating and modeling both systems, the results from the simulation highlighted the economical aspect of using a 10 kW Off-grid SPV Power Plant compared to Solar Home Systems for any remote village electrification.

Sivapriya and Gobind Pillai [17]on solar PV Microgrid for Rural Electrification design have demonstrated that there are numerous numbers of regions in some countries that actually, need electric power. Expansion of the power network to those remote regions is not practically viable from the expenses and power lost within transmission lines, the potential solution is the rural micro-grids has been designed. Photovoltaic (PV) is especially appropriate for some nations because of many elements, for example, the accessible sun-oriented source, the particularity of the innovation, and low innovation cost.

Al-Shamani and Mohd Yusof [18] on design and Sizing of Standalone Solar Power Systems for a house confirmed that Photovoltaic is the immediate change of the sunlight-based energy into electric power. There are numerous reasons why the utilization of sun-oriented energy is so important, proper atmosphere conditions, appropriate climate conditions, etc. The paper characterizes Building a photovoltaic scheme as the way toward planning to choose and to compute the rating hardware utilized in the system. In addition, the authors have presented all apparatuses required in designing an independent solar photovoltaic system that supplies electrical energy to homes and small businesses.

Numerous researchers introduced the techniques to configuration PV systems, however, their work could present the strategies utilized in building and choosing the hardware of the SPV based on the Watt-hour demands, medium energy consumption was selected [18,19].

Navada, Santosh, and Shubhanga [20] focused on Modelling a Solar Photovoltaic Power Plant for Power System Studies, given the amount of power required of the Solar PV power system, and with the choice of technology of SPV panel arrays, model parameters are estimated using the information from the PV panel datasheet. These SPV modules are aggregated to form an SPV power plant. By computing the required number of panels to be connected in series and parallel and considering the minimum and maximum voltage ratings of converters DC input. The results presented form a basic step in power system analysis with Solar PV integration.

CHAPTER 3. RESEARCH METHODOLOGY AND MATERIALS

3.0. Introduction

To perform any renewable energy project, to properly analyze the effective performance of the designed system, the deep assessment may need suitable conditions to be met such as site description, needful technologies, system investigation, and operative performance influence. This research aims at designing and modeling a green PV mini-grid to electrify customers from Rwisirabo village in Kayonza District. Each step used to design such a system will be discussed in this report.

To achieve the research specific objectives, different tools such as solar GIS, and a set of questionnaires were used for gathering the required information including solar radiation, daily energy requirements by end-users, among others.

The design of the green solar PV mini-grid was accomplished through the use of Homer simulation software.

Homer

Homer is a model that is used in optimization and simplifying the activity of power system evaluation designs in various use. Configuration of the PV plant can be made by using the Homer software tool. It is possible when utilizing this software to select different components of the designed system. The core goal of this research is to investigate a green PV plant that can provide stable and reliable electricity at a minimal cost compared to the other energy provision systems. The tool will help to determine how the designed system interrelates with end-use requirements according to the expediency and potentiality of energy in the load region where the system is modeled for.

Simulation

The Homer simulating tool consists of different components, resources, loads, and system constraints. The performance of enormous system configurations is simulated through the calculation of energy balance per hour. The tool will help Simulate a long-term operation of the system with accurate sensitivity. Homer can hold a considerable simulation than other similar tools. Therefore, it is my preference among other simulation tools.

3.1. Site assessment (General)

Site description

The village of Rwisirabo I is located in the Eastern province, Kayonza district, Mwiri sector, Kageyo cell. The coordinates of this location are (-1.83750114025666, 30.6572778700553).

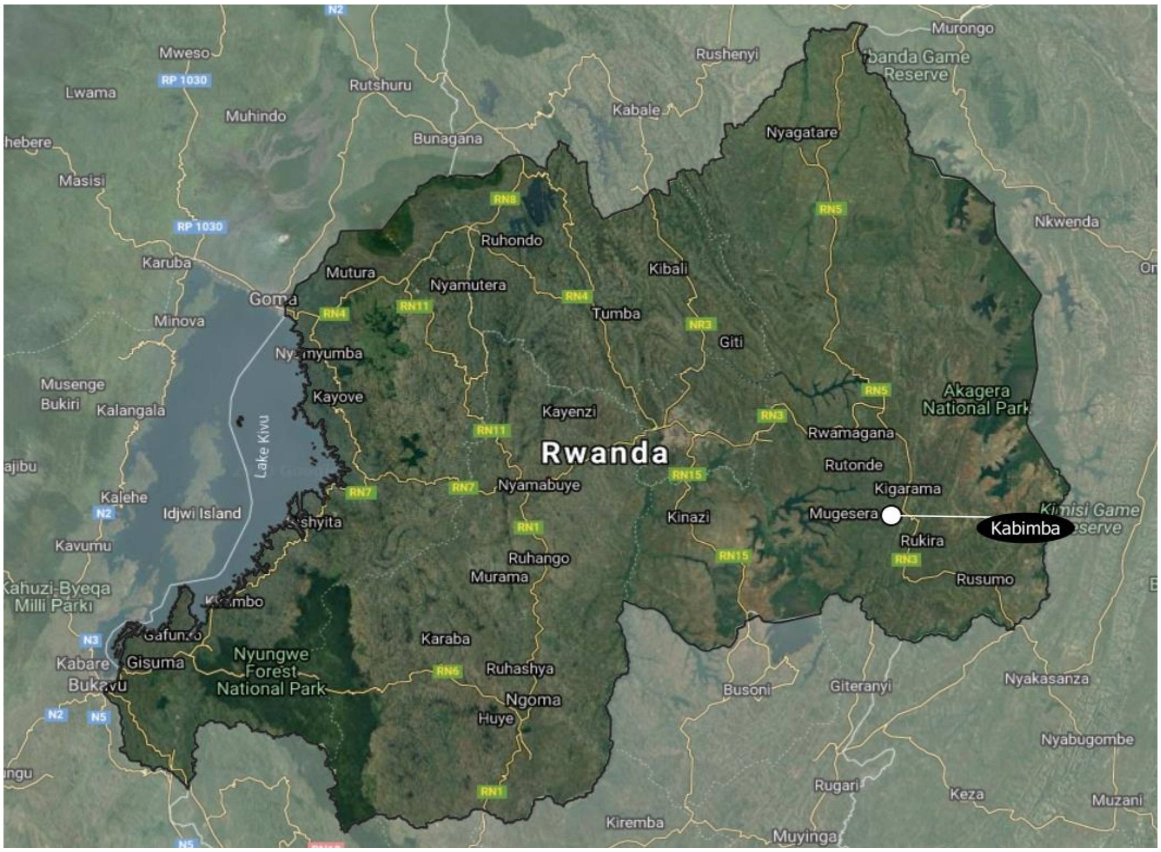

Photo 2: Location of Rwisirabo I in Rwanda (Kabimba center)

The above photo shows a satellite view of Rwisirabo I, highlighting its borders and the distribution of households, businesses, and institutions.

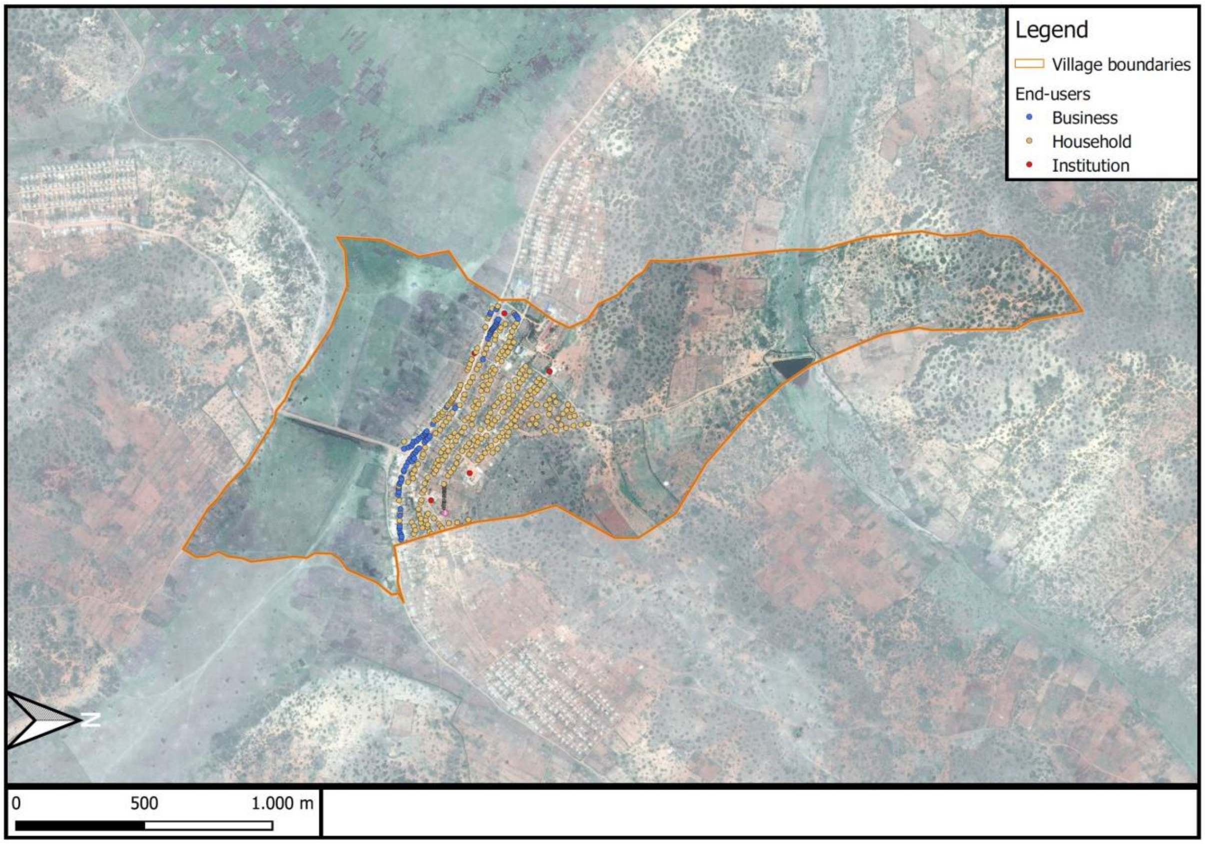

Photo 3: Satellite view of the village showing its administrative borders and the distribution of households, businesses, and institutions.[by GPS]

Site demographics

Rwisirabo I is a village of 760 inhabitants distributed among 286 households. According to an interview with the village leader, Rwisirabo I is growing at a rate of 4 households per year. The list of households per *Ubudehe*[1] category is shown in Table 1.

