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Design and Modelling of PV Power Plant for Rural Electrification in Kayonza, Rwanda

Alexis Bakundukize[1], Maurice Twizerimana[1,2,3*], Dushengere Bernadette[1,4,5], Bizabakoraho Jean Pierre[1] and Nsekambabaye Theoneste[1]

[1]African Centre of Excellence in Energy for Sustainable Development (ACE-ESD), College of Science and Technology, University of Rwanda, Kigali, Rwanda.
[2]Africa Centre of Excellence II in Phytochemicals, Textiles and Renewable Energy (ACE II PTRE), Moi University, Eldoret, Kenya.
[3]Department of Manufacturing, Industrial and Textile Engineering, School of Engineering, Moi University, Eldoret, Kenya.
[4]Department of Mechanical and Production Engineering, School of Engineering, Moi University, Eldoret, Kenya.
[5]Mobility for Innovative Renewable Energy Technologies (MIRET), Moi University, Eldoret, Kenya.

Authors' contributions

This work was carried out in collaboration among all authors. Authors AB and MT designed the study, performed the experiment wrote the protocol and wrote the draft of the manuscript and managed the analyses of the study. Authors DB, BJP and NT managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This study aimed to design and model an off-grid SPV power plant with a storage system to meet the load required in Rwisirabo village.

Study Design: PV modules, inverter, charge controller, and Batteries have been designed, reproduced/simulated, and optimized for the rural area of Rwisirabo village in Kayonza district, Eastern Province, Rwanda.

Place and Duration of Study: The experiment has been done in the University of Rwanda/ African Centre of Excellence in Energy Studies for Sustainable Development (UR/ACE-ESD) High E-Tech Smart Grid Laboratory, Kigali, Rwanda between October 2020 and February 2021.

**Corresponding author: E-mail: twizerimanamaurice@gmail.com;*

Methodology: Different methodologies have been applied to address the objective of this work. The site was identified, problems of the community were clearly stated, data required for the work was collected through various data collection mechanisms, and different literature was reviewed to identify the way to do this work. The data were collected from different sources and were analysed using a software tool (HOMER software) and simulated for getting a solution for the problems and challenged accordingly. An Off-grid Solar Photovoltaic Power Plant was established in Rwisirabo village in Kayonza District, Rwanda. This site has been chosen because, in the Mwiri sector, Kageyo cellule in Rwisirabo (Rwisirabo II) village is listed by National Electrification Plan (NEP) as the site to construct an off-grid solar PV Power Plant.

Results: Based on the load assessment and the design of the SPV system, the primary AC load of the village was 551,718 kWh/day with a peak load of 85.10 kW, the deferrable load was about 9.99 kWh/day and a deferrable peak load of 2.00 kW with the cost of energy (COE) $0.200/kWh were involved during optimization of the power plant. It also found that the peak demand of the community occurs from 18:00 to 20:00 hours because most of the household members would expect to be at their homes. The system items such as PV module, batteries, and inverter size have been found as an optimum system with 220 kW, 860 BAE PVS 210 batteries, and 110 kW respectively with a lifespan of 25 years of the project. The total net present cost (NPC), initial capital, operating cost, and Levelized COE for this off-grid SPV system were $903,829, $517,000, $17,522, and $0.200/kWh respectively. The monthly results of power generation in kW obtained after stimulation with software showed that the solar radiation is high in March, July, August, and September which brings more electric power generation. However, all months the power electricity remain generated. Results from simulation showed that this system generated mean power output of 220 kW and total production of 297,291 kWh/year. It approved that the system converter contributed the lowest NPC with $52,888.25 (6%), followed by PV modules that cost $244,284.28 (27%) and battery bank the first for this SPV system with a cost of $606,656.60 (67%). This optimal system uses 100% renewable energy.

Conclusion: It found that the implementation of an SPV system with battery storage in residential, commercial, and institutions in the area where the solar irradiance is concentrated across a country will reduce the cost of electricity and power interruption on the national grid. Therefore, further work is needed to optimize this system for rural electrification as well by integrating with other renewable sources available in the country and also extend the electrification to another area that is detached from the national grid.

Keywords: Design of SPV; modelling; load estimation; SPV; rural electrification; HOMER software; rwisirabo village.

1. INTRODUCTION

Rwanda, is a small country in East Africa with more than 12,089,721 people on a total area of 26,338 km^2, with 94.7% and 5.3% of it are occupied by land and water respectively [1,2], As of December 2019, the total access to electricity in Rwanda is 52.8% whereby 38.5% and 14.3% of all households in Rwanda are attached to the on-grid and used it through off-grid solutions respectively [3]. 82.7% of Rwandan people live in rural areas [4] and there is a major test of expanding power access especially in provincial towns. Currently, the total installed capacity to generate electricity in Rwanda is 224.6 MW from more than 40 power plants, mainly hydropower sources. Only 11% of the available capacity is imported while the rest is domestically generated (Fig. 1). By generation technology mix, 39% is from hydrological resources, followed by Methane Gas (25%) and thermal sources with 19% [5]. The majority of Rwandan people live in rural areas and they live on farming and cattle breeding but they have no electricity access and as a result, it is impossible for them to add value to their products and live a better and modern life.

As extending a national grid in Rwanda it has many challenges such as ensuring transmission for aligning with the new generation and ensuring timely maintenance and servicing of infrastructure as the maintenance and servicing are costly and challenging. Transmission lines are complex and interconnected with large infrastructure and large numbers of smaller pieces of equipment sometimes in remote areas and many of the existing equipment is decades old. So regular and planned maintenance is required continuously to ensure that it operates efficiently [4]. Grid extension is affected by economic constraints like settlements, which are found in hilly places, forests, or hard to reach areas, being located far away from the existing grid, a small number of population and households, Low daily energy demand probably even soon as the electrical loads are mostly lamps and telecommunication devices and also by considering low-income level, low affordability and technical skills of people live there.

Due to their remote areas, high costs are needed in grid extension, and also high losses will be increased while transporting power to isolated areas from the national grid. Therefore, to minimize this problem, the design of an off-grid solar photovoltaic (SPV) power plant that easily implemented with low cost and making all people served from this technology by installing it around their houses is required. Among the renewable energy sources, SPV systems are encouraging because electric energy generated by solar cells is not harmful to the environment and is quiet, they do not use fuel other than sunlight [5]. Photovoltaic (PV) systems do not produce any harmful air or water pollution into the environment. Solar energy is a locally available renewable resource [7]. The extensive use of photovoltaic plants for electrical power generation, ranging from large scale to solar home system, the design of truthful and reliable system approaches to monitor and analyse their production performance are required [8]. Energy from solar is mainly generated depending on the solar radiation reaching the SPV modules and their wavelengths [9]. The solar PV components such as PV modules, charge controller, inverter, and storage unit (battery bank) are put together depends on the system application, site location, and the required design or the type of SPV system. During hand calculation for sizing and designing this SPV system, the following components (PV modules, inverters, Batteries, Charger Controllers, DC and AC cables) will be focused on. The PV system's efficiency variation is based on different factors where climate conditions, PV module's sort, an inverter's efficiency, and type are majors. Apart from the above-said parameters, site area is also important for a PV plant design [10]. A systematic approach is required and important when designing and modelling off-grid SPV systems. Furthermore, the extensive use of PV plants for electrical power generation, ranging from large scale to solar home system, the design of truthful and reliable system approaches to monitor and analyse their production performance are required [8]. Rwanda's geography is represented by savannah climate with 5 kWhm^2/day of solar radiation intensity, and peak sun hours nearly 5 hours per day, which indicate energy from solar systems would be abundant and reliable once properly exploited [11,12]. The range of day-by-day solar irradiation in Rwanda is 4 kWh/m² in the north region of Rwanda to 5.4 kWh/m² South of Kigali, in the Southern and Eastern regions. Assessment of all-out yearly potential is around 66.8 TWh.

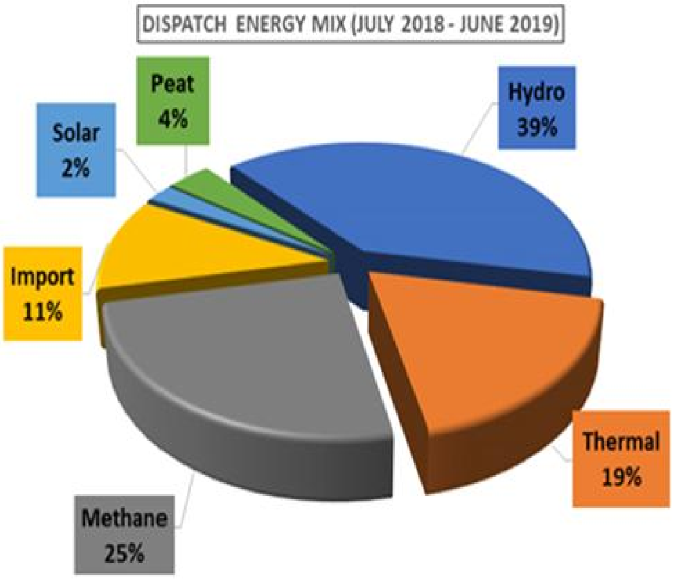


Fig. 1. Total installed capacity in Rwanda [6]

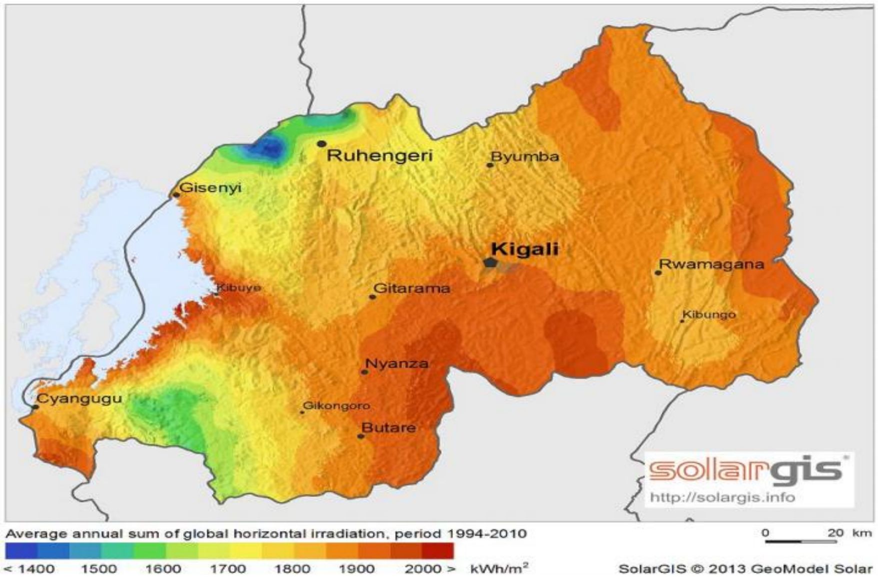


Fig. 2. Global horizontal radiation of Rwanda [12]

