International Journal of Engineering Technology and Scientific Innovation

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

OPTIMAL DESIGN OF A SOLAR PHOTOVOLTAIC MINI-GRID FOR ELECTRIFYING RWUMBA VILLAGE OF RWANDA

Augustin Munyaneza[1*], Keren Kaberere[2] and Maurice K. W Mangoli[3]

[1]Department of Energy Technology, Engineering Building, KU, 43844 Nairobi, Kenya

[2]Department of Electrical & Electronics Engineering, EM Building, JKUAT, 62,000 Nairobi, Kenya

[3] Department of Electrical & Electronics Engineering, Engineering Building, KU, 43844 Nairobi, Kenya

[*]Corresponding Author

ABSTRACT

Universal access of energy is a requisite ingredient for any country geared towards achieving its economic goals. Rural areas of developing countries don't have access to electricity due to the high cost of transmission which hinders their development. Rwumba Village in Rwanda has no access to electricity from the national grid. As such, the current paper proposed the use of solar energy option as a solution to the problem. Therefore, a solar photovoltaic mini-grid that can provide the required power for the village was designed and optimized using HOMER software. The software simulated various combinations of inputs at different reliabilities and proposed the most optimum combinations. The best results corresponding to the optimum PV mini-grid were obtained at capacity shortage of 3%. These results are as follows: PV panels capacity of 34 kW, battery bank storage of nominal capacity of 384 kWh that will be able to store energy for 3 days during cloudy days and power inverter of 15 kW. The cost of energy for the designed mini-grid was found to be USD 0.316 per kWh. Comparing the cost of energy obtained with the existing costs, this was found to be most affordable. Thus, it is worthy to recommend public and private institutions involved in solar mini-grid development and implementation to consider the optimum mini-grids which will result in fair cost of energy that can be afforded by a big number of end users.

Keywords: Homer, Households, Photovoltaic Mini-grid, Rwumba Village

1. INTRODUCTION

Access to electricity is still a challenge in many countries of the world [1]. Over 1.3 billion people living in developing countries have no access to any form of electricity where around 590 million of them live in Africa with electrification rate less than 13% [2]–[4]. This issue hinders the development of many regions of Africa due to the fact that some economical activities can only run during the day [3]. Likewise, schooling and heath care services become more difficult [4]. Recently, the globe has benefited from the increase of integration of PV systems in energy sector [5], [6]. The use of PV systems for increasing the accessibility of electricity in remote areas helps to conserve natural resources and combat the consequences raised from the use of fossil fuel based energy sources [1], [5].

Rwanda is among the countries of Africa that are quickly developing, however, its development is still hindered by low rate of electrification found in her rural areas [8]. In Rwanda, energy sector assists the evolution of socio-economic and the advancement of many other economic sectors including big and small businesses [9]–[11]. Rwanda government has a target of connecting its people up to 70% by the end of 2019 and 100% toward the end of 2024, but the current total installed capacity is still considerably low with only 42% of population having access to electricity [12]–[14]. The country has the total installed capacity of 209 MW with only 5% generated from solar systems [15]. The big distance from national grid to rural areas implies a high cost of transmission; thus, discouraging the electricity providers to connect the remote areas [8]. Rwumba village of Rwanda is located in rural area and suffers from the same problem. Many researchers conducted various studies on finding the optimum stand alone or hybrid systems that can effectively supply the required power and energy to the households located in remote areas in different parts of the globe.

Antony et.al, 2012 [16] carried out a study to design of an off-grid Photovoltaic system for electrifying a village of Denmark. During their study, HOMER and PVSUN3 software were used for simulations and the results obtained from each software were compared to check for the most optimum. For their case study, they run the simulations with the same inputs and got different results. PVSUN3 proposed 90 batteries and 23 kWp module while HOMER proposed only 44 batteries and 15 kWp module. With deep analysis the concluded that the most accurate optimized results can be achieved using HOMER.