[1] *Ubudehe* is a household classification system exclusive to Rwanda.

Table 2: General demographic data of Rwisirabo

Demographic characteristic	**Data**
Estimated Population	760
Estimated number of Households	286
% Household *Ubudehe* Category 1	13%
% Household *Ubudehe* Category 2	7%
% Household *Ubudehe* Category 3	80%
% Household *Ubudehe* Category 4	0%

Organizational structure

The governance and organizational structure of the village are centered around the village committee which is composed of five roles: the village leader, a security officer, the social affairs officer, development agents, and the information officer and the village leader is the formal leader of the village.

Economic Activities

Farming is the main economic activity of the village and the main crops are rice, sorgho, maize, and potatoes. The village represents 62 businesses.

Electrification Status

In the village of Rwisirabo I there are bout 100 SHSs present. These SHSs can run up to 4 hours per day and the access to electricity has been flagged by the village leader as an issue.

3.2. Socio-economic characteristics

Households

There are 286 households in Rwisirabo at the time of the survey, from which 20 were interviewed which is about 7% of the total number of households present in the village. The information reported in this section has been extracted from interviews with the households performed during the site visits.

Energy consumption

The distribution of energy sources currently used in the village is shown in Figure 12, while Figure 13 reports the appliances owned and desired by the interviewees.

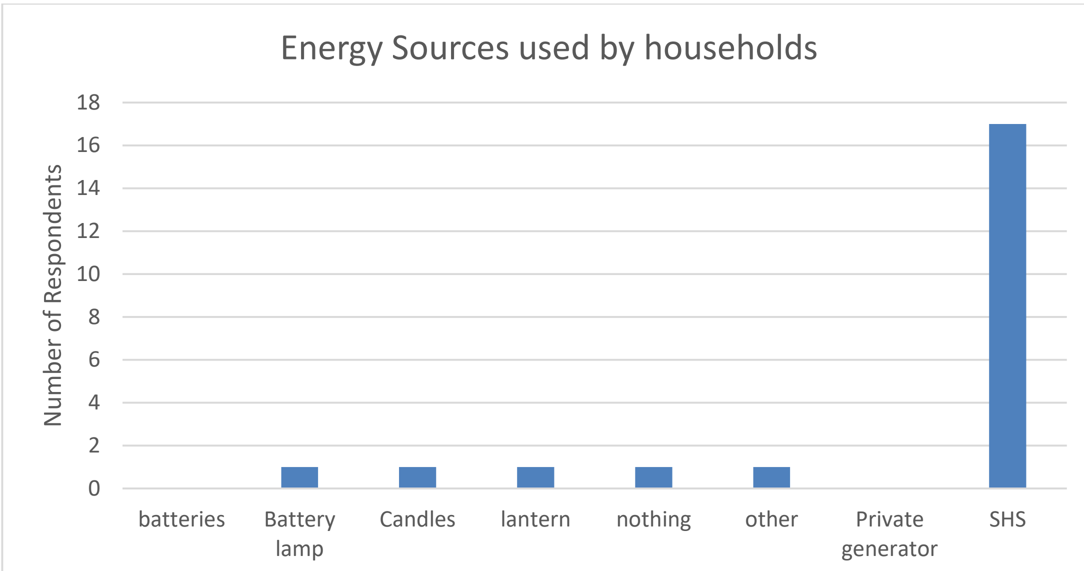

Figure 12: Energy Sources used by households

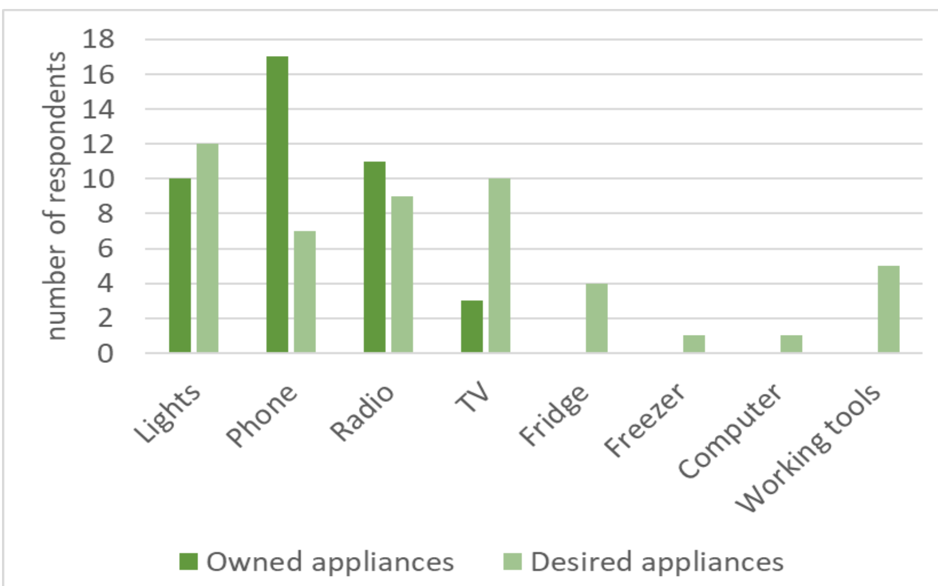

Figure 13: Appliances Owned and Desired - Households

Willingness to Pay

A relatively low willingness to pay has been obtained as a result of the different energy packages proposed to the households during the surveys as shown in Figure below.

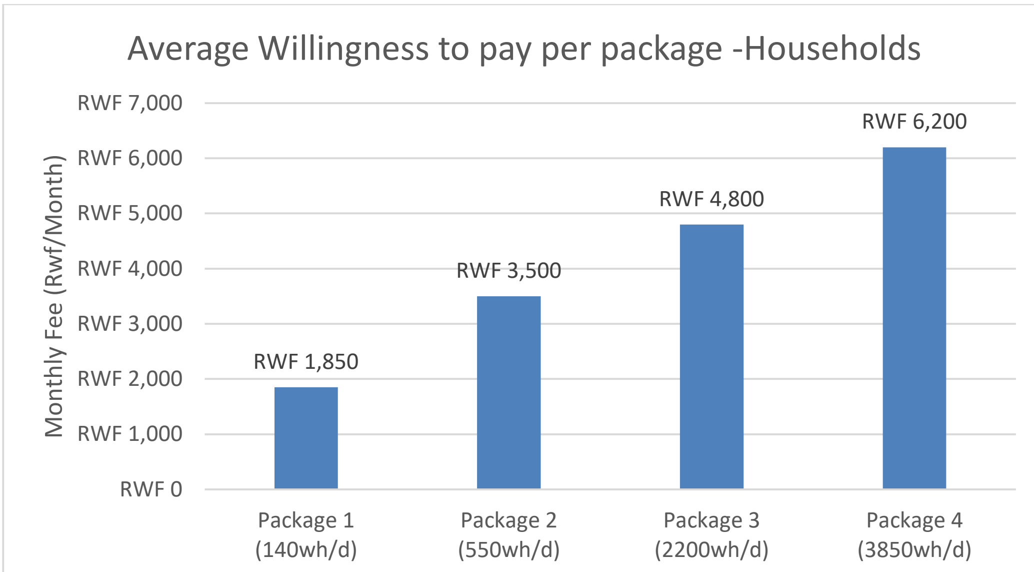

Figure 14: Average WTP per package -Households

When asked which package they will pick out if such electricity services were provided, the respondents answered as shown in Figure below.

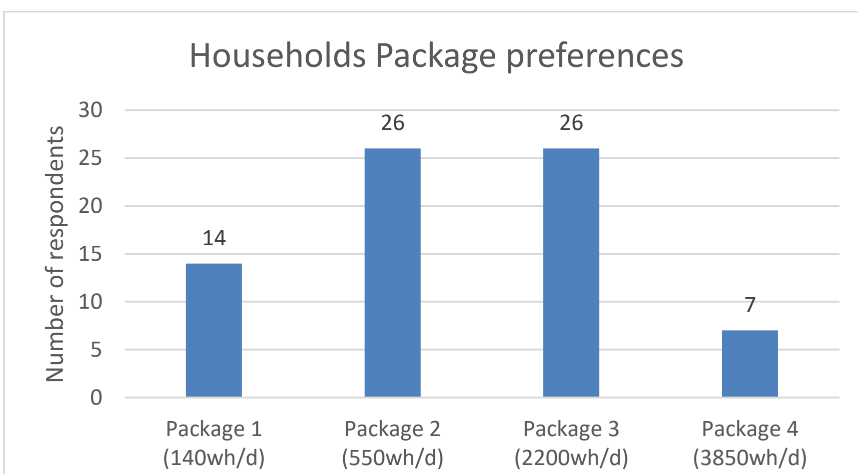

Figure 15: Packages preferences

Demand EC estimation

To estimate the energy demand of the households, they have been divided into four energy categories (ECs) according to their electricity needs and affordability. The share of each category has been derived from the electricity needs assessment of each visited household, the currently available appliances, the willingness to pay, and the ability to pay.

Table 3: Domestic Load table per energy categories

Household Load						
Type	Appliance type	Rating (W)	No of Appliance	Total Power (W)	Run time h/day	Wh/day
High class	Lamps	6	4	24	4	96
	Lamps	6	3	18	8	144
	TV	120	1	120	2	240
	Radio	0	0	0	0	0
	Mobiles	5	2	10	2	40
	Fan	40	1	40	2	80
	Refrigerator	200	1	200	8	1600
Total				412		2200
No. of houses						15
Sub Total	6,180					33,000
Middle class	Lamps	5	2	10	7	70
	Lamps	5	2	10	7	70
	Mobiles	5	2	10	2	20
	Fan	60	1	60	2	120
	Radio	6	1	6	5	30
	TV	120	1	120	2	240
Total				216		550

No. of houses						149
Sub Total				32,184		81,950
Low class	Lamps	6	3	18	3	54
	Lamp	6	1	6	2	12
	Mobiles	6	2	12	2	24
	Radio	10	1	10	5	50
Total				46		140
Nº of houses						134
Sub Total				6,164		18,760
Total						**133,710**

Note: The above calculations are for domestic use only. For the businesses and institutions, the calculations were done considering the same rating per appliance, lamps for instance.