Numerous studies have been led to show where insolation is concentrated concerning the Rwandan map, how the SPV system is designed, its parts, and model [5,12,13]. Rwanda has weather parameters that allow the harvesting of enough solar energy for electricity production [14]. However, until now in this country, there are only three SPV power plants that are on–grid-connected while there are many areas in different villages located far away from the National grid which need electricity for supplying AC primary and deferrable load. This work will fill the gap by designing and modelling cost-effectively scalable storage an off-grid SPV system in Rwanda at Rwisirabo village to provide reliability and energy efficiency. The Hybrid Optimization Model for Electric Renewable (HOMER) software was used for accomplishing a task. It is exceptionally not the same as related works regarding the application, load consumption, weather parameters, and region of the chosen zone. This site has been chosen because, in the Mwiri sector, Kageyo cellule in Rwisirabo (Rwisirabo II) village is listed by the National Electrification Plan (NEP) of constructing an off-grid SPV Power Plant. The main objective of this work was to design the SPV power plant to electrify rural areas in Rwanda so that further the Government has the required knowledge for implementing similar projects in rural villages of Rwanda. Estimation of the average daily energy consumption at the selected site, analysis of the monthly solar radiation at the selected site, design an efficient SPV plant with an optimized storage system and components, and Model and simulate the performance of PV power plant have been done in this study.

2. MATERIALS AND METHODS

2.1 Introduction

Different methodologies have been applied to address the objective of this work. The site was identified, problems of the community were clearly stated, data required for the work was collected through various data collection mechanisms and different literature were reviewed to identify the way to do this work and the data collected from different sources were analysed using a software tool (HOMER software) and simulated for getting a solution for the problems and challenged accordingly. An Off-grid Solar Photovoltaic Power plant was established in Rwisirabo village in Kayonza District, Rwanda. This site has been chosen because, in the Mwiri sector, Kageyo cellule in Rwisirabo (Rwisirabo II) village is listed by National Electrification Plan (NEP) as the site to construct an off-grid solar PV Power Plant (Fig. 3). The experiment has been done in the University of Rwanda/ African Centre of Excellence in Energy Studies for Sustainable Development (UR/ACE-ESD) High E-Tech Smart Grid Laboratory, Kigali, Rwanda between October 2020 and February 2021.

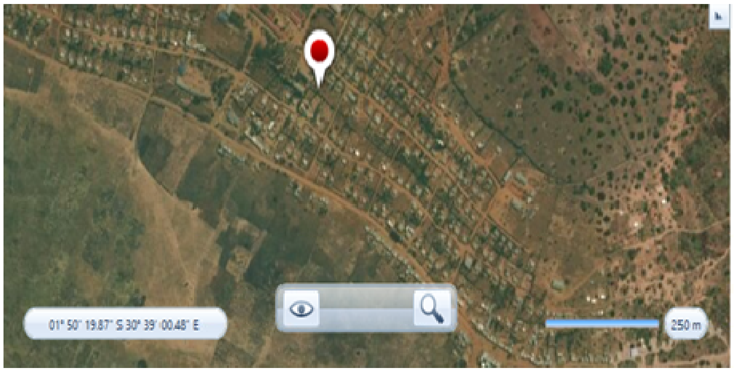


Fig. 3. Rwisirabo village location

2.2 The Data Collection

The first data were solar radiation, wind speed, number of households, and energy equipment cost related to the proposed system configuration and technologies were collected from the National Aeronautics and Space Administration (NASA), Kayonza District Administration office, and different literature respectively (Table 3). The second data was collected by conducting a field survey. During the field survey, the primary data necessary for this project were the number of religious institutes (churches), bars, unisex salons, small factories, and types of community services, such as schools, health centres, and Administration posts (Table 1).

Data sourced from NASA from surface meteorology and solar energy database using geographical coordinates through HOMER software; longitude $30^{0}39.4'$E and latitude $-1^{0}50.4'$S shows the 22 years 'monthly average solar source of the region changes from 5.220 kWh/m^2/day in February to 4.540 kWh/m^2/day in November, and an average monthly global horizontal radiation and Temperature are 4.88 kWh/m^2/day and 20.47℃ respectively (Table 2).

2.3 Assessment of Energy required

In off-grid SPV systems, estimating the total daily energy which is required from the village and assessing the solar resource availability to the input of PV module are the most important works which have to be done properly. The load estimation is mainly concerned with calculating the power and energy demand of the community by considering different dimensions, site location, load type, and time. The variation of the load depends on time, therefore, in planning daily load variations are needed. The community's load for Rwisirabo village have been categorized into five classes as follows:

1. Home or domestic area which incorporates with lighting, Charger, television (TV), Radio, and so forth.
2. Commercial load includes flour processing machines, smaller shops, and so forth.
3. Community loads which comprise secondary school lighting, personal computer, printer, scanner, and others.
4. Health facility which incorporates immunization cooler, correspondence radio, TV, magnifying instrument, personnel computer (PC) and printer, DVD player, and others.
5. Administration post office.

Table 1. The primary data collected

Primary data collected	Value	Data source
Number of primary schools	0	Field survey
Number of secondary schools	1	Field survey
Number of Health Centre	1	Field survey
Number of the police post	1	Field survey
Number of churches	1	Field survey
Number of bars & chops	8	Field survey
Number of unisex salons	2	Field survey
Small factories	1	Field survey

Table 2. An aerial view of Kageyo community accessed from NASA database

Month	Daily solar radiation horizontal kwh/m^2/d	Temperature	Wind speed (m/s)	Clearness Index
January	4.930	19.850	2.870	0.481
February	5.220	20.680	2.970	0.497
March	4.970	20.180	2.750	0.473
April	4.830	19.720	2.770	0.479
May	4.710	20.620	3.310	0.498
Jun	4.830	21.130	3.890	0.531
July	5.140	21.260	3.600	0.555
August	5.090	22.040	3.440	0.519
September	5.070	21.680	2.990	0.491
October	4.680	19.960	2.650	0.448
November	4.540	19.20	2.500	0.443
December	4.570	19.260	2.370	0.452
Annual	4.88	20.47	3.01	

Table 3. Secondary data collected for the village understudy

Secondary data collected	Range	Data source
Solar Irradiance, Wind and Temperature source	July 1983-June 2005 (22 years)	NASA and Meteo Rwanda
Number of households	500	District office

2.3.1 Stepladders for load assessment

1. List all of the 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 number of hours per day each item will be used.
5. Multiply steps 2, 3, and 4 to calculate the total electrical energy required per day.

2.3.2 Estimation of primary Load

Tables 4-10 show the estimation of the primary load of domestic, Administration police post, commercial loads, mini shops, unsex hair salon, health post, Community Church, secondary school, and the summary of total AC daily primary load of village respectively.

2.3.3 Deferrable load

Deferrable load is electrical demand that can be met within some period, yet the specific timing is not significant. This type of load is generally categorized as deferrable because they have some storage associated with them. Water pumping is a typical example, there is some flexibility as to when the pump essentially operates, providing the water tank does not run dry. Other examples consist of ice making and battery charging [15]. The water pumps are required for the household community, health clinic, and school, church, and police posts. For considering 100 litres/day as average water required per house and 2000 litre/day for each one of Health centre, school, church and police station [16]. For Water pump estimation, domestic animals were included in the estimation of daily water demand per family per day. The total amount of water required for 500 households will calculate as:

$$500 \times 100 = 50{,}000 \text{ litres/day } (50\text{m}^3/\text{day})$$

The Flow rate $(\mathrm{Q}) = \frac{50 \times 1000}{6 \times 3600} = 2.3 \text{ litre}/\sec$, taking 6 hours as pump operating time per day.

The power rating of the water pump (P) will be

$$\mathrm{P} = {}^{\mathrm{ghQ}}/_{\eta}\,, \tag{1}$$

by taking 20 m as height (h), and gravity force (g) as $9.81\, m/S^2$, and η is a pump efficiency (90 %). The energy storage capacity (W) will be calculated as follows

$$\mathrm{W} = \text{pump rating} \times \text{capacity of pumps storage/day} \times \text{running hours/day} \tag{2}$$

Here, water storage capacity for 3 days was used in this work. Therefore, W for households is

$$\mathrm{W} = 0.5 \times 3 \times 6 = 9\text{kWh}$$

Table 4. Domestic load

Residential Load							
Type	**Appliance type**	**Rating (W)**	**No. of Appliance**	**Total Power**	**Run time (h/day)**	**Wh/day**	**Time Interval**
High class	Lamps	11	4	44	8	352	21:00-06:00
	Lamps	11	8	88	3	264	18:00-21:00
	TV	120	1	120	3	360	18:00-21:00
	Radio	10	1	10	12	120	05:00-17:00
	Mobiles	5	4	20	2	40	05:00-07:00
	Iron	1000	1	1000	1	1000	06:00-07:00
	Refrigerator	200	1	200	12	2400	05:00-17:00
	DVD player	30	1	30	2	60	11:00-13:00
	Computer	100	1	100	2	200	17:00-19:00
	Water pump	0	0	0	0	0	
Total				1612		4796	
No. of hours						50	
Total				80,600		239,800	
Middle class	Lamps	11	2	22	8	176	21:00-05:00
	Lamps	11	4	44	3	132	18:00-21:00
	Mobiles	5	2	10	2	20	05:00-07:00
	Radio	10	1	10	4	40	17:00-21:00
	TV	120	1	120	2	240	18:00-20:00
Total				206		608	
No. of hours						200	
Total				41,200		121,600	
Low class	Lamps	11	4	44	3	132	18:00-21:00
	Lamp	11	1	11	9	99	21:00-05:00
	Mobiles	5	4	20	2	40	05:00-07:00
	Radio	10	1	10	14	140	06:00-21:00
Total				85		411	
No. of houses						250	
Total				21,250		102,750	