Oscar Pederzini, 2017 [17] carried out a research on the design of a Solar Micro-grid for the Community of Mpaga, Gabon based on its social and economic context. Along with his research, he used HOMER to optimize the system. He estimated the load profile for Mpaga based on the residents' habits, lifestyle and facilities. After the design and optimization works, he evaluated

ISSN: 2456-1851
Volume: 04, Issue: 05 "September-October 2019"

all costs that could be spent on the designed micro-grid and concluded that the system was economically viable and convenient to the community and recommended the same system to be adopted in many regions of Gabon.

Abdulateef et al, 2012 [18] conducted a study on Economic Analysis of a Stand-Alone PV System to Electrify a Residential Home in Malaysia. The results obtained allowed them to conclude that electrifying a remote household using PV systems is beneficial and suitable for long-term investments [19].

Abdelkader Chaker et.al, 2017 [20] used HOMER to optimize a hybrid power system composed by PV and fuel generator. With their study, they considered a daily load of 4.8 kWh with 1.5 kW as nominal peak power demand. The results obtained from the achieved optimum system indicated that 96 % of total production was to be generated from PV and only 4% was to be generate from the fuel generator. Yet, the cost of PV was found to be only 57% of the total cost of the entire system. This shows the potential of using photovoltaic system for energy production in the regions having a fairly high average of annual solar radiations [20].

Rawat & Chandel, 2013 [21] also used HOMER for simulating and Optimizing a Solar Photovoltaic-Wind stand-alone Hybrid system in Hilly Terrain of India. During their work, the techno-economic characteristics of existing and optimum hybrid system configurations with 0%, 5%, 10 and 20% maximum capacity shortage were studied. As the results, they obtained optimum system configuration to be corresponding to capacity shortage of 3.1%.

In this paper, an optimum photovoltaic mini-grid for electrifying Rwumba Village of Rwanda was designed and optimized using HOMER. It was designed to run a daily load of 110.326 kWh for serving 108 households (residential load), a shopping center comprising 14 shops (commercial load) and one office of the chief of the village (community load).

2. METHODOLOGY

Simulation and optimization process was accomplished using HOMER. Moreover, Questionnaires and interviews were used to collect the data from the residents of Rwumba village. Data collected include main economic activities undertaken by the residents, number of households interested in buying electrical appliances and using electricity from solar.

2.1. Estimation of energy consumption

In the design of any type of power generating plant for a particular location, it is worth to start by evaluating the energy to be consumed. According to the data collected from the field, Rwumba village has 108 households and 14 shops. Type, size and quantity of appliance to be used by each household interested were considered and this has given a crucial idea of estimating energy to be consumed in the village. Figure 1 is showing the hourly daily load that curve generated from HOMER software after estimating the cumulative energy consumption.

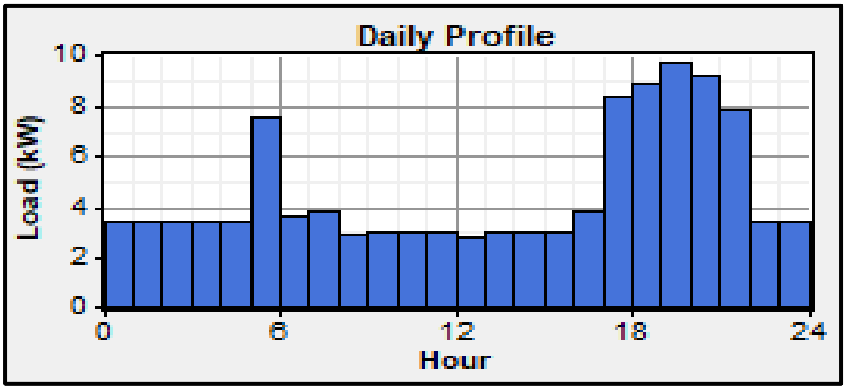


Fig. 1: Hourly Daily Load for Rwumba Village

The peak power demand for Rwumba village was evaluated and found to be 9.72 kW which occurs at 8 PM. The daily energy required at Rwumba village was also estimated to be 110.326 kWh with 81.86% being consumed by the residential load, 16.14% being consumed by the commercial load and 2% consumed by the community load. Figure 2 is showing the configuration window for data input in HOMER software for designing Rwumba mini-grid.