Table 4: Load profile for businesses (Shops)

Load profile for businesses (Shops)						
Type	Appliance type	Rating (W)	No of Appliance	Total Power (W)	Run time h/day	Wh/day
High class	Lamps	10	6	60	4	240
	TV	120	1	120	2	240
	Mobiles	5	2	10	2	40
	Fan	40	1	40	2	80
	Refrigerator	200	1	200	8	1600
Total				430		2200
No. of houses						3

Sub Total	1,290					6,600
Middle class	Lamps	5	4	20	7	140
	Mobiles	5	2	10	2	20
	Radio	6	1	6	5	30
	TV	120	1	120	3	360
Total				156		550
No. of houses						10
Sub Total				1,560		5,500
Low class	Lamps	5	3	15	4	60
	Mobiles	5	2	10	4	40
	Radio	8	1	8	5	40
Total				33		140
No. of houses						38
Sub Total				1,254		5,320
Total						**17,420**

Table 5: Load profile for Pharmacy

Load profile for Pharmacy					
Appliance type	Rating (W)	No of Appliance	Total Power (W)	Run time h/day	Wh/day
Lamps	7	1	7	5	35
Mobiles	5	1	5	1	5
Fan	50	1	50	2	100
			62		**140**
No of Pharmacy					3
			186		**420**

Daily Energy for streetlights

The consumption allocated to street lighting is assumed to be a maximum of 7.5% of the total electricity demand. The consumption has been assumed to be covered by the mini-grid developer without additional charges to the community.

Stepladders for load assessment

1. List all electrical appliances to be powered by the PV system.
2. Separate types of loads and enter them in the appropriate table.
3. Record the operating wattage of each item.
4. Specify the working time per day during which every component will be working.
5. Multiply steps 2, 3, and 4 to calculate the total electrical energy required per day.

Summary of the results for Rwisirabo are the following:

Table 6: Classification of households in ECs

EC	Indicative service	Estimated demand (Wh/day)	Share of households (%)
EC 0	None	0	0%
EC 1	Lights, phone, radio	140	45%
EC 2	Lights, phones, fan, radio, TV	550	50%
EC 3	Lights, phones, fans, TV, fridge	2200	5%
EC 4	Lights, phones, fans, TV, freezer and productive use appliance	3850	0%

Businesses

There are 62 businesses in Rwisirabo I, from which 42 were interviewed (67.7%). The number of businesses interviewed and the total number of businesses in the village are shown in Table 4.

Table 7: Type and number of Businesses present in Rwisirabo

Type of Businesses	Number of Businesses in the village
Shops / Boutique	46
Pharmacy	3
Bakery	0
Phone Charging	0
Mill	0
Car Repair Shop	0
Sewing Workshop / Tailor	8
Bars / Restaurants	2
Carpentry Workshop	0
Storehouses	0

Hotels	0
Farmers with pump	0
Welding Workshop	0
Hairdresser / Barber	3
Butcher / Slaughter House	0
Chicken Farming	0
Local beer industry	0
Coffee Washing Station	0

Energy consumption – Business

The energy sources used by businesses are shown in Figure 16. The distribution of appliances among businesses is reported in Figure 17.

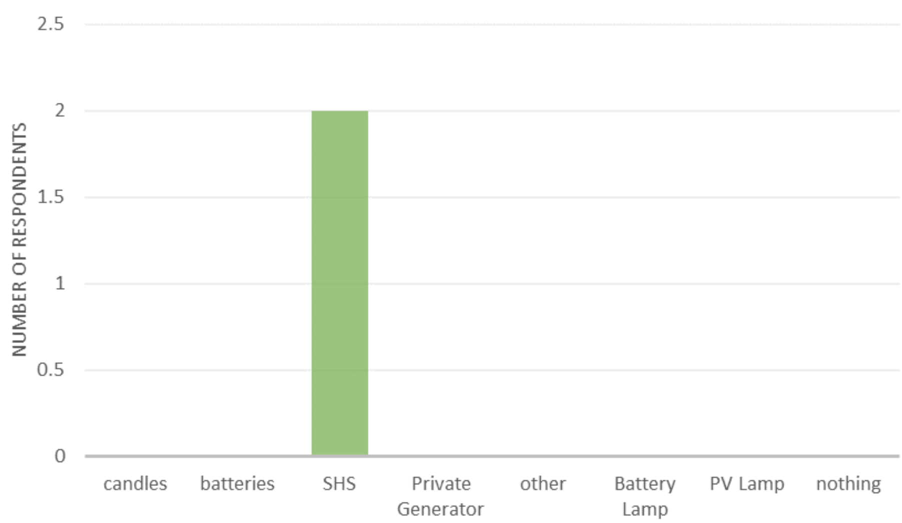

Figure 16: Energy Sources used by businesses

Figure 17: Appliances Owned and Desired Businesses

Demand ECs estimation

The energy demands for each business of Rwisirabo I are available in Table 6 of the present report.

Public Institutions

There are 4 institutions in Rwisirabo I, of which 2 were interviewed (50%).

Table 8: Type and Number of Institutions present in Rwisirabo

Type of Institutions	Number of Institutions in the village	Number of Institutions Interviewed
Education facilities	1	1
Health Post	0	0
Health Centre	0	0
Place of worship	3	3
Cooperatives Building	0	0
Public / Administrative buildings	1	1

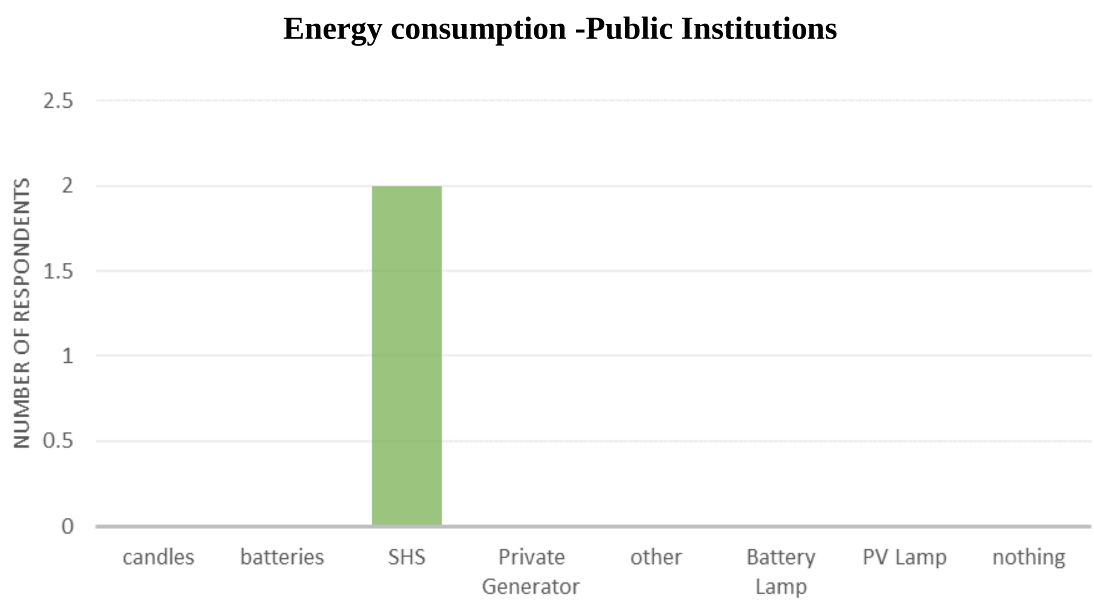

Figure 18: Energy sources used by institutions

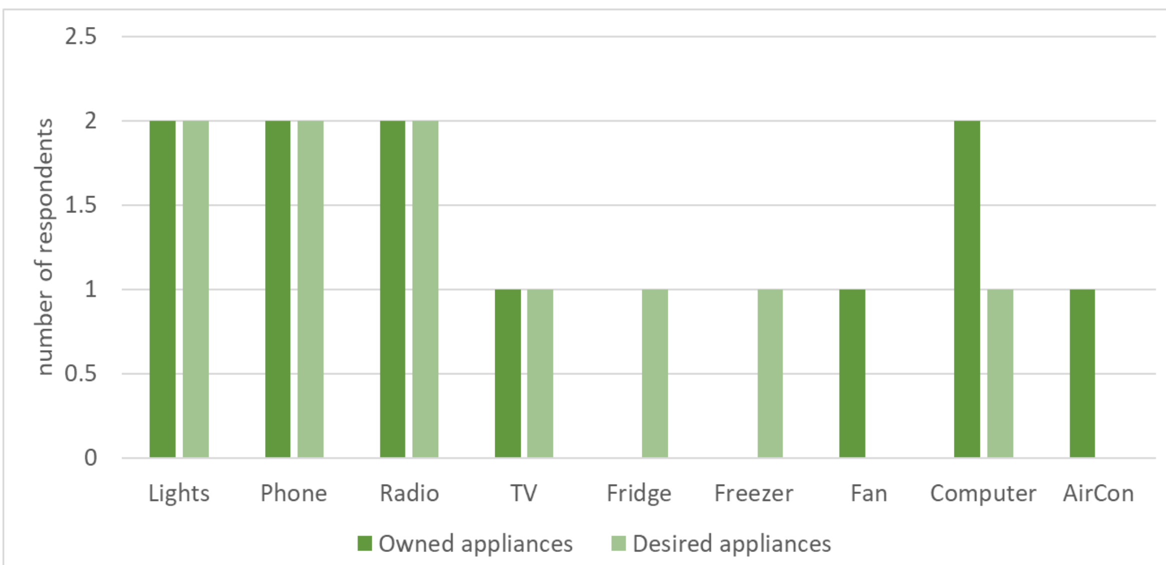

Figure 19: Appliances owned and desired by institutions

3.3. Load forecast

Based on the above analysis of the collected data, the total energy demand of Rwisirabo I has been estimated, as per the considerations and methodology explicitly described in the present report.

Energy Baseline

Numbers of connections and associated demand

The total number of connections considered for the design of the mini-grid at year 4 in Rwisirabo I is 362 (298 households, 60 businesses, and 4 institutions), making up an average daily demand of 158.21 kWh/day. The details of the numbers of users and associated energy demand are presented in Table 6.