Table 5. Administration police post

Type of Appliances	No of Appliance	Rating (W)	Total Power (W)	Run time (h/day)	Wh / day	Time Interval
Lamps	10	11	110	3	330	18:00-21:00
Lamps	4	11	44	8	352	21:00-05:00
Radio	1	10	10	10	100	10:00-20:00
Charger	7	5	35	2	70	15:00-17:00
TV	1	75	75	2	150	19:00-21:00
Computer	1	100	100	2	200	11:00-13:00
Printer	1	800	800	1	800	15:00-16:00
Other		250	250	2	500	
Total			1424		2,502	
No. of Adm. Post					1	
Total			1,424		2,502	

Table 6. Commercial loads

Small factory						
Type of Appliances	**No of Appliance**	**Rating (W)**	**Total Power (W)**	**Run time (h/day)**	**Wh/day**	**Time Interval**
Flour mill	1	1,000	1,000	2	2,000	12:00-14:00
	1	1,000	1,000	2	2,000	14:00-16:00
Lamps	2	11	22	3	66	18:00-21:00
Radio	1	10	10	4	40	12:00-16:00
Mobile	7	5	35	2	70	12:00-14:00
Others		250	250	3	750	10:00-13:00
Total			2,317		4,926	
No. of Factory					1	
Total			2,317		4,926	
Mini shops and unisex hair salon						
Lamps	4	11	44	3	132	18:00-21:00
Lamps	2	11	22	9	198	21:00-05:00
Radio	1	10	10	10	100	10:00-20:00
Charger	2	5	10	2	20	11:00-13:00
Refrigerator	1	200	200	12	2,400	08:00-20:00
TV	1	75	75	3	225	18:00-21:00
Computer	1	100	100	2	200	12:00-14:00
Total			461		3,275	
No. of commercial					10	
Total		4,610			32,750	

Table 7. Health post

Type of Appliances	No. of Appliance	Rating (W)	Total Power (W)	Run time (h/day)	Wh/day	Time Interval
Lamps	30	11	330	12	3960	18:00-06:00
Charger	7	5	35	2	70	12:00-14:00
TV	1	100	100	8	800	08:00-16:00
Computer	3	75	225	6	1350	08:00-14:00
Printer	1	800	800	1	800	14:00-15:00
Lab equipment	1	1,000	1,000	24	24,000	00:00-24:00
Other		100	100	4	400	10:00-14:00
Total			2,590		31,380	
No. of Health post					1	
Total			2,590		31,380	

Table 8. Community church

Type of Appliances	No of Appliance	Rating (W)	Total Power(W)	Run time h/day	Wh/day	Time Interval
Lamps	10	11	110	3	330	18:00-21:00
Charger	10	5	50	2	100	12:00-14 :00
TV	1	100	100	2	200	15:00-16:00
Computer	2	75	150	2	300	12:00-14:00
DVD player	1	30	30	3	90	10:00-13:00
Other		250	250	4	1000	08:00-12:00
Total			690		2,020	
No. of church					1	
Total			690		2,020	

Table 9. Secondary school

Type of Appliances	No of Appliance	Rating (W)	Total Power	Run time (h/day)	Wh/ day	Time Interval
Lamps	50	11	550	12	6600	18:00-06:00
Charger	5	5	25	2	50	17:00-19:00
TV	1	100	100	3	300	18:00-21:00
Computer	20	75	1500	4	6000	10:00-14:00
Radio	2	10	20	2	40	06:00-08:00
Other		250	250	4	1000	08:00-12:00
Total			2445		13,990	
No. of school					1	
Total			2,445		13 ,990	

Table 10. Summary of total AC daily primary load of village

Types	Number	Amount in energy required (Wh/day)	The total amount of Energy required (Wh/day)
Households (500)	High class (50)	4,796	239,800
	Middle class (200)	608	121,600
	Low class (250)	411	102,750
Community Church	1	2,020	2,020
Secondary School	1	13,990	13,990
Health Post	1	31,380	31,380
Admin Police Post	1	2,502	2,502
Small Factory	1	4,926	4,926
Mini shops, salon,	10	3,275	32,750
Total AC Primary load			551,718

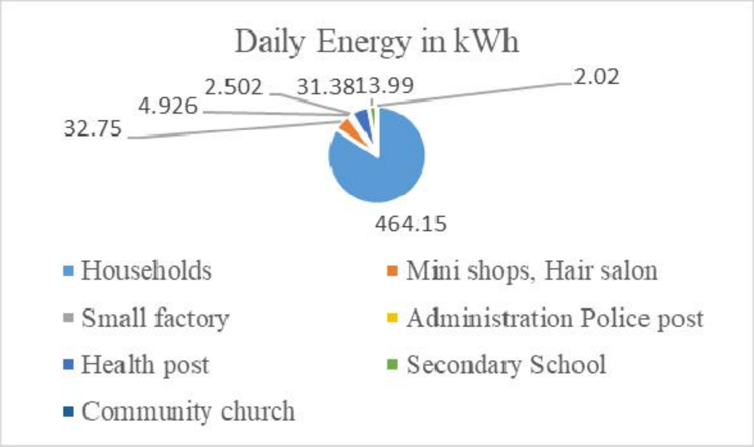


Fig. 4. Daily AC primary energy profile

Table 11. Energy demand of the AC primary and deferrable load

Energy demand	Amount
Daily Energy Use (kWh)	551.718
Monthly Energy Use (kWh)	16,551.54
Annual Energy Use (kWh)	198,618.48
Peak Sun Hour (PHS)	4.88 hours
Deferrable load in kWh	10.8

Energy storage capacity for public infrastructure is 1.8 kWh, hence the total energy storage for deferrable load is 10.8 kWh. Table 11 shows the energy demand of the AC primary and deferrable load.

2.3.4 Energy forecasting

The current electric load was taken to be 551,718 kWh/day, the following formula is used for Energy forecasting calculation [16].

$$\mathrm{E_n} = \mathrm{E_0}(1 + \frac{\mathrm{r}}{100})^{\mathrm{n}} \tag{3}$$

Where: E_n = electric energy at the nth year in kWh, E_0 = current electric energy demand, and r = annual electric load growth, is 10% [2]. Fig. 5 shows the approximate results of AC primary load forecasting (energy) in ten years of Rwisirabo village.

2.4 Solar Photovoltaic Power Plant Design

In this work, the input parameters are solar irradiance and temperature from the identified site which was Rwisirabo village. The main system design methods were based on the daily energy demand assessment in Rwisirabo which was 551,718 kWh/day. The work also dealt with the sizing and specifying of PV array, inverter, battery bank, and Charger controller.

2.4.1 Mathematical modelling of SPV system component

2.4.1.1 Mathematical modelling of PV system

The operation and performance of the PV module are based on its maximum power, the models that describe the PV module's maximum power output behaviours are more practical for PV system assessment. The output power (P_{PV}) of the SPV will be calculated by using the input parameters which are the solar radiation available on the titled surface, the ambient temperature, and the manufacturer's data for the PV modules [17–19].

$$\mathrm{P_{PV}} = \eta_{\mathrm{g}} \times \mathrm{N} \times \mathrm{A_m} \times \mathrm{G_t} \tag{4}$$

Where η_g = instantaneous PV generator efficiency, A_m = area of a single module (m^2), G_t = global irradiance incident on the tilted plane (KW/m^2), and N = number of modules. Assuming that all energy losses in the PV array (connection loss, wiring loss) are zero.

The instantaneous PV generator efficiency is calculated (Equation 5) [18,20].

$$\eta_{\mathrm{g}} = \eta_{\mathrm{r}} \times \eta_{\mathrm{pt}} \times [1 - \beta_{\mathrm{t}}(\mathrm{T_c} - \mathrm{T_r})] \tag{5}$$

Where η_r = PV generator reference efficiency, η_{pt} = efficiency of power tracking equipment equals 1 when MP tracking is being used [18], T_c = temperature of PV cell (℃), T_r = PV cell reference temperature, and β_t = temperature coefficient of efficient, ranging from 0.004 to 0.006 per ℃ for silicon cells.

2.4.1.2 Mathematical model of the solar charge controller

Solar charge controller (Q_{PV}) is utilized to avoid overcharging/ under the discharge of a battery bank, used to detect when the batteries are completely charged and blocking the amount of energy spilling out of PV modules to the batteries. The charger regulator rating is displayed underneath [10]:

$$\mathrm{Q_{PV}} = \mathrm{I_{SC}} \times \mathrm{N_P} \times 1.3 \tag{6}$$

Where 1.3 = charge controller oversizing factor, I_{sc} = Total short circuit current of PV array, and N_p = Total number of panels connected in parallel

The energy of the charge controller is also calculated (Equation 7).

$$\mathrm{E_{cc-out}}(\mathrm{t}) = \mathrm{E_{cc-in}}(\mathrm{t}) \times \eta_{\mathrm{cc}} \tag{7}$$

Where $E_{cc-out}(t)$ = output energy from charge regulator in (kWh), E_{cc-in}(t) = input energy to regulator in kwh, and η_{cc} = charge regulator efficient

2.4.1.3 Mathematical model of battery

The battery works as an energy source entity when discharging and a load when is charging.