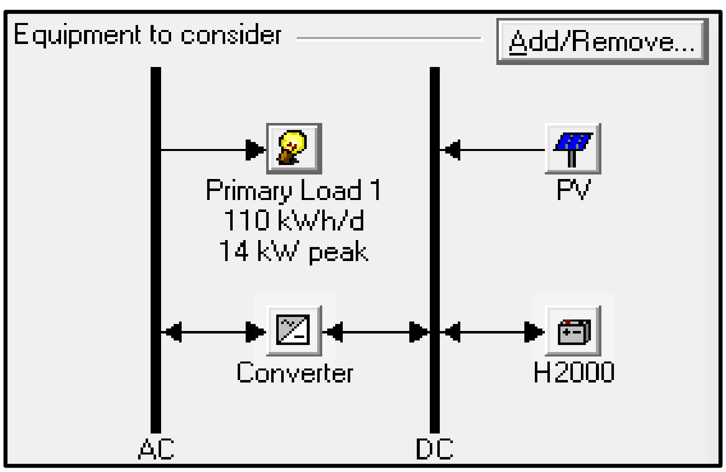


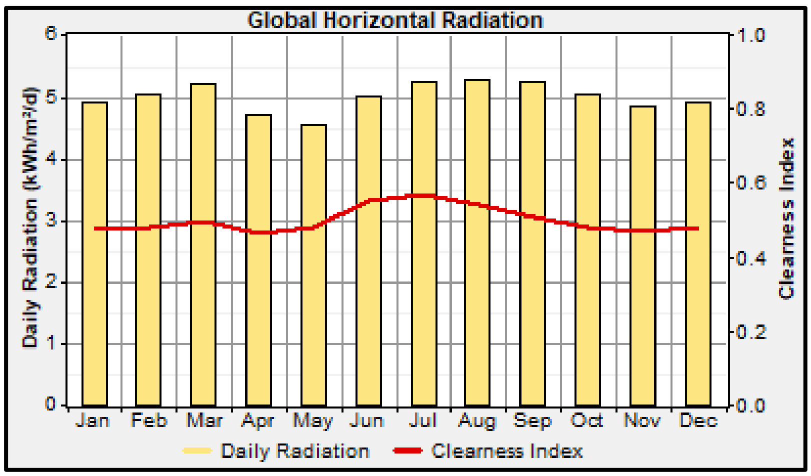
Fig. 2: Configuration of mini-grid for Rwumba Village.

2.2 Solar Resources Assessment for Rwumba Site

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

The latitude and longitude coordinates were used to specify the exact location of Banda site on the Earth's surface depending on the specified time zone. The site for Banda mini-grid is located at the latitude of 2^0 30' S and longitude of 29^0 0' E. Figure 2 is showing the corresponding solar resources retrieved from the website of NASA upon proper entering the coordinates in HOMER.



2.3 Optimization Model for Rwumba Mini-grid

Data on load profile shown on Fig.1, main equipment and their associated costs were used to design an optimization model for the designed mini-grid for Rwumba village. During the data input in HOMER for PV modules, storage battery and Power inverter, the replacement cost of each component was taken to be the same as its capital cost whereas the operating and maintenance cost was assumed to be 1% of capital cost [22]. The following sections tackle on the main components input in HOMER.

2.3.1 Banda PV Modules Inputs

For PV data inputs in HOMER software, monocrystalline solar panel type SUNMODULE PLUS SW 270 MONO was selected and related specifications are mentioned in the data sheet and on the name plate by the manufacturer. Different sizes and corresponding costs were entered in HOMER as shown in Fig.3. The type of the panel selected is available in Rwanda at the cost of USD 1056 per kW.