Table 9: Numbers of users and associated energy demand

Type	EC	EDA (Wh/day)	Year 1 Actual	Considered Year 4	
			Number	Number	Total EDA (Wh/day)
Households	0 (none)	0	286	0	0
	1	140		134	18,760
	2	550		149	81,950
	3	2200		15	33,000
	4	3850		0	0
TOTAL Households Connected			286	**298**	**133,710**
BUSINESSES					
Shop	1	140	46	38	5,320
	2	550		10	5,500
	3	2,200		3	6,600
	4	3,850		0	0
Pharmacy	1	140	3	3	420
Bakery	1	140	0	0	0
Phone Charging	1	140	0	0	0
Mill	3	2,200	0	0	0
Car Repair Shop	4	3,850	0	0	0
Sewing Workshop / Tailor	3	2,200	8	0	0
Bars / Restaurants	1	140	2	1	140
	2	550		1	550

	3	2,200		1	2,200
Carpentry Workshop	3	2,200	0	0	0
Storehouses	1	140	0	0	0
Hotels	2	550	0	0	0
Farmers with pump	Custom	0	0	0	0
Welding Workshop	4	3,850	0	0	0
Hairdresser / Barber	2	550	3	3	1,650
Butcher / Slaughter House	2	550	0	0	0
Chicken Farming	2	550	0	0	0
Local beer industry	Custom	33,000	0	0	0
Coffee Washing Station	Custom	2,500	0	0	0
TOTAL Businesses			**62**	**60**	**22,380**
INSTITUTIONS					
Education facilities	Custom	0/960	0	0/1	0/960
Health Post	2	550	0	1	0/550
Health Center	3	3850	0	0	0
Place of worship	2	550/140	3	1	1,650/140
Cooperatives Building	2	550	0	0	0
Public / Administrative buildings	2	550	1	1	550
TOTAL Institutions			**4**	**4**	**2,200**
STREET LIGHTING					
Street lighting		6,827			
TOTAL				**362**	**158,290**

Load profile for the design year

The load curve associated with the energy demand in Rwisirabo for year 4 is shown in Figure 20.

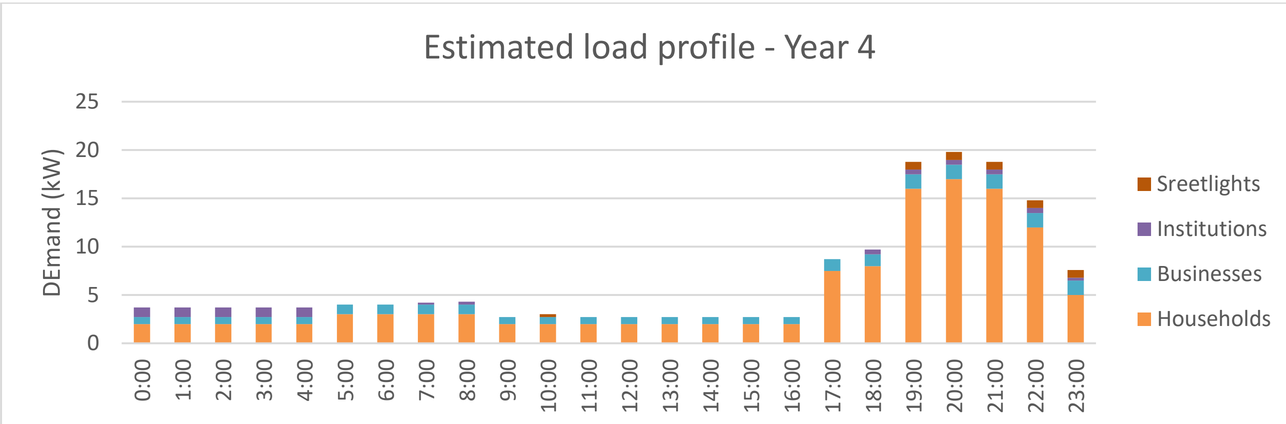

Figure 20: Estimated load profile - Year 4

The load curve is of a residential type, with peak demands occurring in the evening and a maximum of around 20 kW.

The share of the connections is dominated by households as shown in figure 21.

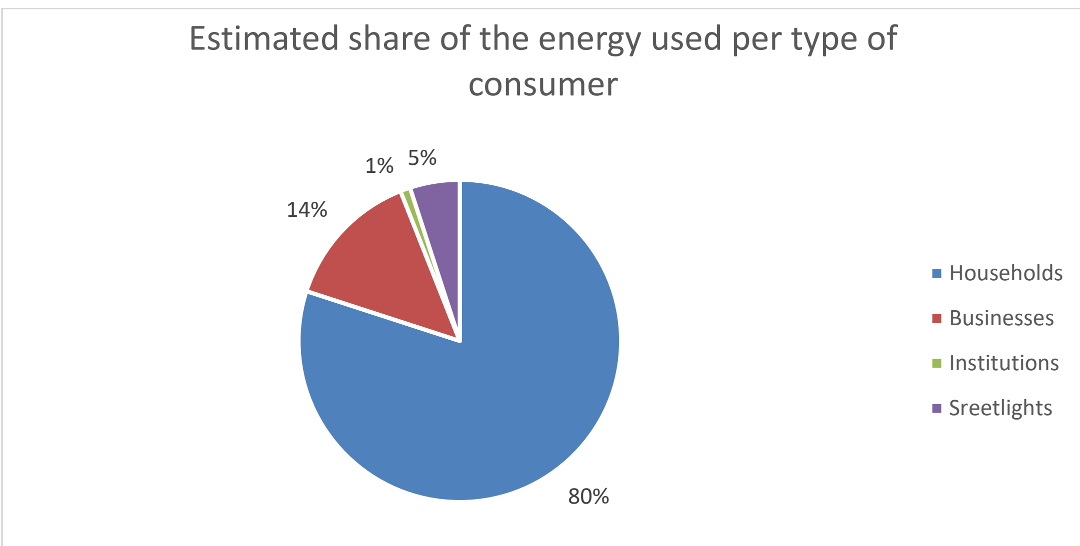

Figure 21: Estimated share of the energy used per type of consumer

Evolution of the demand up to year 4

Figure 22 and Table 10 show the estimated demand and load profiles in years 1 and 4 according to the assumptions explained in the present Thesis report.

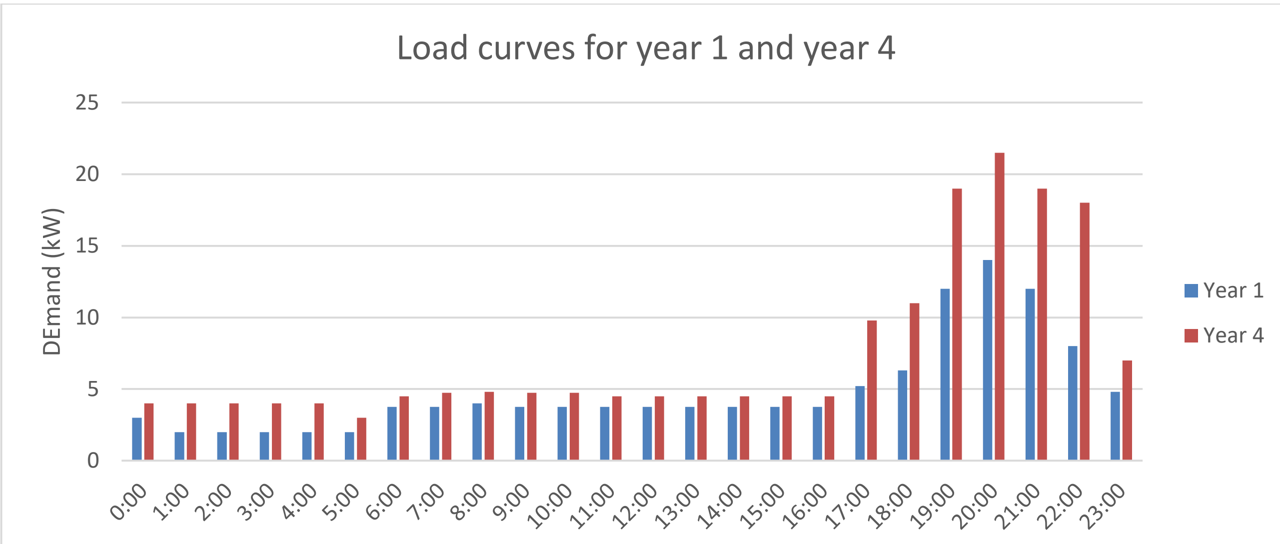

Figure 22: Load curves for year 1 and year 4

Table 10:Demand estimation in year 1 and 4

	Demand (kWh/day)	**Peak power demand (kW)**
Year 1	92.61	1.27
Year 4	158.29	20.46

Components Sizing

in the case of the off-grid PV system, based on the load requirement and available inverters, the system voltage depends. With a proper study of characteristics of inverter available, the system voltage should be selected when the load requires AC power.

$$P_{array} = \frac{E \times 1.3}{PS \times H_{Tlt}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.1)$$

Whereby:

- P_{array}: is the power produced by the system array
- E: average daily energy consumption of load in kWh/day
- PS: Peak solar intensity at the earth surface1kW/m^2
- H_{tilt}: Average solar radiation for tilt angle specified during peak hour's incident.
- 1.3: PV array sizing coefficient

The PV modules that are to be connected in series were determined by the ratio of the selected systems voltage V_{sytem} to the nominal voltage V module of the module at standard testing conditions.

$$N_s = \frac{V_{System}}{V_{module}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.2)$$

Whereby:

- N_s: is the number of PV modules to be connected in series
- V_S: the system voltage
- V_{module}: voltage per each PV module

The number of PV modules to be connected in parallel was calculated based on the ratio of the power produced by the array to the product of the number of PV modules connected in series and the power dissipated by each PV module.

$$N_p = \frac{P_{array}}{N_S \times P_{modle}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3.3)$$

Whereby:

- N_P: is the number of PV modules connected in parallel
- P_{module}: is the power dissipated by each PV module

Therefore the required total number of PV panels to be connected to satisfy the level of service was calculated obviously by multiplying the number of modules connected in series and the ones connected in parallel.

$$N_T = N_S \times N_P \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.4)$$

Whereby:

- N_T: Is the total number of PV modules for the entire system

Battery Bank Sizing

During the battery bank sizing the following formula was considered to ensure that the battery bank will be able to serve the load in any case due to the intermittency for at least 2 days:

$$C_B = \frac{E \times DoA}{V \times DoD \times \eta} \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.5)$$

Whereby:

- C_B: Battery back capacity in (Ah)
- E: Daily energy demand (Wh)
- V: system voltage (in Volts)
- DoD: Battery depth of discharge in (assumed to be 98%)
- η: Battery efficiency (here estimated to be 90%)

During the sizing, I used to select the battery with the following technical specifications, detailed datasheet can be found in the annex to the present thesis report:

Model: Fortress power eVault LFP 15

Battery voltage: 48V

Energy storage: 14.4kWh (300Ah)

As all battery cannot be connected in the same way, in the present work report, the designed number of batteries to be connected in series was as calculated as follow:

$$N_{Bs} = \frac{C_B}{B_{sc}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . \dots \dots \dots (3.6)$$

Whereby:

- N_{Bs}: number of batteries connected in series
- C_B: battery bank capacity in (Ah)
- B_{sc}: single battery capacity in (Ah)

In this case, the calculated battery bank capacity was 7.477kAh (7477Ah); Therefore 25 batteries must be connected in series while all the batteries are assumed to have been connected in parallel as one string.