The net capacity that the battery can store in Ah/day must be [10]:

$$\mathrm{BC_n} = \frac{\mathrm{E_{Tot}}}{\mathrm{V_{nom,batt}}} \tag{8}$$

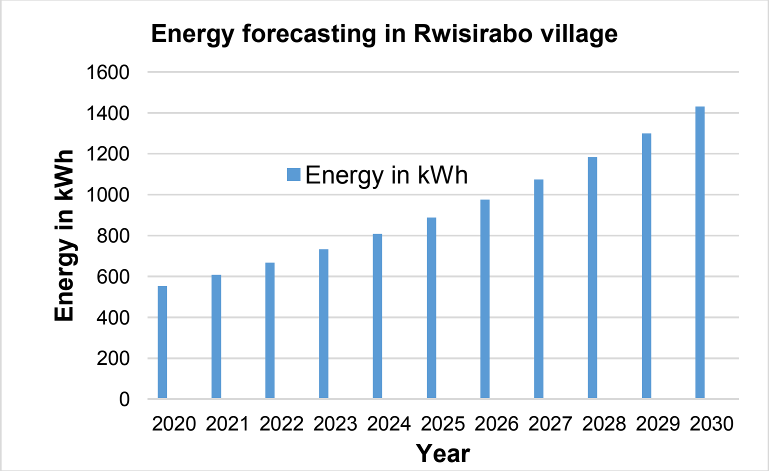


Fig. 5. Energy forecasting of village

Where BC_n = net capacity of the battery, E_{Tot} = Total Energy, and $V_{nom,batt}$ = Nominal battery voltage (i.e. 12 V_{dc}, 48 V_{dc})

The number of batteries connected in parallel for meeting the Ah required capacity by the system can be calculated by using the formula (Equation 9).

$$B_p = \frac{B_c}{B_R} \tag{9}$$

Where B_p = batteries connected in parallel, B_c = battery capacity, and B_R = required battery bank capacity in Ah

The number of batteries to be connected in series for reaching the system voltage required is calculated as fellows

$$B_s = \frac{V_{nbatt}}{V_{batt}} \tag{10}$$

Where, B_s: is the number of series-connected batteries, V_{nbatt}: is a nominal battery voltage, and V_{batt}: is battery voltage.

During the charging process, when the total output energy of generation is exceeding the load demand, the available battery bank capacity at time (t) can be calculated using Equation 11.

$$E_{bat}(t) = E_{bat}(t-1) - E_{cc-out}(t) \times \eta_{chg} \tag{11}$$

Where, $E_{bat}(t)$ = battery stored energy in hour t, kWh, $E_{bat}(t-1)$ = energy stored in battery at hour t-1, kWh, and η_{chg} = battery charging efficiency.

On the other hand, when the load demand is greater than the existing energy produced, the battery bank is in discharging state. Therefore, the available battery bank capacity at time (t), can be expressed as (Equation 12):

$$E_{bat}(t) = E_{bat}(t-1) - E_{needed}(t) \tag{12}$$

Where, $E_{needed}(t)$ is the hourly load demand or energy needed at a particular period.

Let *d* be the ratio of minimum allowable state of charge (SOC) voltage limit to the maximum SOC voltage across the battery terminals when it is fully charged. The Depth of Discharge (DOD) will be (Equation 13) [21].

$$DOD = (1-d) \times 100 \tag{13}$$

DOD is a measure of how much energy has been withdrawn from a storage device, expressed as a percentage of full capacity. The maximum value of SOC is 1, and the minimum SOC is determined by maximum DOD.

$$SOC_{min} = 1 - \frac{DOD}{100} \tag{14}$$

2.4.2 Mathematical cost model of energy systems

1. The Annualized Cost of a component: The annualized cost of a component includes annualized capital cost, annualized replacement cost, annual operation and maintenance (O&M) cost, and emissions cost. Operation cost was calculated hourly on daily basis.

2. Annualized capital cost: The annualized capital cost of a system component was calculated by taking the initial capital cost multiplied by the capital recovery factor [22].

$$\mathrm{C_{acap}} = \mathrm{C_{cap}} \times \mathrm{CRF}(\mathrm{I}, \mathrm{R_{proj}}) \tag{15}$$

Where: C_{acap} = annualized capital cost, CRF (I, R_{proj}) = capital recovery factor, I = interest rate, R_{proj} = project lifetime, and C_{cap} = initial capital cost of equipment.

3. Annualized Replacement cost: This is the annualized value of all the replacement costs that occur throughout the lifelong of the project minus the salvage value at the end of the project lifespan [22].

$$\mathrm{C_{arep}} = \mathrm{C_{rep}} \times \mathrm{f_{rep}} \times \mathrm{SFF}\left(\mathrm{I}, \mathrm{R_{comp}}\right) - \mathrm{S} \times \mathrm{SFF}\left(\mathrm{I}, \mathrm{R_{proj}}\right) \tag{16}$$

Where: C_{rep} = replacement cost of the component, SFF= sinking fund factor, R_{comp} = lifetime of the component, S = salvage value of the component, and f_{rep} = replacement factor.

$\mathrm{f_{rep}}$, a factor arising because the lifespan of a component can be different from the project lifelong,

4. Annualized operating cost ($\mathbf{C_{aop}}$): the operating cost is the annualized value of all costs and revenues other than initial capital costs and is calculated as follows [22] (Equation 17).

$$\mathrm{C_{aop}} = \sum_{t=1}^{365}\{\sum_{t=1}^{24}[\,\mathrm{C_{oc}}(t)]\} \tag{17}$$

Where, $C_{oc}(t)$ = cost of the operating component.

$$\text{Total cost of a component} = \text{Economic cost} + \text{Envoronment cost}$$

Where $Economic\ cost = Capital\ cost + O\&M\ cost$ and

$$\text{Emissions cost} = \text{Environment cost} = 0$$

2.4.3 Solar PV power plant components sizing

1. System Voltage Selection

The system voltage was selected based on the SPV power plant estimated total load while the system voltage increases proportionally to the daily load. In the case of this research, the system depends on the selected inverter and the estimated daily AC loads [23], 48 V system voltage was selected.

2. PV panel/module sizing

Based on the above data from load estimation, Module type: LONGI Solar RR6-72PH was being selected. Some Specifications of the selected PV Panel are shown in Table 12.

PV system design for 551,718 kWh (TEED) average AC primary daily load as has been shown in Table 10 from the previous section (section 2.3.2), the number of modules were calculated as follows

$$\mathrm{E_{pv}} = \mathrm{TEED}\ \times 1.3 \tag{18}$$

Where 1.3 is the energy lost in the system, *TEED* = total electrical energy demand, and E_{PV} = Total PV panels energy needed per day.

$$\mathrm{E_{pv}} = 551{,}718 \times 1.3 = 717233.4\mathrm{Wh/day}$$

$$\mathrm{P_{peak}} = \frac{\mathrm{E_{PV}}}{\mathrm{PSH}} \tag{19}$$

$$\mathrm{P_{peak=}} \frac{717233.4}{4.8} = 149{,}424\mathrm{W_p}$$

$$\mathrm{N_{Panels}} = \frac{\mathrm{P_{peak}}}{\mathrm{P_{module}}} = \frac{149{,}424}{370} = 404\ \text{PV Panels}$$

Table 12. PV panel specifications

Specifications	Range
Maximum Power Rating STC	370 Watt
Number of Cells per Module	72
Maximum Power Voltage (V_{mp})	39.4 V
Maximum Power Current (I_{mp})	9.39 A
Open Circuit Voltage (V_{oc})	48.3 V
Short Circuit Current (I_{sc})	9.84 A
Efficiency	19.1%
Module Dimension	1956x991x40 mm
Weight	22.5 kg
Manufacturer	LONGI Solar Technology CO Ltd

3. Inverter selection

As a maximum power demand of AC loads of this off-grid SPV system was 160 kW;

$$\text{Inverter size (kw)} = \text{Maximum power of AC loads} \times 1.3 = 160 \times 1.3 = 208 \text{ kw}$$

250 kW pure sine wave off-grid inverter DC to AC was selected for this work. Therefore,

$$\text{Number of Modules in Series} = \frac{\text{maximum open circuit voltage of inverter}}{\text{Open circuit voltage of each module}} \qquad (20)$$

12 PV Modules are connected in series and 34 are installed in parallel to make an off-grid solar photovoltaic for meeting the voltage and current according to the PV module and inverter specifications (Table 14). Now, the maximum number of PV modules required for satisfying this village demand is 408 PV modules.

4. Battery sizing

The battery capacity will depend on the following:

1. The total energy that the battery bank must supply to loads.
2. Maximum depth of discharge
3. Maximum power demand
4. System voltage
5. Charge current and recharge time.

Total Electrical Energy Demand per day is 551,718 kWh and days of autonomy is 2 days; 2 cloud days.

According to the selected Battery

$$\text{B}_\text{C} = \frac{\text{TEED} \times \text{Day of autonomy}}{\text{V}\times\times\text{DOD}} \qquad (21)$$

$$\text{B}_\text{C} = \frac{551{,}718 \times 2}{48 \times 0.85 \times 0.6} = 45{,}075 \text{ Ah}$$

Hence, the capacity of the battery is 45,075 Ah, the selected battery was BAE PVS Block 210 Ah, 12 V_{DC}. The number of batteries (B_P) which are connected in parallel to meet Ah required by the system will be

$$\text{B}_\text{P} = \frac{45075}{210} = 215 \text{ Batteries}$$

The number of batteries (B_S) to be connected in series for meeting the system voltage of 48 V_{DC}, is calculated as follow (Equation 22).

$$\text{B}_\text{s} = \frac{\text{V}_\text{nbatt}}{\text{V}_\text{batt}} = \frac{48}{12} = 4 \text{ Batteries} \qquad (22)$$

The total number of Batteries (B) of the whole PV system will be

$$\text{B} = \text{B}_\text{s} \times \text{B}_\text{P} = 215 \times 4 = 860 \text{ Batteries} \qquad (23)$$

5. Charger controller sizing

The typical ratings of voltage controllers are capacity of voltage and amperage. It plays an important role in matching the voltage between PV arrays and batteries [23].

$$\text{Q}_\text{PV} = \text{I}_\text{sc} \times \text{Total number of modules connected in parallel} \times 1.3 \qquad (24)$$

$$\text{Q}_\text{PV} = 9.48\text{A} \times 34 \times 1.3$$

Table 13. Inverter datasheet

Technique specifications	
Specifications	**Range**
Rated input voltage	540VDC or 600VDC
Rated input current	463A 0r 417A
Input voltage range	486-750V or 540-850V
Rated power	250kw
Rated output voltage	380V or 480
Rated output current	379A
Isolation mode	Low-frequency transformer
Number of phases	3 phase 4 wires
Inverter efficiency	>93%
Overload ability	150% (10s)
Cooling method	Fan-cooled
Working temperature	+5F`~+122F (-15℃~+50℃)

$= 435A$, maximum power point Tracking (MPPT-B (500 A)) solar charger controller 2,400W/48V was selected. In the design of this system, a total of 408 panels are required. Each panel has an area of 1956 mm x 991mm (1.938396 m^2), therefore more than the 790.9 m^2 (408 x 1.938396 m^2) land area is required for this SPV Power Plant. Fig. 6 shows the charger controller selected specifications.