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

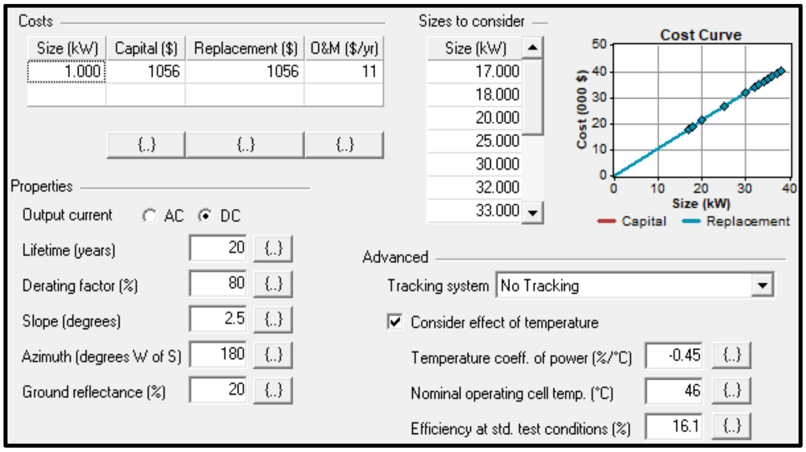


Fig. 3: PV Data Input in HOMER

2.3.2 Storage Battery Inputs

HOMER component library contains many types of batteries and their associated properties that designers use when designing solar PV systems. It is then easier to choose an appropriate battery type from the list based on predetermined specification that can efficiently match with the used PV system production. For this particular case study, Hoppecke 16OPzS 2000 battery of 2 V and 2000 Ah costing $850 was selected. Figure 4 is showing more details on the battery considered in this case study.

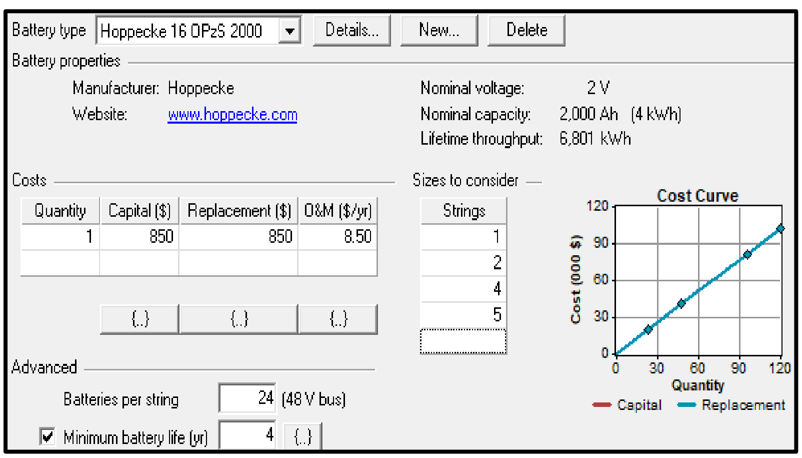


Fig. 4: Battery Data Inputs in HOMER

2.3.3 Power Inverter Inputs

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

Converter is needed for power systems that require the use of both AC and DC Power. It can work as an inverter in case of DC to AC conversion or a rectifier for AC to DC case or can serve both purposes. Figure 5 shows the details concerning different sizes and cost that HOMER considered while choosing optimal size of the converter. The type of converter selected is available in Rwanda to the cost of USD 433 per kW. Efficiency of 95% that is used by the converter for conversion from DC into AC was considered [23].