Solar charge controller was used to controlling over/under Charging/discharge of a battery bank. The charger regulator rating is presented below

$$CC_r = I_{sc} \times N_P 1.25 \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . . \dots \dots (3.7)$$

Whereby:

- CC_r: charge controller rating
- I_{sc}: Short circuit current of the PV array
- N_P: Number of PV modules connected in parallel
- 1.25: Charge controller sizing factor

CHAPTER 4: SOLAR PV MINIGRID SYSTEM DESIGN AND ANALYSIS

4.1.PV Plant location

Photo 4 shows the satellite image of the proposed location for the PV plant in the village while photo 5 below shows a photograph of the plot of land considered.

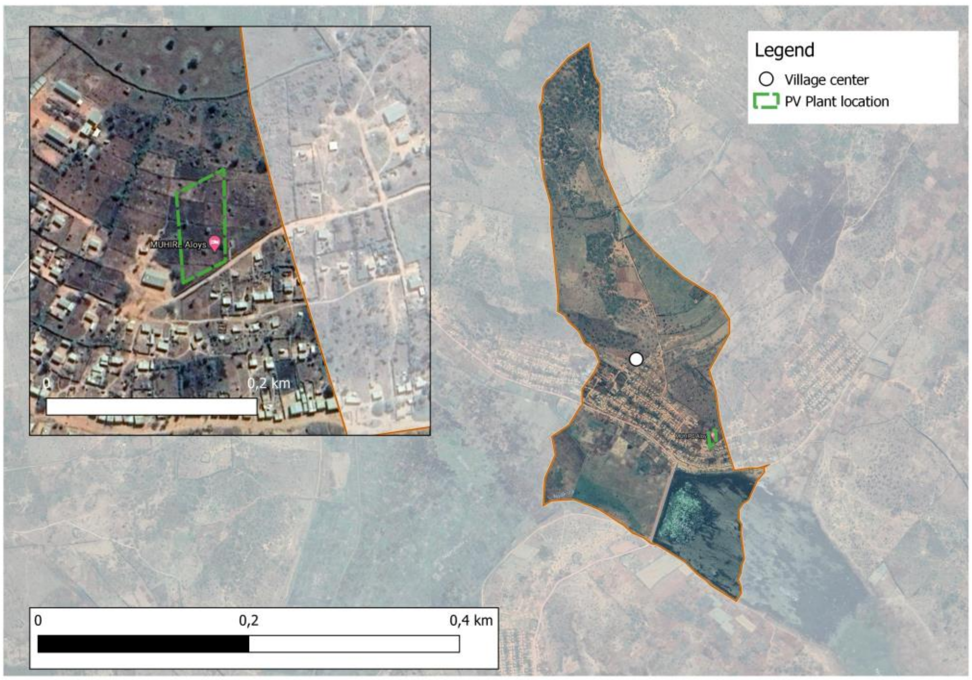

Photo 4: The satellite image showing the location of the PV plant

Month	Clearness Index	Daily radiation (kWh/m2/day)	Temperature	wind speed
Jan	0.481	4.93	21.33	3.23
Feb	0.497	5.22	21.99	3.24
March	0.472	4.97	21.54	3.17
Apr	0.478	4.83	20.66	3.43
May	0.497	4.71	20.25	3.88
Jun	0.531	4.83	20.3	4.17
Jul	0.556	5.14	20.42	4.45
Aug	0.52	5.09	21.41	4.27
Sept	0.492	5.07	21.63	3.95
Oct	0.448	4.68	21.16	3.66
Nov	0.442	4.54	20.54	3.23
Dec	0.452	4.57	20.77	3.12
Annual average (kWh/m2/day)		4.88		

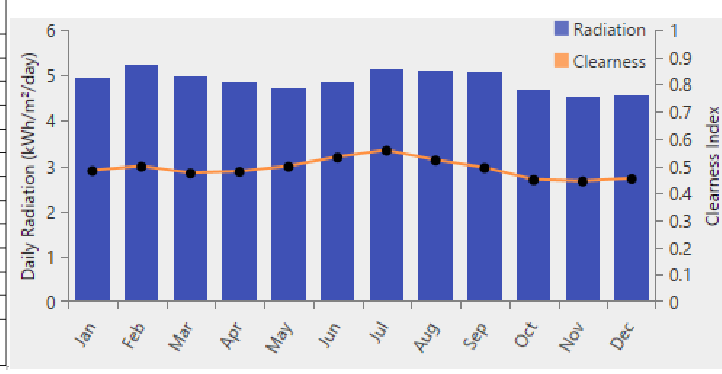

Figure 23: Solar Resources in Rwisirabo I. Source: NASA Database

4.2.Technical considerations for the design of the generation plant

The simulations carried out with the HOMER PRO software provide a basic sizing of the generation plant, specifying the required PV capacity (total kWp), battery capacity (total kWh), and battery inverter capacity (kW). To move into a more detailed design, closer to that required, several technical considerations have to be set in advance.

These considerations also help specify the components required in the generation plant in more detail, which is necessary to ensure a more accurate cost estimate of the generation plant CAPEX before the implementation phase.

Electrical configuration

In a DC-coupled configuration, the PV generator and the battery are coupled in the DC busbar through PV charge controllers. On the other hand, in an AC-coupled configuration, the PV generator and the battery are coupled in the AC busbar through (grid-following) PV inverters and (grid-forming) multimode battery inverters.

Analytical Design & Simulation of 79kW Off-Grid Village PV System

To test the hypothesis of mini-grid solar PV systems superiority over solar home systems, I analytically design and simulated a village solar PV system for Rwisirabo village in the Kayonza District where solar energy flourishes. The below inputs data were utilized for designing the stand-alone PV mini-grid system and the simulation was done using Homer software [21].

- PV panel size is 79 kW, with a capital cost of $118,500, operation and the per year were assumed to be $5,049 [22] [23].

- The peak load demand is 20.46 kW, and average daily demand is 158.29 kWh/d with a load factor of 0.34

- Solar irradiance is 4.88 kWh/m^2/d, the clearness index is 0.488 and the average temperature is 21°C [22]

- The selected battery for this design is the 48V Fortress Power eVault presenting a nominal capacity of 346 kWh with a round-trip efficiency of 98% with a capital cost of $144,000. The approximated replacement cost is $ 104,424 while the operation & maintenance costs are assumed to be $920.40, and the salvage cost is estimated at $13,979 [24]
- The selected system converter is Sinexcel type 30kW of which the capital cost was assumed to be $5,800, the replacement cost was estimated to $5,047 while its operations and maintenance costs were estimated to be $6,547

Photo 5: The proposed location of the PV plant in the village of Rwisirabo I

The above photo shows the proposed location of the PV plant. The terrain has enough area to accommodate the designed PV capacity and the powerhouse. The terrain inclination is minimal or negligible, with a reasonably flat ground level that does not present any challenge for the execution of the civil works.

A small amount of clearing work is needed before construction. According to the village leader, the site is not located within a zone prone to flooding, the access to the site is through dirt roads through which a truck can pass, and the community can build a concrete building for the powerhouse if required.

Table 11 below summarizes the various criteria used for the selection of the PV power plant, as detailed in the methodology section of this thesis report.

Table 11: Matrix of selection criteria for the proposed location of the PV plant

Factor	Green	Orange	Red
Voltage drop	< 10%	N.A.	> 10%
Area	Area available > area required16	Area available > 0,6 x Area required	Area available < 0,6 x Area required
Owner	Community (public)	Private, willing to donate/sell for PV plant location	Private, to be negotiated
Flood risk	None	Some	High
Inclination of terrain	0-5 degrees	5-40 degrees	Above 40 degrees

4.3.Standardized Sizing

Following the HOMER simulations, the design of the generation plant in Rwisirabo village has been standardized according to the methodology explained earlier in this thesis report.

The standardized sizing of the generation plant in Rwisirabo I, for both scenarios, is shown in the table below.

Table 12: Standardized Generation Plant Sizing

Parameter	48 hours battery autonomy	Unit
Total, designed PV capacity (Array)	81.5	kWp
Number of LFP battery units (fortress power eVault 15)	25	Unit
Designed battery capacity	357	kWh
Designed Inverter capacity	30	kW
Back-up Diesel Generator	n/a	kW
Battery Autonomy	48	hours

4.4.Simulation Results

Inputs parameters for modeling

Below are the inputs data used for simulating this off-grid SPV system which gives the appropriate outputs of HOMER software.

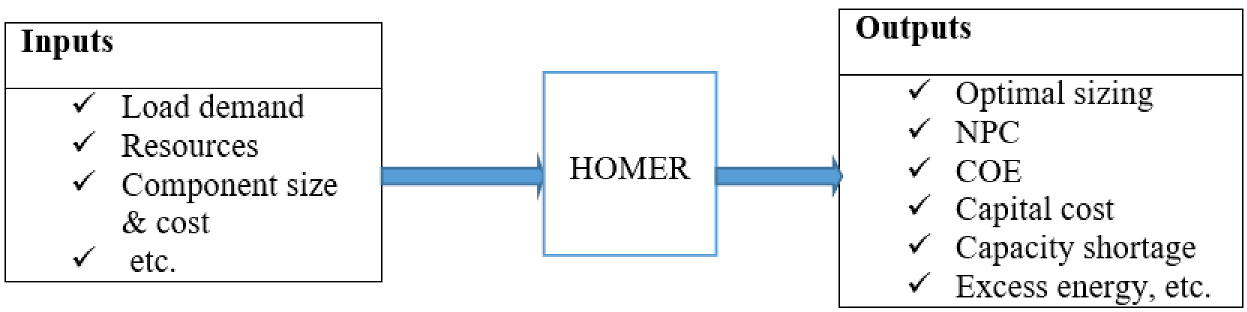

Figure 24: Inputs and outputs of the simulation software (Homer)

Once the load profile for year 4 has been built for Rwisirabo, performed a preliminary mini-grid power plant sizing exercise using HOMER Pro modeling software. The results of this exercise are presented in this section".

The simulations were performed for the two scenarios of battery autonomies described in the methodology section:

- Optimised Autonomy Scenario
- 48 hours battery Autonomy Scenario

The least-cost electricity supply method, aiming to obtain the system with the lowest Net present cost, was used. The resulting sizing obtained for a potential mini-grid in Rwisirabo is shown below:

Table 13: HOMER simulation results

Parameter	**Optimized Autonomy**	**48 hours Battery Autonomy**	**Unit**
Average daily demand (year 4)	92.61		kWh/day
Average daily demand per connection (year 4)	158.29		Wh/day
PV capacity	78	79	kWp
Battery capacity	187	357	kWh
Inverter AC output power	30	30	kW
Back-up Diesel Generator	30	n/a	
Solar Fraction	100	100	%

The figure below shows the indications of the global Horizontal solar vs PV panel power output within the village.