Table 14 shows the equipment specifications, description of each, and the results based on the energy estimate required of the sized system which will be used in the SPV off-grid system in Rwisirabo village.

2.5 Modelling of Solar PV Power Plant

HOMER software was used to model a power system's physical behaviour and its life-cycle cost, which was the total cost of installing and operating the system over the lifespan. The designer compared several different design options based on their technical and economic behaviour by using HOMER. And it was also used in understanding and enumerating the effect of modifying the inputs. The design of an off-grid SPV power plant with a storage system for a community of 500 households, 1 police station, 1 small factory, 1 secondary school, health post, and 10 commercial loads, with an


Item no: JN-MPPT

Rated Volatge: 12V/24V/48V Auto

Rated Current: 30A/40A/50A/60A

Conversion Efficiency : >96%

Communication Function: RS485 andUSB to RS232 (optional parts by customers)

Working Temperature: -35℃ - +45℃

Size : 280*225*114mm

Charging ways: MPPT charge-equalizing charge- improving charge- floating charge.(MPPT charging efficiency is 30% higher than PWM)

Fig. 6. Charger controller specification

Table 14. Results of the sized system

Item	Description	Results
Electrical Load	Per day consumption of the AC load	551,718 kwh/day
PV Array	Capacity (TEED)	160 kW
	Modules to be connected in series	12 PV Modules
	Modules to be connected in parallel	34 PV Modules
	Total number of modules	408 PV Modules
Battery Bank	The capacity of total Batteries	45075Ah
	The selected Battery is BAE PVS Block 210 Ah, 12 V_{DC}	210 Ah
	Batteries connected in series	4 Batteries
	Batteries connected in parallel	215 Batteries
	Total Number batteries	860 Batteries
Inverter	Capacity	208 kW
	250 kW pure sine wave off-grid inverter	250 kW
	Total Number of Inverters	1 inverter
Charger Controller	Capacity	500A
	Total number of controller	1Controller
Land area	408 x 1.938396 m^2	790.9 m^2

Energy demand of 551,718 kWh/day based on the hand calculation. HOMER software was used as a tool for accomplishing this work. It did this in three main tasks such as simulation, optimization, and sensitivity analysis as is indicated in Fig. 7.

Simulation: It related the energy supply from the system and the load demand in 60 minutes, of the entire hours of the year. Throughout this time, it chooses either to utilize load following or dispatch methodology to work batteries and sunlight-based PV power. A system that comprises battery and SPV system requires having dispatch strategy. Dispatch techniques are two sorts, load following, and cycle charging systems.

Optimization: In this cycle, it simulated each extraordinary system arrangement looking for the most reduced NPC and recorded each power system that satisfies the load need. The reason for optimizing was to decide the optimal system dependent on the choice factors executed by the designer. HOMERs choice variables may incorporate; PV module size, size of the converter, amount of batteries, dispatch system, and so forth. Looking through the optimal system incorporates choosing the mix of power components such as size, amount simultaneously quantity the dispatch technique.

Sensitivity Analysis: It analyses the impact of outer factors and optimization for every sensitivity variable. However, first characterizing the variables that may influence the system over its whole life is obligatory to enter into the software. The optimization process was repeated after identifying the sensitive parametric variables as a contribution to the software. The sensitivity variables can be climatic information varieties, components and fuel cost, interest rate, capacity shortages, operating reserves, and others. HOMER does multiple optimizations utilizing different sensitive inputs to perceive how sensitive output of the power system. The sensitivity results from HOMER were displayed in tabular and graphical structures.

3. RESULTS AND DISCUSSION

3.1 Solar Photovoltaic System Simulation and Result Analysis

3.1.1 Inputs parameters for modelling

The following are the input data used for simulating this off-grid SPV system which gave the appropriate outputs of HOMER software (Fig. 8).

where NPC**:** Net Present Cost and COE: Cost of Energy

3.1.1.1 Solar resources for Rwisirabo village

In SPV system design that requires solar radiation as an input parameter to converts it into electricity, having all data relating to solar radiation is very helpful. The Average Monthly Solar Global Horizontal Irradiance (GHI) data from HOMER are plotted (Fig. 9), including the daily radiation in kWh/m^2 /day and clearness index for every month as their values have been shown in Table 2 (section 2.2).

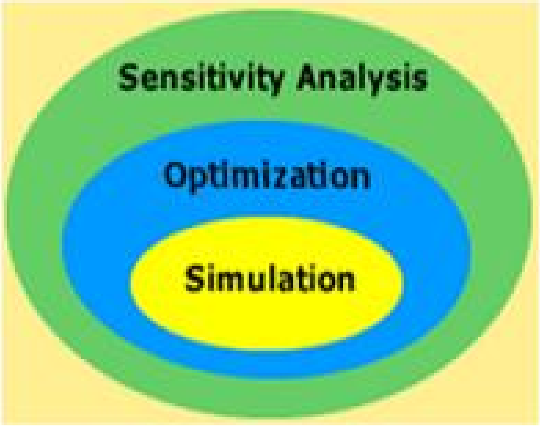


Fig. 7. Three main task of HOMER software [24]

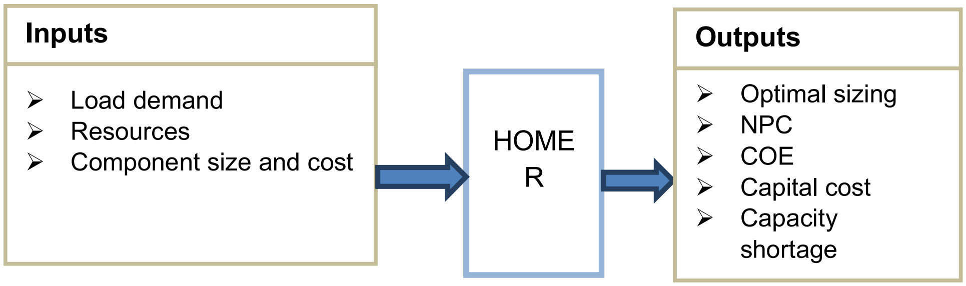


Fig. 8. Inputs and Output of HOMER software

In February the amount of 5.220 kWh/m^2/day was the highest amount of irradiance and the lowest was 4.540 kWh/m^2 /day in November for this selected location on this work. The yearly average solar radiation was found to be 4.88 kWh/m^2 /day and the temperature was 20.47℃.

3.1.1.2 Components size and its cost

- PV panel size was 220 kW, with the capital cost of $1000, the replacement cost of $800 per kW, and the O&M cost per year was $10, the PV module lifespan was the same as the project which was 25 years.
- The average of the AC primary daily demand was 551,718 kWh, the peak load demand was 85.10 kW and a load factor of 0.27 while the deferrable load of 9.99 kWh/day and 2.00 kWh of peak power was entered into this system.
- The selected Battery was BAE PVS Block 210 Ah, 12 V_{DC} that used in this work with a capital cost of $300, a replacement cost of $300 per Battery, and an O&M cost per year was $10 per year.
- 250 kW pure sine wave off-grid inverter was selected for this work with the capital cost of $300, the estimated replacement cost and O&M cost per one kW of inverter were $300 and $0 per year respectively.
- The selected charger controller for this work was MPPT-B (500 A) solar charger controller 2400W/48V with the capital cost of $400, the replacement cost of $300, and O&M cost per year is zero but it is not being modelled by HOMER.
- In the case of deferrable load, the rain season's months of the water pump were reduced by 15%.

Fig. 9 Monthly global radiation for Rwisirabo village

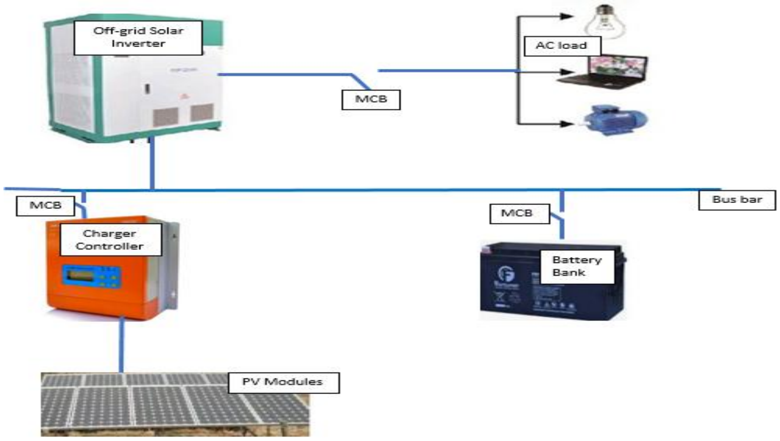


Fig. 10. Single line diagram of an off-grid SPV system

A schematic representation of the off-grid SPV system by HOMER is shown in Fig. 11 based on the previous mathematical design and sizing.

Based on the above primary and deferrable load estimation of Rwisirabo village, the software optimization model profile is shown as follows respectively (Fig. 12).

The peak demand of the community occurs from 18:00 to 20:00 hours because most of the household members would expect to be at their homes; lighting their houses, listen to Radio, and watching television. Additionally, iron, commercial, and small manufacturing loads make a high demand in the morning time.

3.2 Results Analysis

The optimal off-grid SPV system is the one that will supply electricity which needs to be at the lowest price so that the power plant will be having the lowest total net present value while supplying the electricity at the required level of availability. In this part, the results of the feasibility of an off-grid SPV with storage batteries were presented and discussed, the results obtained from the software simulation and the selection of components size based on discount rate were also analysed. This chapter also discussed the performance of the system, components design, the economic viability of the project, and energy management in the off-grid system. From the generated simulation results, the combination of components that has a low cost (minimum total Net Present Cost and less Cost of Energy) was considered as the selected energy system for each scenario analysis. For the off-grid electrification of Rwisirabo village, various combinations of different components such as PV modules, Batteries, Converter, and charge controller were made. Table 15 describes the simulated results which give the following information: Nominal Discount, Deferrable load minimum load ratio, and peak load, Component size, Net Present Cost, Cost of Electricity. Only a 3.00% Nominal Discount was considered in the analysis of the results of this work. Table 16 and 17 show Optimized Results of the system.