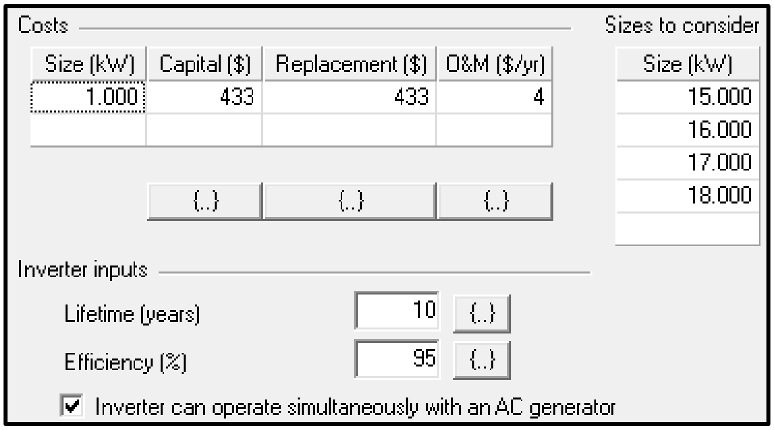


Fig. 5: Power Converter Data Input in HOMER

2.3.4 Charge Controller Design

HOMER does not model the battery charge controller as a separate component. So it is recommended to include its cost and efficiency in the values of other specified components like PV array. Therefore, to design the charge controller for this study, equation (1) was used. To determine the charging current, the total short-circuit current resulted from parallel connection of the modules was multiplied by a safety factor of 1.25 [24]. The voltage rating of the charge controller was taken to be the same as the system voltage.

$$\mathrm{I} = I_{SC} \times N_P \text{ x safety factor} \qquad (1)$$

I: Current rating of the charge controller
I_{SC}: Short-circuit current for one PV string
N_P: Number of parallel PV strings.

2.4 Days of Autonomy

The continuous number of days that the battery system supplies the power to the load without any charging supply from the PV array is known as the days of autonomy. Thus, when designing

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

and sizing a battery storage system, the amount of time that the battery will supply the power to the load has to be given much consideration. Due to economic reasons, the most economical number of days of autonomy is 1 day but the system designer could use up to 3 days beyond which the storage system becomes uneconomical [23]. HOMER defines this as the ratio of the battery bank size to the electric load and calculates the days of autonomy converted in hours using Equation (2).

$$A_{batt} = \frac{N_{batt} \times V_{nom} \times Q_{nom}\left(1 - {}^{q_{min}}/_{100}\right)\left(24\,{}^{h}/_{d}\right)}{L_{prim,ave}\left(1000\ Wh/kWh\right)} \qquad (2)$$

Where:

A_{batt}:	Days of Autonomy expressed in hours [h]
N_{batt}:	Number of the batteries in the battery bank
V_{nom}:	Nominal voltage of a single battery [V]
Q_{nom}:	Nominal capacity of a single battery [Ah]
q_{min}:	Minimum state of charge of the battery bank [%]
$L_{prim,ave}$:	Average primary load [kWh/d]

3. RESULTS AND DISCUSSION

The optimum results are essential in designing the PV system which can meet the entire load throughout the year. It is with this regard that data collected from Rwumba site on load to be electrified (Residential, Commercial and community) were entered in HOMER software as primary load to come up with a model of the mini-grid for electrifying Rwumba village.

3.1 Results

Optimization results were obtained by running various simulations in HOMER with different inputs like sizes and associated costs for PV modules, storage batteries and converter. Based on these variety of inputs, the software simulated, calculated, and displayed various possibilities of optimum results starting by the possibility with lower Net Present Cost. Sensitivity variables like capacity shortage (percentage of unmet load) were considered during simulations. Table 1 is showing optimum results obtained from simulation at 0%, 1%, 3%, 5%, 6%, 7% and 10% Capacity shortages.

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

Table 1: Optimization Results for Rwumba mini-grid at different capacity shortages

Max. Cap. Shortage (%)	PV (kW)	H2000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)
0.0	38	120	15	$ 148,623	1,814	$ 169,432	0.368
1.0	37	96	15	$ 127,167	1,599	$ 145,510	0.319
3.0	34	96	15	$ 123,999	1,566	$ 141,963	0.316
5.0	33	96	15	$ 122,943	1,555	$ 140,781	0.316
6.0	32	96	15	$ 121,887	1,544	$ 139,599	0.318
7.0	38	48	15	$ 87,423	2,761	$ 119,097	0.275
10.0	34	48	15	$ 83,199	2,627	$ 113,331	0.268

3.2 Discussion

The optimization process for the designed mini-grid for Rwumba village was achieved by the help of HOMER software. The software accepted data inputs like daily load, daily solar radiation, different sizes of PV modules, storage battery and power inverter. Annual capacity shortages indicating level of unmet load were also considered during simulation. The software simulated all these data entered and generated the optimum results for each case of capacity shortage presented in Table 1. HOMER considers infeasible the system designed with a high value of capacity shortage, this is because such system will not be trustworthy and will not meet the load for a long period of the year. Thus, in order to get a reliable, optimized, smaller and less expensive power system, the designers of HOMER recommended the allowable range for setting the annual capacity shortage, this is from 1% to 5%. Therefore, the results obtained at 6%, 7% and 10% were given less consideration in this study because they can only meet the load at 94%, 93% and 90% respectively, which would mean unreliable power systems.