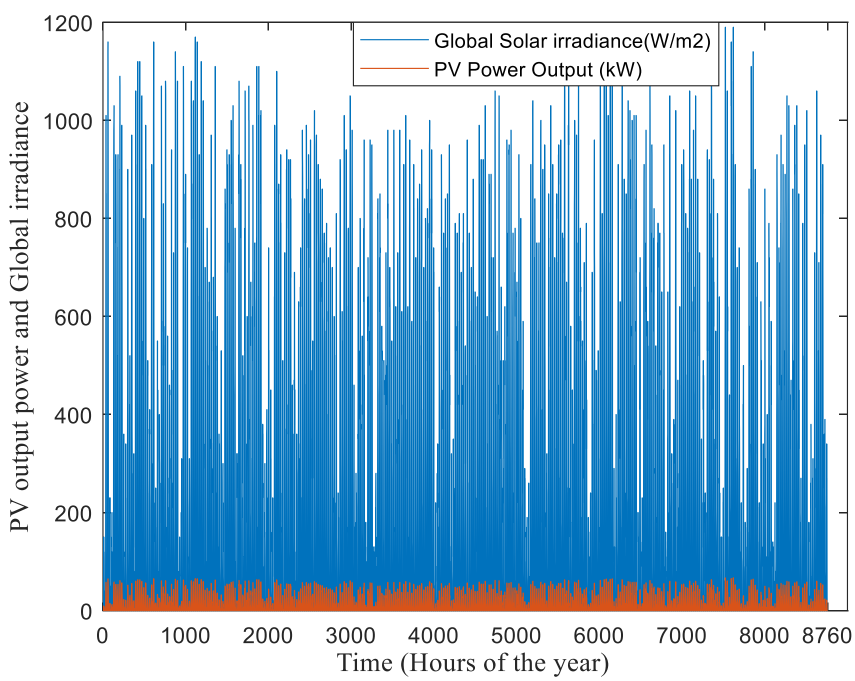

Figure 25:Fluctuation of Global Solar Irradiance and PV output power over the year

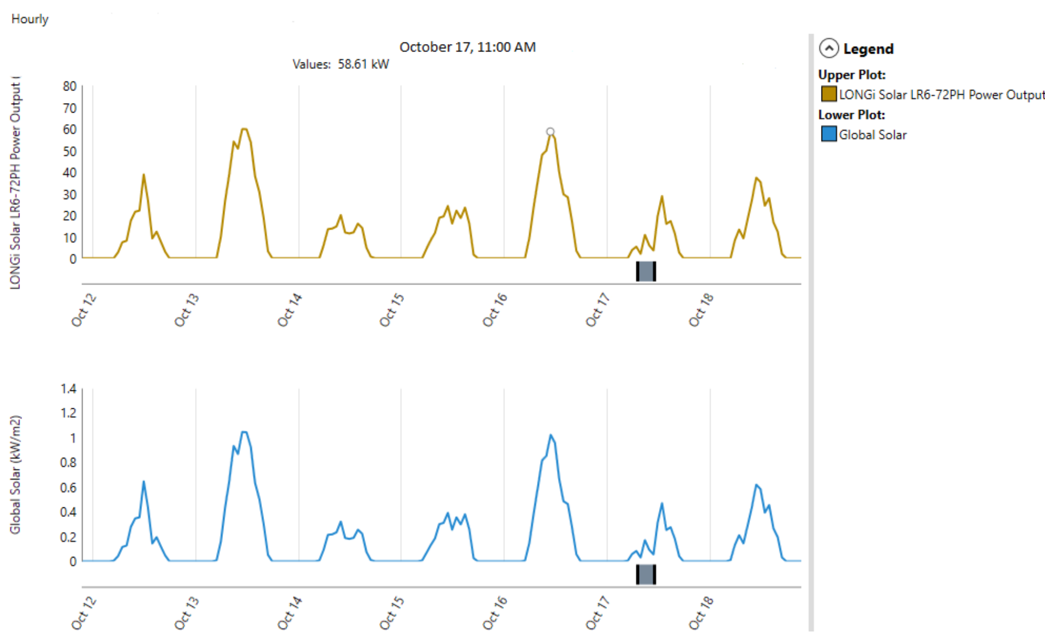

Figure 26: Global solar (kW/m2) vs PV power output (kW)

Below are the indications of the sample of load curve that will be served by the proposed mini-grid solar power plant at a given period.

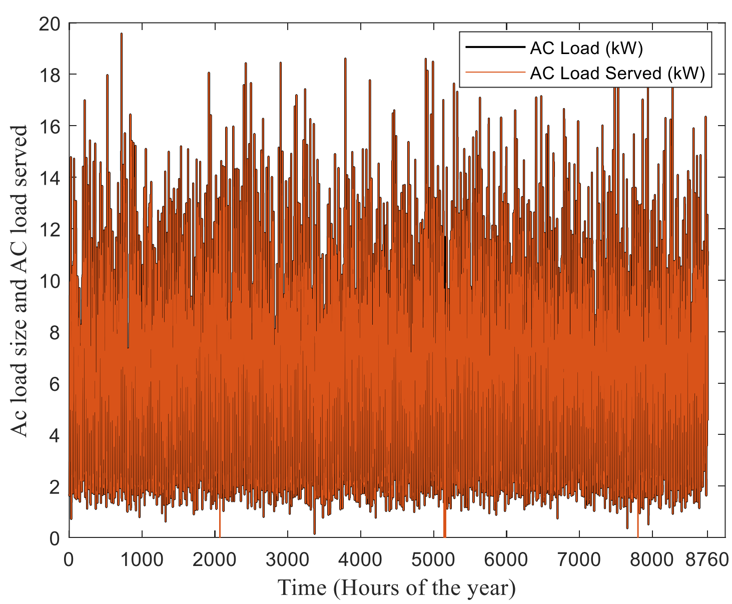

Figure 27:Status of the AC load size and AC load served over the year

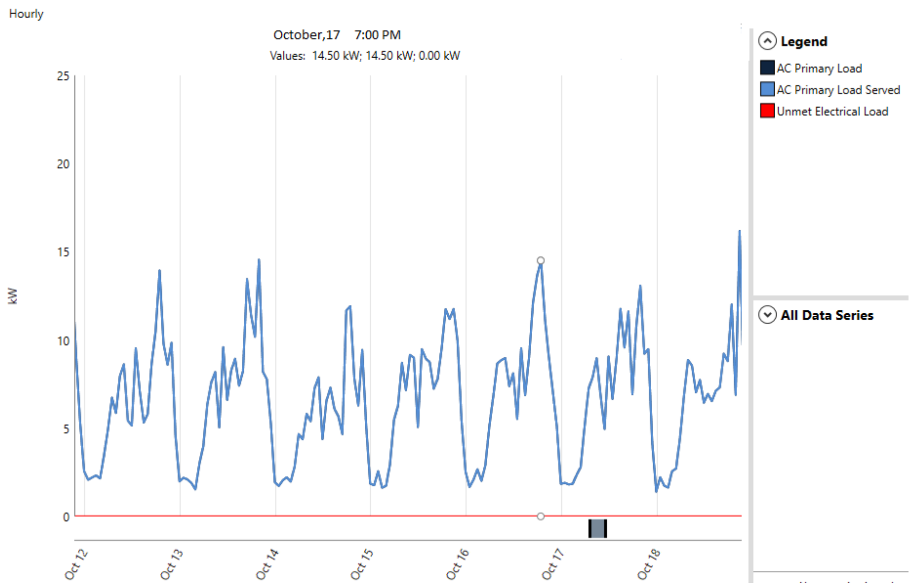

Figure 28:Total electrical load served in kW.

During peak hours, the power plant will be able to serve all required loads.

Table 14:Summary of the analysis of the results from Homer

Architecture/LR6-72PH (kW)	79		System/Ren Frac (%)	100
Architecture/eVault LFP-15	24		System/Total Fuel (L/yr)	0
Architecture/Sinexcel 30 (kW)	29		LR6-72PH/Capital Cost ($)	118500
Architecture/Dispatch	LF		eVault LFP-15/Autonomy (hr)	43.99844
Cost/NPC ($)	369703.2		eVault LFP-15/Annual Throughput (kWh/yr)	31972.51
LR6-72PH/Production (kWh/yr)	107067.2		eVault LFP-15/Nominal Capacity (kWh)	345.6
Cost/COE ($)	0.4435848		eVault LFP-15/Usable Nominal Capacity (kWh)	328.32
Cost/Operating cost ($/yr)	7932.438		Sinexcel 30/Rectifier Mean Output (kW)	0
Cost/Initial capital ($)	268300		Sinexcel 30/Inverter Mean Output (kW)	7.442648

Figure 29 shows the variation of energy storage and output over the year while figure 30 shows the fluctuations for the storage state of charge over the year. Figures 31 and 32 respectively highlight such indications over specific days.