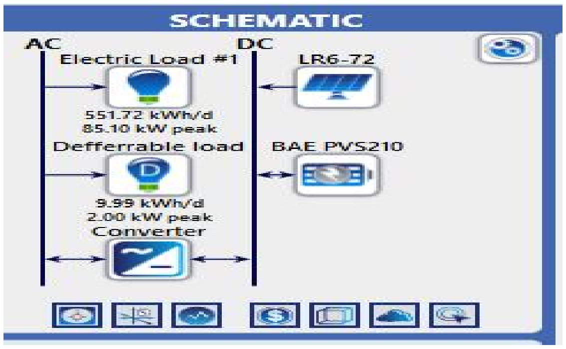


Fig. 11. Configuration schematic of the system

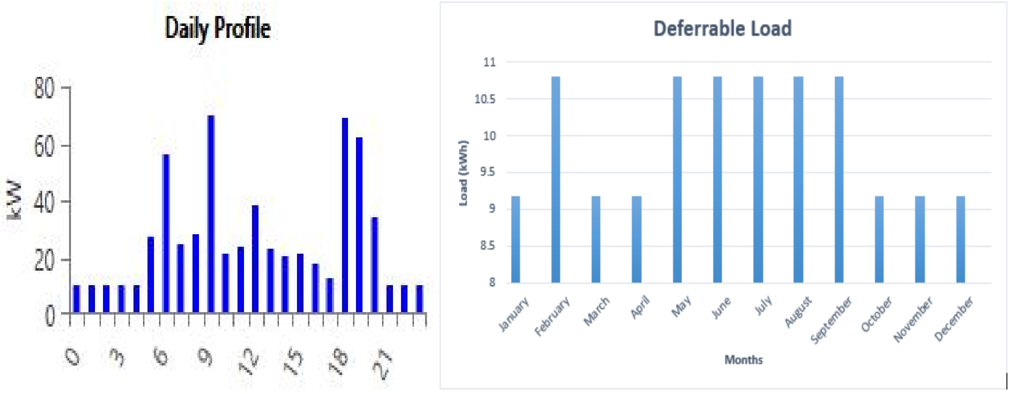
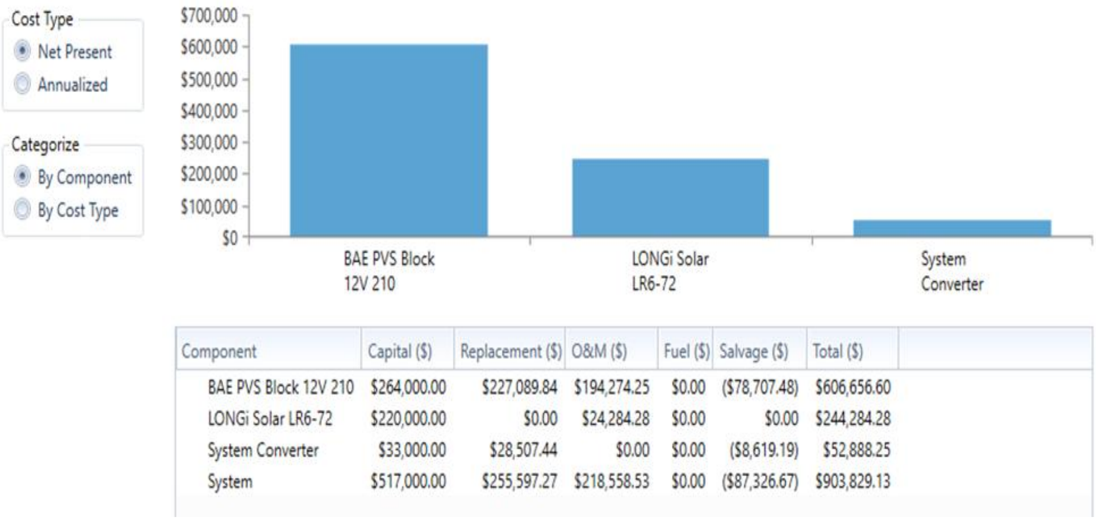


Fig. 12. Daily primary load and monthly deferrable load profile



Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
BAE PVS Block 12V 210	$264,000.00	$227,089.84	$194,274.25	$0.00	($78,707.48)	$606,656.60
LONGi Solar LR6-72	$220,000.00	$0.00	$24,284.28	$0.00	$0.00	$244,284.28
System Converter	$33,000.00	$28,507.44	$0.00	$0.00	($8,619.19)	$52,888.25
System	$517,000.00	$255,597.27	$218,558.53	$0.00	($87,326.67)	$903,829.13

Fig. 13. Cost summary of the system by component type

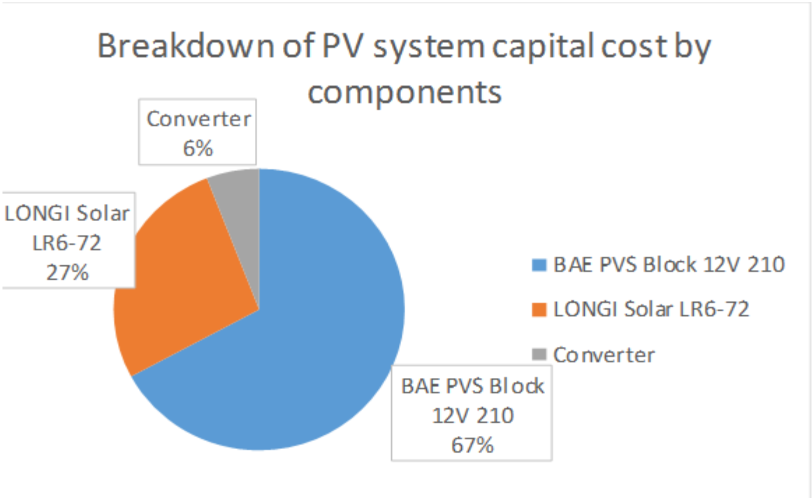
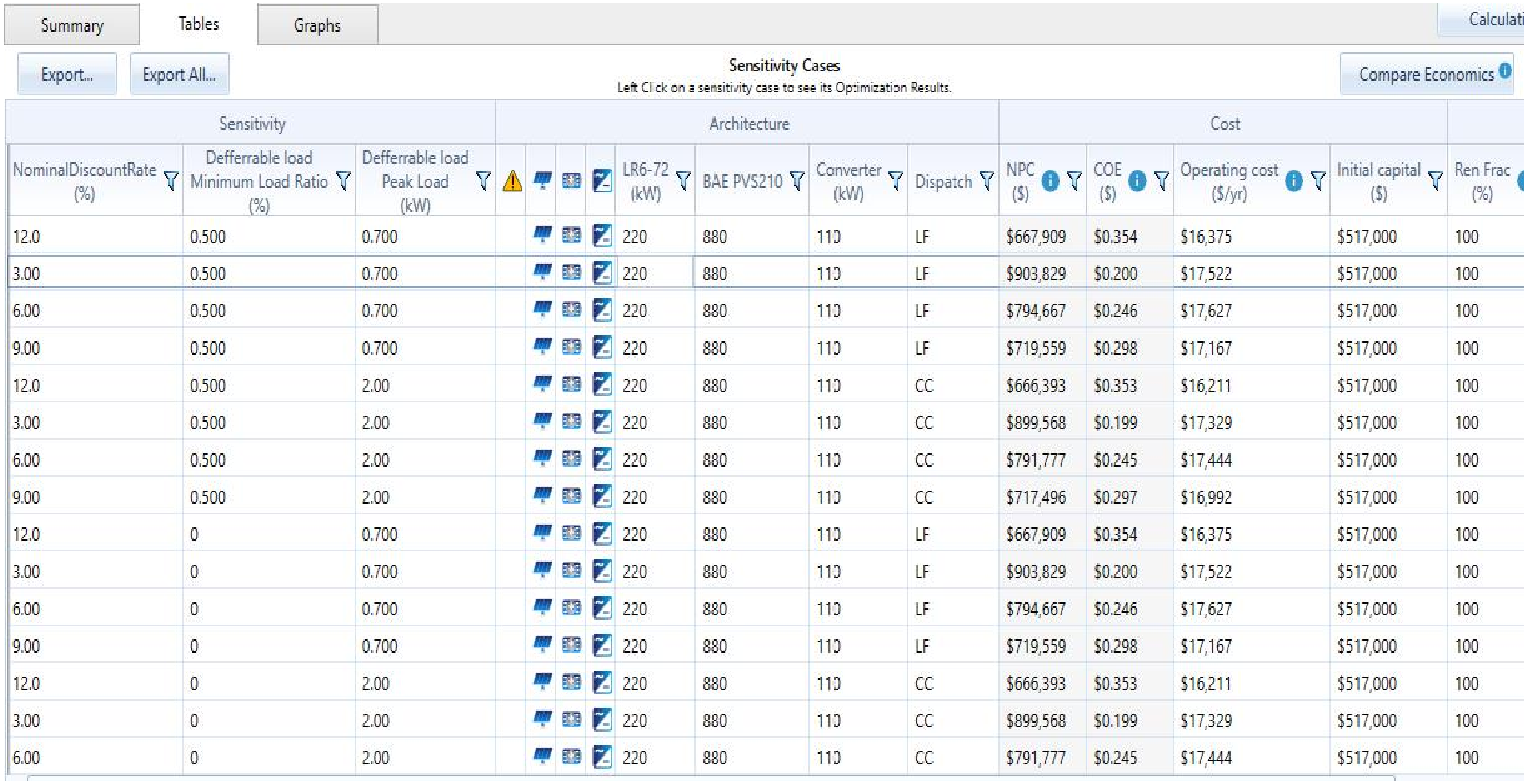