Results given by simulation using HOMER at 0% capacity shortage mean that the corresponding system will meet the load at 100% reliability throughout the year; but this will not be economical because the system has to include large, expensive equipment that is not fully used most of the time [21]. Having analyzed the results presented in Table 1 obtained from simulation at various annual capacity shortages, it is clear that the optimum results proposed by HOMER at 0% imply a bigger and expensive system meaning high initial and operating cost leading to high cost of energy. Consequently, the results corresponding to 0% capacity shortage were also given less consideration in this study.

Though the results obtained at 1%, 3% and 5% capacity shortages show that the corresponding systems can accurately meet the load during their operation, the power system corresponding to 2% will be expensive compared to the rest. This is remarked from the results where the

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

associated initial cost is USD 127,167 while the others require the initial cost of only USD 123,999 and USD 122,943 at 3% and 5% respectively. Moreover, comparing the two remaining systems corresponding to capacity shortage of 3% and 5%; it is clear that the difference in their initial cost is not significant. Consequently, much preference was given to the results obtained at 3%. This is because the corresponding PV solar system can meet the load with high reliability (97%) compared to PV solar system corresponding to 5% that can meet the load at only 95% throughout the year.

Achieving optimum results at capacity shortage of 3% for this case study has a strong agreement with the results obtained by Rawat & Chandel, 2013. For their research, they carried out a study on Simulation and Optimization of Solar Photovoltaic-Wind stand-alone Hybrid system in Hilly Terrain of India using HOMER and they obtained the results for optimum system at capacity shortage of 3.1%.

3.2.1 PV Modules

PV Modules for the optimum Rwumba mini-grid was designed to have the rated capacity of 34 kWp and are supposed to produce enough power for running a daily load of 110.326 kWh. Number of PV Modules needed was calculated and found to be 126. This was evaluated by dividing total rated capacity of PV modules by the rated capacity of available panel; this is 270 Wp. The available PV panel is rated as follows: Short-circuit current of 9.44 A, Rated current of 8.81 A, Rated voltage of 30.9 V. Taking into consideration the system voltage of 48 V, the PV Modules can be arranged in such a way that they will form 63 strings whereby each string is composed by 2 PV Modules in series. This arrangement yields total short-circuit current of 595 A, Rated current of 555 A, and Rated voltage of 62 V.

3.2.2 Storage System

The storage system for Rwumba mini-grid was optimized to have 96 batteries connected in four strings with 2000 Ah and 2 V each. The nominal capacity for this storage system is 384 kWh and has around 3 days of autonomy (60.7 hours). Days of Autonomy were calculate using equation (1).

3.2.3 Power Inverter

Power inverter of 13 kW was designed to be used for the optimum designed Rwumba mini-grid. This will accommodate the power generated by the PV modules during the day and power drawn by the load from the battery bank during the night. This power inverter will also handle the peak load of 9.7 kW expected to be experienced by Rwumba solar mini-grid.

3.2.4 Charge Controller

The current to be handled by the Charge Controller to be used at Rwumba mini-grid was determined by applying Equation (2) and was found to be 743.4 A. Considering a Charge Controller of 60 A, the number of Charge controller to be installed in parallel was obtained to be 13. The Charge Controller will operate at system voltage of 48 V.

3.2.5 Number Days of Autonomy

Number of days of autonomy was obtained by applying Equation 2. These was obtained to be 3 days which means that during the cloudy days, the designed mini-grid for can supply the power to the end users for three days without any power supplied from the PV panels.

3.2.6 Cost of Energy

The cost of energy for the designed system was found to be USD 0.316 per kWh. This was found to be easy affordable compared to the existing cost which is USD 0.375.