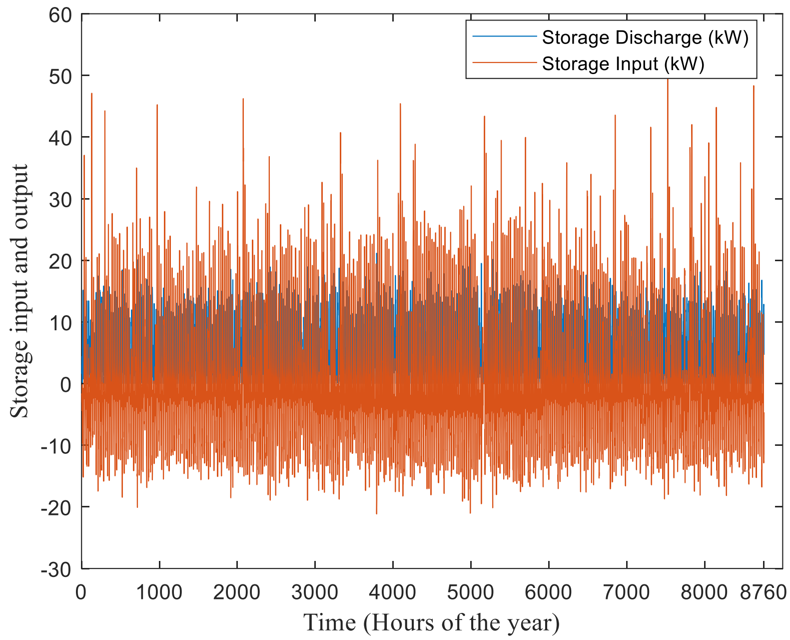

Figure 29: Variation of Storage input and output over the year

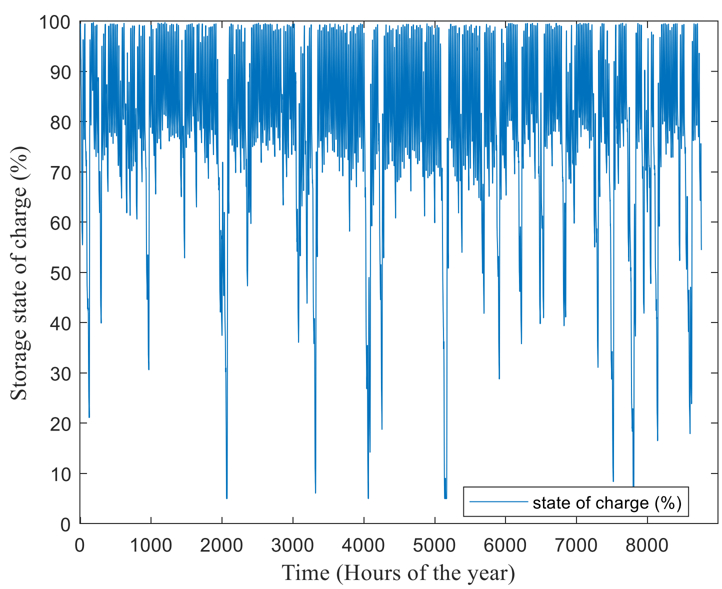

Figure 30: Fluctuation for the storage state of charge over the year

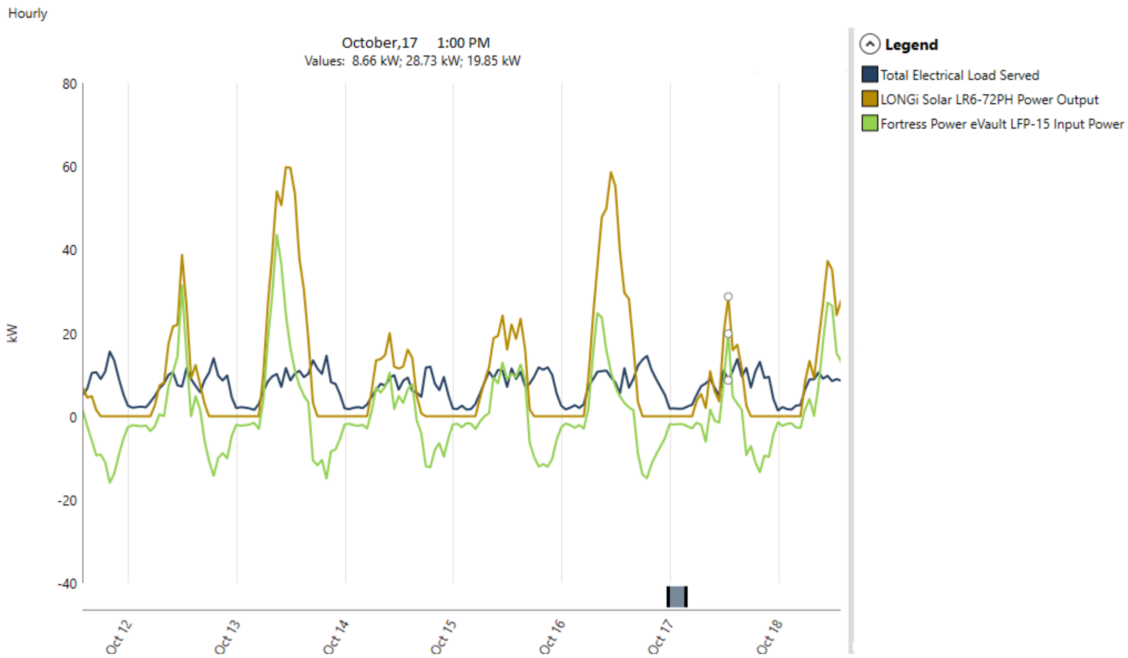

Figure 31: Battery bank input power and state of charge (LFP4

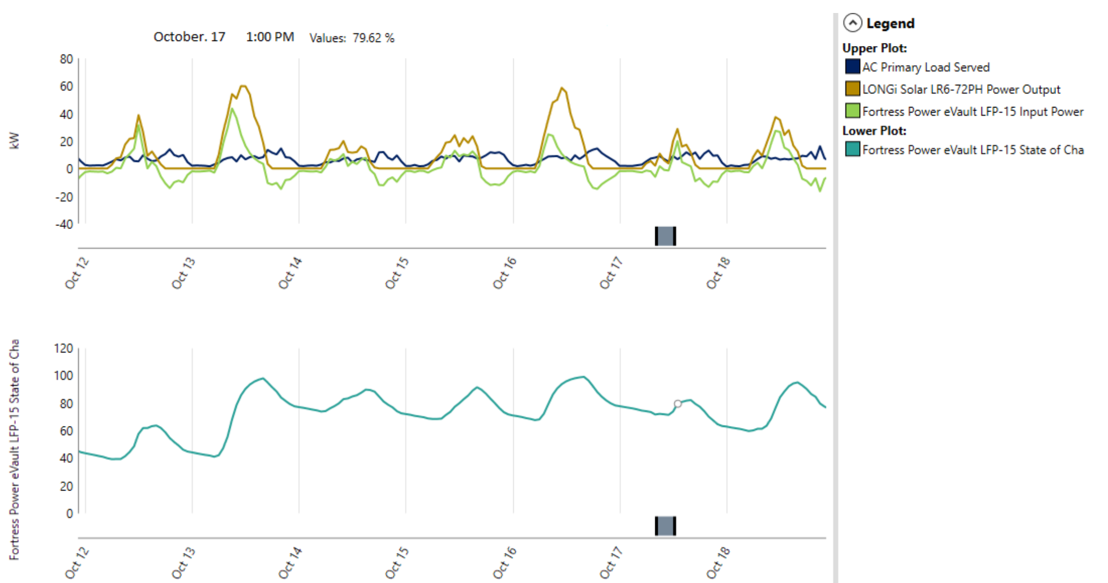

Figure 32:Fortress Power eVault 15 LFP State of Charge (%) on 17th day of October

The figure below shows the inverter output (kwh)

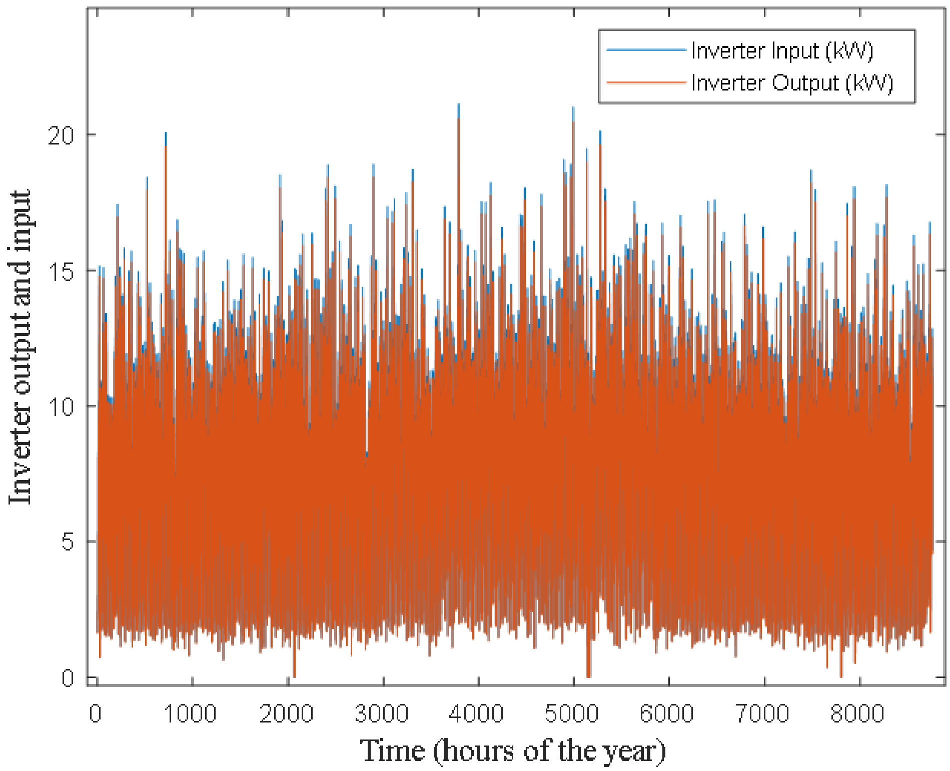

Figure 33: Variation of the Inverter input and output over the year

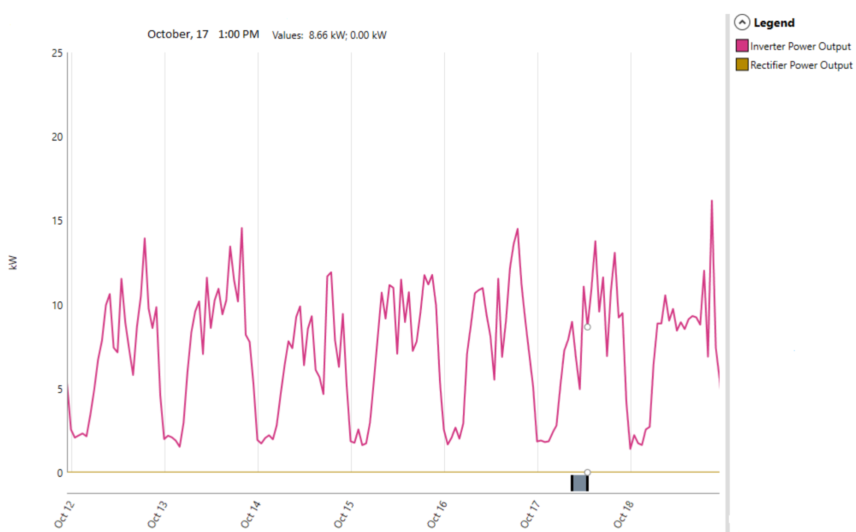

Figure 34: Converter Inverter Output (kW)

4.5.Reticulation network

Following a technical survey on-site and analysis of satellites images, as described in the methodology section, a preliminary design of the reticulation network of Rwisirabo was performed. Table 15 shows the main characteristics of the network

Table 15:Reticulation Network characteristics

Number of Connections considered for the Distribution network	LV Network (m)	Number of poles
327	4,346	87

4.6.Economic analysis

Table 16: plant economic analysis

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Fortress Power eVault LFP-15	$144,000.00	$104,423.94	$920.40	$0.00	($13,979.92)	$235,364.42
LONGi Solar LR6-72PH	$118,500.00	$0.00	$5,049.43	$0.00	$0.00	$123,549.43
Sinexcel 30kW	$5,800.00	$5,047.16	$617.86	$0.00	($675.70)	$10,789.32
System	$268,300.00	$109,471.10	$6,587.69	$0.00	($14,655.61)	$369,703.17

Summary of the Project cost

Table 17: project cost summary from Homer

	Base System	Proposed System
Net Present Cost	$369,703	$369,703
CAPEX	$268,300	$268,300
OPEX	$7,932	$7,932
LCOE (per kWh)	$0.444	$0.444
CO2 Emitted (kg/yr)	0	0
Fuel Consumption (L/yr)	0	0

In this section, the initial investments that need to be undertaken for the development of the mini-grid are presented. The CAPEX capital expenditure presented here corresponds to the designed power generation system and network plan, including pre-development costs, and allows for a 5% cost in contingencies. All equipment costs include installation. The OPEX operational expenditure and other recurring costs are not included in this research.