Fig. 14. NPC percentage by components

Table 15. All components of sensitivity results

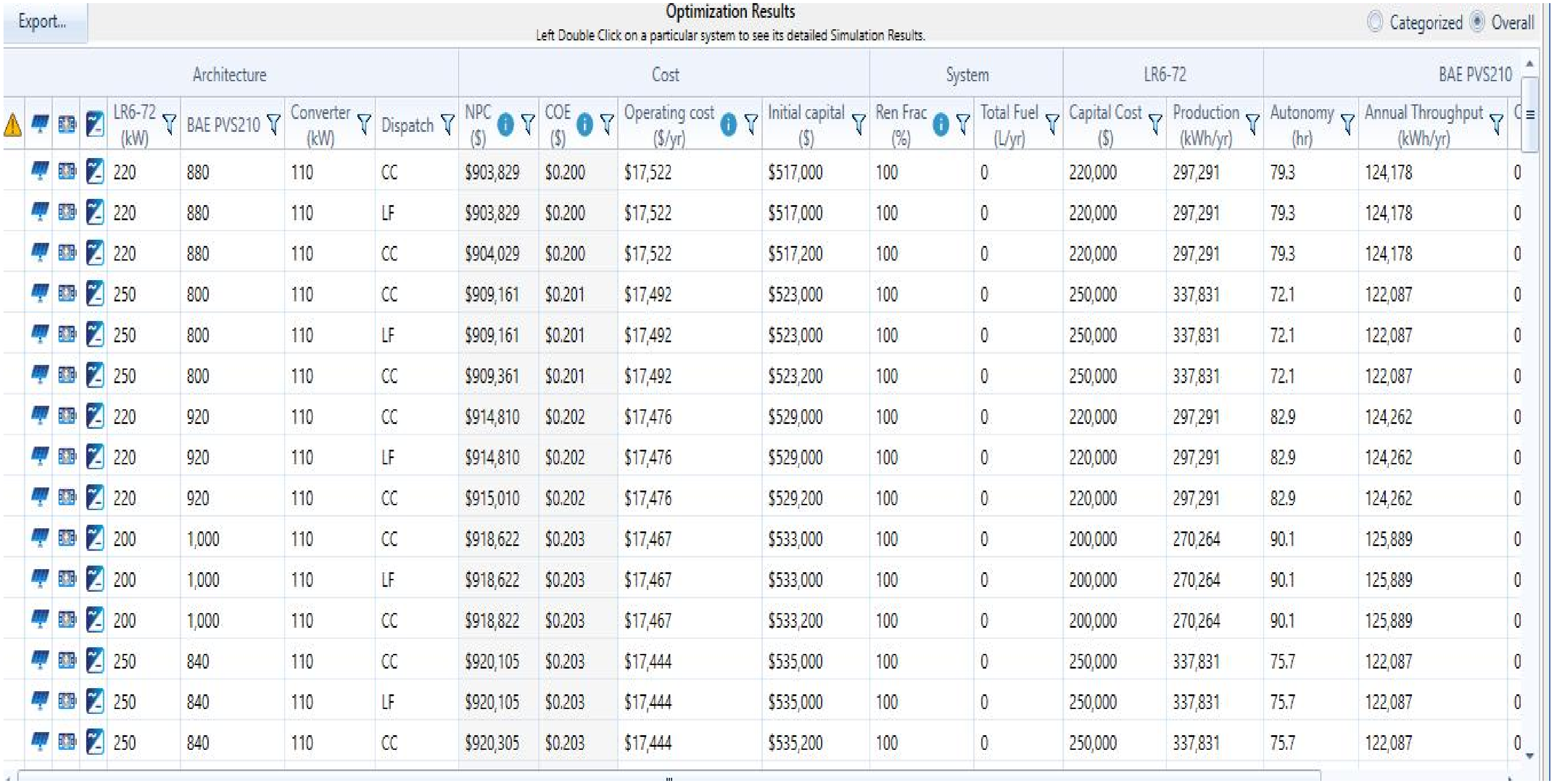


Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Sensitivity			Architecture				Cost				
NominalDiscountRate (%)	Defferrable load Minimum Load Ratio (%)	Defferrable load Peak Load (kW)	LR6-72 (kW)	BAE PVS210	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
12.0	0.500	0.700	220	880	110	LF	$667,909	$0.354	$16,375	$517,000	100
3.00	0.500	0.700	220	880	110	LF	$903,829	$0.200	$17,522	$517,000	100
6.00	0.500	0.700	220	880	110	LF	$794,667	$0.246	$17,627	$517,000	100
9.00	0.500	0.700	220	880	110	LF	$719,559	$0.298	$17,167	$517,000	100
12.0	0.500	2.00	220	880	110	CC	$666,393	$0.353	$16,211	$517,000	100
3.00	0.500	2.00	220	880	110	CC	$899,568	$0.199	$17,329	$517,000	100
6.00	0.500	2.00	220	880	110	CC	$791,777	$0.245	$17,444	$517,000	100
9.00	0.500	2.00	220	880	110	CC	$717,496	$0.297	$16,992	$517,000	100
12.0	0	0.700	220	880	110	LF	$667,909	$0.354	$16,375	$517,000	100
3.00	0	0.700	220	880	110	LF	$903,829	$0.200	$17,522	$517,000	100
6.00	0	0.700	220	880	110	LF	$794,667	$0.246	$17,627	$517,000	100
9.00	0	0.700	220	880	110	LF	$719,559	$0.298	$17,167	$517,000	100
12.0	0	2.00	220	880	110	CC	$666,393	$0.353	$16,211	$517,000	100
3.00	0	2.00	220	880	110	CC	$899,568	$0.199	$17,329	$517,000	100
6.00	0	2.00	220	880	110	CC	$791,777	$0.245	$17,444	$517,000	100

Table 16. Overall optimization results



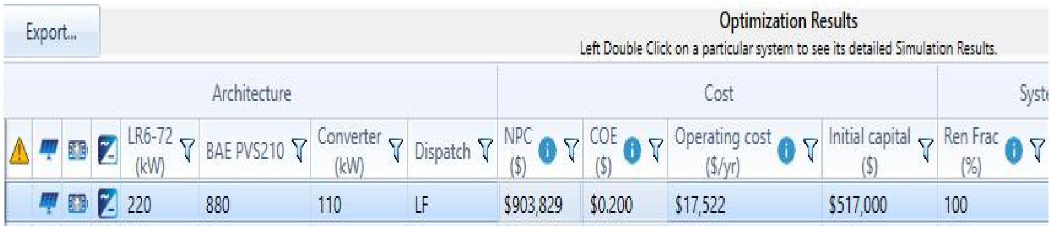
Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

○ Categorized ● Overall

Architecture				Cost				System		LR6-72		BAE PVS210		
LR6-72 (kW)	BAE PVS210	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost ($)	Production (kWh/yr)	Autonomy (hr)	Annual Throughput (kWh/yr)	C
220	880	110	CC	$903,829	$0.200	$17,522	$517,000	100	0	220,000	297,291	79.3	124,178	0
220	880	110	LF	$903,829	$0.200	$17,522	$517,000	100	0	220,000	297,291	79.3	124,178	0
220	880	110	CC	$904,029	$0.200	$17,522	$517,200	100	0	220,000	297,291	79.3	124,178	0
250	800	110	CC	$909,161	$0.201	$17,492	$523,000	100	0	250,000	337,831	72.1	122,087	0
250	800	110	LF	$909,161	$0.201	$17,492	$523,000	100	0	250,000	337,831	72.1	122,087	0
250	800	110	CC	$909,361	$0.201	$17,492	$523,200	100	0	250,000	337,831	72.1	122,087	0
220	920	110	CC	$914,810	$0.202	$17,476	$529,000	100	0	220,000	297,291	82.9	124,262	0
220	920	110	LF	$914,810	$0.202	$17,476	$529,000	100	0	220,000	297,291	82.9	124,262	0
220	920	110	CC	$915,010	$0.202	$17,476	$529,200	100	0	220,000	297,291	82.9	124,262	0
200	1,000	110	CC	$918,622	$0.203	$17,467	$533,000	100	0	200,000	270,264	90.1	125,889	0
200	1,000	110	LF	$918,622	$0.203	$17,467	$533,000	100	0	200,000	270,264	90.1	125,889	0
200	1,000	110	CC	$918,822	$0.203	$17,467	$533,200	100	0	200,000	270,264	90.1	125,889	0
250	840	110	CC	$920,105	$0.203	$17,444	$535,000	100	0	250,000	337,831	75.7	122,087	0
250	840	110	LF	$920,105	$0.203	$17,444	$535,000	100	0	250,000	337,831	75.7	122,087	0
250	840	110	CC	$920,305	$0.203	$17,444	$535,200	100	0	250,000	337,831	75.7	122,087	0

Table 17. Categorized optimization results of system



Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture				Cost				Syst
LR6-72 (kW)	BAE PVS210	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
220	880	110	LF	$903,829	$0.200	$17,522	$517,000	100

For each case scenario, the parameters that follow were obtained from simulation works and they are very helpful for making analysis and discussion on total NPC, Levelized cost of electricity, and operating cost of electricity.

3.2.1.Optimization analysis of system

The only single scenario of categorized optimization results was shown in Table 17 depicts the result from HOMER modelling for Rwisirabo village. The modelling simulates one year of operation and system configuration. The system with the overall in Table 16, least cost of energy is the one first on the list. The first three columns of the software results in Table 17 above show graph icons which are representing each component being used in the simulation of this system, the next columns show the optimized capacity of every apparatus, the NPC, the COE in $/kWh, the initial capital cost, renewable fraction.

3.2.1.1 Techno-economical analysis of the results

In the categorized results, only one scenario is found means that the Techno-Economic analysis of this project work was focused on a single option from Table 18, as it was only one best scenario that met the load at the low cost and this energy cost is cheaper compared to currently one from on grid.

A. Economic Analysis

As it shows in Table 18 based on HOMER modelling, the optimal system for Rwisirabo village in Categorized optimization results are the mean Power of 220 kW SPV, 880 BAE PVS210 batteries (each of 210 Ah capacity), and 110 kW DC to AC converter are required to supply the selected village. This optimal system uses a hundred percent renewable energy and the COE is $0.200/kWh Cost of while the national power grid tariff for household is $0.262/kWh. The total NPC, initial capital, operating cost, and Levelized COE for this off-grid SPV system are $903,829, $517,000, $17,522, and $0.200/kWh respectively. Fig. 13 shows the cost of the system by component type.