The table below shows the different investment costs estimated for the potential mini-grid in Rwisirabo I for the 48 hours battery autonomy scenario.

Table 18: estimated CAPEX

Material	Unit	Unit cost (USD)	Quantity	Total cost (USD)
CAPEX Generation				
Solar PV Generator	kWp	1,100	80	88,000
Power conversion (Battery Inverters)	KW	400	30	12,000
Battery bank (LFP, DC, nominal)	KWh	450	390	175,500
Powerhouse	Unit	16,350	1	16,350
Contingencies (5% of CAPEX)				14,593
Total Generation				306,443
CAPEX Distribution				
Reticulation network	m	22	4345.8	95,608
Connection costs (meter and indoor wiring)	per connection	56	362	20,272
Contingencies (5% of CAPEX)				5,794
Total Distribution				121,674
TOTAL				428,116

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

The core target of this thesis work was to find a best technical analysis of an off-grid green solar PV power plant with an acceptable autonomy period to feed a rural area especially Rwisirabo Village (as the case study). In the design of this system for the village, the yearly average solar radiation and temperature were 4.88 kWh/m^2/day and 20.47^{0}C respectively with a total number of 362 households and other infrastructures both primary AC load and deferrable loads such as water pumping. The overall average energy demand is about 158.29 kWh/day with a peak of 21kW. An off-grid SPV system cannot give a continuous supply of electricity without storage due to its intermittency, battery bank was selected upon designing suitable components including PV modules, inverter, and charge controller. The designed PV mini-grid for the Rwisirabo village system was modeled and simulated by Homer software, and therefore it was observed that designed PV mini-grid, once the implementation takes place, the cost of electricity won't exceed $0.444/ kWh).

The immense integration of renewable energy in power systems implies new challenges to the system operator due to their intermittent nature attributed to climatic conditions.[25] The system operator has limited control over the amount of electricity produced by these means. Thus, a strong contribution of these energies can cause imbalances and make electric system management more difficult.

The intermittence of the renewable energy unit results in fluctuations at the level of the produced power. For the sake of cost reduction and 'de-risking investment for prospective mini-grid developers, the Government of Rwanda would need to first identify suitable sites and undertake a financial and technical feasibility study. Where the provision of access through a mini-grid represents the least cost option, Government will need to undertake measures to stimulate demand, through either policy or investment such as subsidy mechanisms.

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APPENDICES

ANNEX1. PV MODULE DATASHEET

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR6-72HPH-365M		LR6-72HPH-370M		LR6-72HPH-375M		LR6-72HPH-380M		LR6-72HPH-385M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	365	270.4	370	274.1	375	277.8	380	281.5	385	285.2
Open Circuit Voltage (Voc/V)	48.4	45.2	48.6	45.4	48.8	45.6	49.0	45.7	49.2	46.0
Short Circuit Current (Isc/A)	9.71	7.82	9.79	7.89	9.87	7.95	9.96	8.02	10.03	8.09
Voltage at Maximum Power (Vmp/V)	40.0	36.9	40.2	37.1	40.4	37.3	40.6	37.5	40.8	37.7
Current at Maximum Power (Imp/A)	9.13	7.32	9.21	7.38	9.28	7.44	9.36	7.50	9.43	7.57
Module Efficiency(%)	18.3		18.5		18.8		19.0		19.3	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25℃, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20℃, Spectra at AM1.5, Wind at 1m/S

Temperature Ratings (STC)

Temperature Coefficient of Isc	+0.057%/℃
Temperature Coefficient of Voc	-0.286%/℃
Temperature Coefficient of Pmax	-0.370%/℃

Mechanical Loading

Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

ANEX 2. BATTERY DATASHEET

FORTRESS POWER

eVault Max 18.5 Lithium Battery Storage

FORTRESS POWER
Secure your energy

EVAULT MAX 18.5 LITHIUM BATTERY STORAGE

The newest innovative Lithium Iron Phosphate battery from Fortress Power is the eVault Max 18.5 kWh. An all-in-one solution for your residential and commercial needs. Scalable up to 370kWh with a serviceable top cover access to make installation of this battery simple and worry free. The eVault Max is AC/DC coupled to solar arrays and works for many applications that require solar storage, including Off-Grid, Back Up power, self-supply and Peak Charge Reduction just to name a few.

The eVault Max 18.5 is The Largest Single Residential Battery On The Market!

- Safe Lithium Iron Phosphate Technology (LiFeP04)
- High Durability and Long-Lasting
- Closed Loop Communication with Inverters
- Scalable from 18.5 kWh - 370 kWh
- Intelligent Digital Processor Based BMS
- Advanced cell level monitoring and balancing
- IP55 Aluminum Industrial Grade Enclosure
- Touch screen LCD performance display

Electrical Specifications	
Nominal Voltage	51.2V
Nominal Capacity	360AH
Rated Capacity @ 0.5C (180A)	18.43 kWh
Resistance	<10 mΩ
Communication Protocol	CAN/RS485
Efficiency (at 0.5C)	98%
Self-Discharge	<1 % / Month
Maximum Allowed Modules in Parallel	20

Charge Specifications	
Recommended Charge Current	150A
Maximum Charge Current	180A
Recommended Charge Voltage	54.4V

Mechanical Specifications	
Dimensions: (L*W*H)	20.3" x 20.3" x 42.2" (515 x 515 x 1073mm)
Weight	520 lbs (235.87 kg)
Terminal Type	M10
Ring Terminal Size	1/2" or larger
Terminal Torque	7.0 - 7.7 Nm (5.1 - 5.7 ft - lb)
Case Material	Industrial Grade Aluminum
Enclosure Protection	IP55
Cell Type Chemistry	Prismatic - $LiFePO_4$

Compliance Specifications:	
Certifications	UL1642, UL1973, UL9540
Shipping Classification	UN 38.3. UN 3480, Class 9

Discharge Specifications	
Recommended Continuous Discharge Rate	150A (7.6 KW)
Peak Continuous Discharge Rate	180A (9.2 KW)
Maximum Surge Power Rate	200A (10.2kW 10S)
Recommended Low Voltage Disconnect	48V
Battery Low Voltage Protection	<46V
Battery Recovery Voltage	47V

Temperature Specifications	
Discharge Temperature	-4°F~140°F (-20°C ~ 60°C)
Charge Temperature	32°F ~ 120°F (0°C ~ 49°C)
Storage Temperature	6 months: 14°F ~ 77°F (-10°C ~ 25°C) 3 months: -4°F ~ 113°F (-20°C ~ 45°C)

ANEX 3. INVERTER DATASHEET

Model: PWS2-30k-EX

Features

- 30kW High power density
- Bi-directional Power Conversion System
- Grid-support functions
- Virtual Synchronous Generator (VSG) technology for parallel off-grid application

Specification

Battery Side	
Charging and Discharging voltage range	150V-750V(350V-750V @full load)
Rated Power	30kW
Maximum Power	33kW
Maximum Charging and Discharging Current	90A
Battery Switch-off Mode	Relay
Over Voltage Protection	Software Protection
Over Current Protection	Software Protection & DC Fuse
Bus Side	
Rated Power	45kW
Input Voltage Range	700V-830V
Maximum Input Current	32.5A*2

AC Grid-tied Output	
Rated Output Power	30kW
Maximum Apparent Power	33kVA
Maximum Active Power	33kW
Rated Grid Voltage	3/n/PE, 400VAC
Power Factor	Listed: 0.8~1 leading or lagging Actual:0.1~1 leading or lagging
THDi	<3%
AC Off-grid Output	
Rated Output Power	30kW
Maximum Apparent Power	33kVA
Maximum Active Power	33kW
Rated Grid Voltage	3/n/PE, 400VAC
Power Factor	Listed: 0.8~1 leading or lagging Actual:0.1~1 leading or lagging
Overload Capacity	110%~120%, 10 min

	120%~150%, 200 ms	
Off-grid and parallel mode		
	Droop control parallel	Communication parallel
Whether need transformer	Yes	No
Maximum number of parallel	10	8
Total length of parallel lines	No limit	7m
Efficiency		
Peak Efficiency	97.3%	
CEC Measured Efficiency	96.5%	
Communicaiton		
Communication Port	CAN/RS485/Ethernet/WIFI	
General Specification		
Dimension(W*H*D)	440*173*596mm	
Cooling	Forced Air Cooling	
Weight	43kg	
Topology	Non-isolation	
Operation Altitude	4000m(>2000m derating)	
Operation Environment Contamination Level	≤2	
Temperature & Humidity	-30℃~60℃（>45℃ derating）& 0-95%	
Noise	≤65dB	
IP Rating	IP20	

ANNEX 4: SUMMARY OF ELECTRICAL SIMULATED RESULTS FROM HOMER

Simulation Results

System Architecture: Sinexcel 30kW (29.0 kW)
LONGi Solar LR6-72PH (79.0 kW) HOMER Load Following
Fortress Power eVault LFP-15 (24.0 strings)

Total NPC: $369,703.20
Levelized COE: $0.4436
Operating Cost: $7,932.44

Cost Summary | Cash Flow | Compare Economics | Electrical | Renewable Penetration | Fortress Power eVault LFP-15 | LONGi Solar LR6-72PH | Sinexcel 30kW | Emissions

Production	kWh/yr	%
LONGi Solar LR6-72PH	107,067	100
Total	107,067	100

Consumption	kWh/yr	%
AC Primary Load	57,620	88.4
DC Primary Load	0	0
Deferrable Load	7,577	11.6
Total	65,198	100

Quantity	kWh/yr	%
Excess Electricity	39,675	37.1
Unmet Electric Load	188	0.287
Capacity Shortage	260	0.398

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	1,899	%