Fig. 14 displays the components cost flow summary in the percentage of an off-grid SPV system scheme. It is clear from the Figure that the system converter contributes the lowest NPC with $52,888.25 (6%), followed by PV modules that cost $244,284.28 (27%) and battery bank the first for this SPV system with a cost of $606,656.60 (67%).

B. Technical Analysis

The electricity generated by an off-grid SPV power plant and consumed by AC and deferrable load is illustrated in following Fig. 16, the power plant produces 297,291 kWh/year (100%), while the total electrical power consumption is 204,931 kWh/year (100%) i.e. 201,299 kWh/year (98.2%) and 3,632 kWh/year (1.77%) are consumed by the AC primary load and deferrable load respectively. Besides, excess electricity of 62,297 kWh/year (21.0%), the unmet electric load of 79.1 kWh/year (0.0386%), and a capacity shortage of 118 kWh/year (0.0574%) were experienced during the year as is shown in Fig. 16, the amount of excess electricity will be used in the irrigation system and AC future load as the forecasting energy was calculated from the previous section (Section 2.3.4) but it is also possible for transferring to the nearest villages.

The System load variation and power generated from solar PV modules were given in Fig. 18. The generation capacity of the SPV system varies based on the weather parameters such as solar irradiation and temperature. The monthly results of power generation in kW obtained after stimulation with software as displayed in Fig. 17, the solar radiation is high in March, July, August, and September which bring more electric power generation on those months. All months or year the power electricity remain generated. Results from the simulation show that this system generates a mean power output of 220 kW and total production of 297,291 kWh/year as is summarized in Table

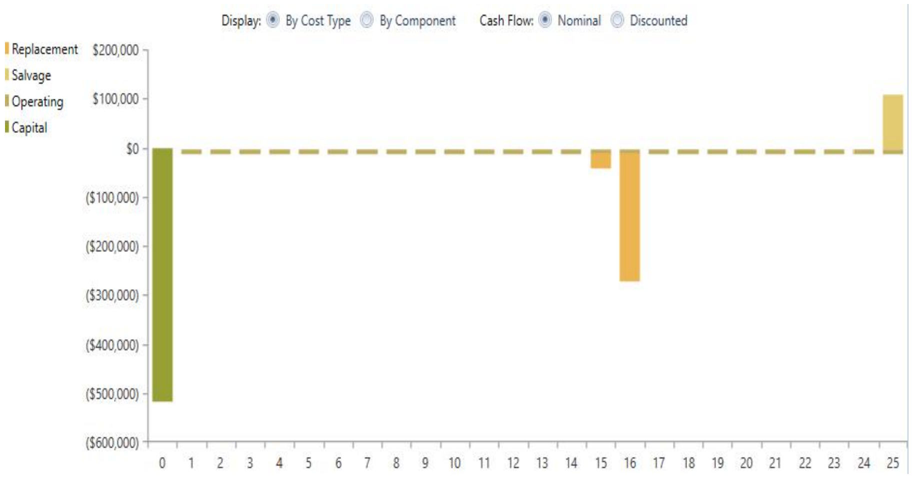


Fig. 15. Cash flow summary of the system

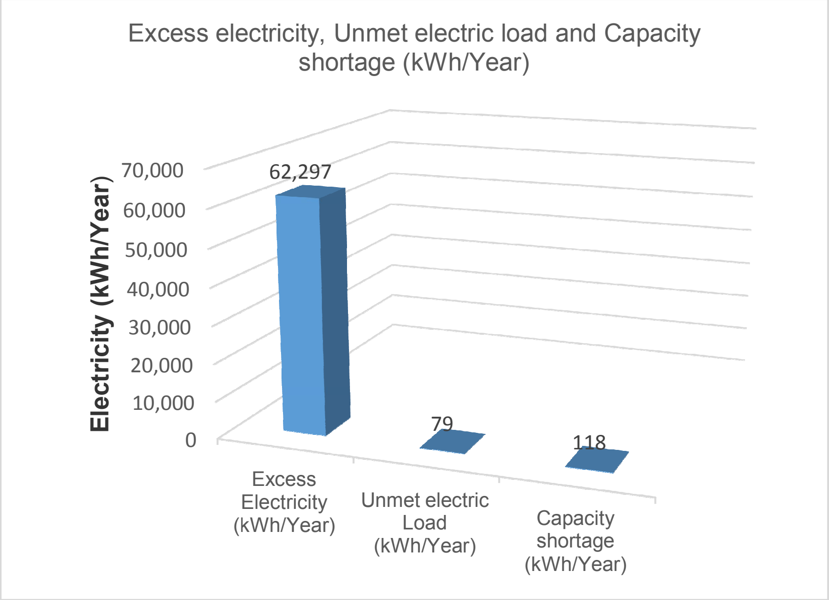
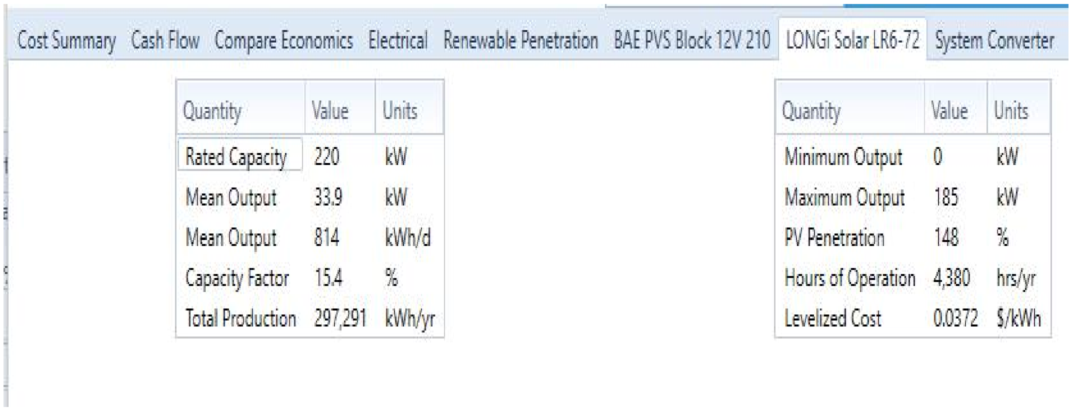


Fig. 16. Excess of electricity, unmet load, and Capacity shortage

Fig. 17. Monthly electric production

Table 18. SPV scheme simulation result



Quantity	Value	Units
Rated Capacity	220	kW
Mean Output	33.9	kW
Mean Output	814	kWh/d
Capacity Factor	15.4	%
Total Production	297,291	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	185	kW
PV Penetration	148	%
Hours of Operation	4,380	hrs/yr
Levelized Cost	0.0372	$/kWh

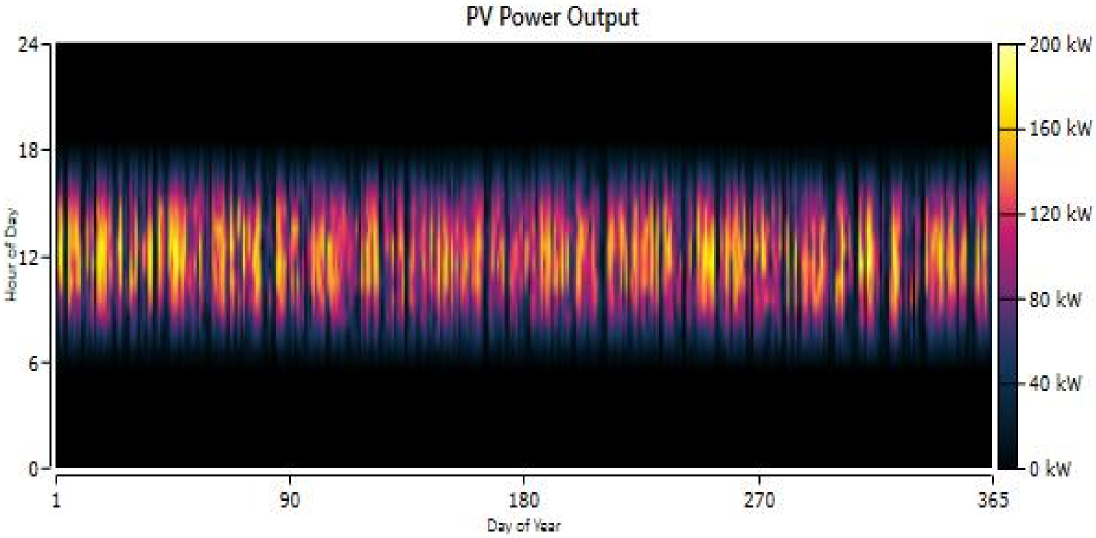


Fig. 18. Solar PV power production

Fig. 18 shows the annual operation of the PV modules, which are given to illustrate the operation control strategy according to the Rwisirabo village load demand and weather parameters.

4. CONCLUSIONS

In the design of this system for Rwisirabo village, the annual average of solar radiation and the annual average temperature are 4.88 kWh/m^2/day and 20.47℃ respectively with a total number of 500 households and other infrastructure (AC primary load and deferrable load). The total average energy demand was about 551,718 kWh/day with a peak of 85.10 kW. An off-grid SPV system cannot give a continuous supply of electricity without storage; a battery bank was being selected after designing appropriate PV modules, Inverter, and Charger controller. After designing all components of the system and studied their behaviours. The system has been modelled and simulated by HOMER software, the simulation was made to get the best components size that can satisfy the demand with the necessary power availability at a low cost ($0.200/ kWh). The system items such as PV module, batteries, and inverter size have been found as an optimum system with 220 kW, 860 BAE PVS 210 batteries, and 110 kW respectively with a lifespan of 25 years of the project. It found that the implementation of SPV system with battery storage in residential, commercial, and institutions in the area where the solar irradiance is concentrated across a country will reduce the cost of electricity and power interruption on the national grid. Therefore, further work is needed to optimize this system for rural electrification as well by integrating with other renewable sources available in the country and also extend the electrification to another area that is detached from the national grid.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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