4. CONCLUSION

In this work, a study with HOMER software was done to design an optimum solar mini-grid that could be used to electrify Rwumba Village. To achieve this, data collected on energy to be consumed were used to estimate the daily energy requirement and thus the daily load curve was generated. Optimum solar mini-grid for electrifying Rwumba village was successful achieved. This was obtained to be composed by 34 kW of PV Panels capacity, Battery Bank capacity of 384 kWh and the power inverter of 15 kW. These results were obtained at the reliability of 3% (capacity shortage) which means that the designed mini-grid will be able to meet the entire load at 97% throughout the year. Based on the number of the days of autonomy obtained, the system will also be able to supply the required power for electrifying the load for 3 days during the time of low level of solar radiation and cloudy days. Thus, it is recommended to the public and private solar mini-grid developer to consider the optimum system taking into account the available load to be electrified in order to avoid the higher initial cost leading to higher cost of energy that may arise in the case of an oversized system. Once the optimum system is used, this will enhance its safer functioning.

ACKNOWLEDGEMENT

This research was funded by Rwanda Polytechnic and Germany Academic Exchange Service (DAAD). The authors are grateful to the owner and staffs of RENEG Ltd for their willingness and participation by providing the adequate Data to make this research more fruitful.

ISSN: 2456-1851

Volume: 04, Issue: 05 "September-October 2019"

REFERENCES

[1] S. B. Gwenaelle Legros, Ines Havet, Nigel Bruce, "Energy Access Situation in Developing Countries," *UNDP WHO New York*, p. 142, 2009.

[2] R. Bocca, "Scaling Up Energy Access through Cross-sector Partnerships," *World Econ. Forum*, no. August, 2013.

[3] UNECA, "Accelerating Sustainable Development Goals Achievement Policy Brief Review At the United Nations Political Forum," 2018.

[4] Luciane, *Impacts of Rwanda's Electricity Access Roll-Out Program*. 2015.

[5] C. S. Lai and M. D. Mcculloch, "Levelized Cost of Energy for PV and Grid Scale Energy Storage Systems," pp. 1–11, 2017.

[6] Mininfra, "Rwanda Energy Sector Overview," no. September, 2016.

[7] H. G. Beyer, "Design of Photovoltaic System for Rural Electrification in Rwanda," 2017.

[8] S. G. B. Paul Baringanire, Murphy, Kabir Malik, "Scaling up access to electricity : The case of Rwanda," *Livewire*, vol. 20, no. 88701, pp. 1–8, 2014.

[9] B. Safari, "A review of energy in Rwanda," *Renew. Sustain. Energy Rev.*, vol. 14, no. 1, pp. 524–529, 2010.

[10] J. Munyaneza, M. Wakeel, and B. Chen, "Overview of Rwanda Energy Sector: From Energy Shortage to Sufficiency," *Energy Procedia*, vol. 104, pp. 215–220, 2016.

[11] T. I. Jean de Dieu Uwisengeyimana, Ahmet Teke, "Current Overview of Renewable Energy Resources in Rwanda," *J. Energy Nat. Resour.*, vol. 5, no. 6, pp. 92–97, 2016.

[12] Mininfra, "Rural Electrification Strategy," p. 29, 2018.

[13] G. Bensch and G. Bensch, "Impacts of Rural Electrification in Rwanda Impacts of Rural Electrification in Rwanda," no. 6195, 2011.

[14] A. K. Azad, M. G. Rasul, M. M. K. Khan, T. Ahasan, and S. F. Ahmed, "Energy Scenario : Production , Consumption and Prospect of Renewable Energy in Australia," no. April, pp. 19–25, 2014.

[15] I. Gemma, "Energy Landscape of Rwanda and Institutional Framework," *Sci. Res.*, vol. 5, no. 3, p. 16, 2017.

[16] Antony, "Design of an off-grid Photovoltaic system for electrifying a Village of Denmark," 2012.

[17] O. Pederzini, "Design of a Solar Microgrid for the Community of Mpaga, Gabon based on its social and economic context," 2017.

[18] B. B. and O. S. J. Abdulateef, K. Sopian, W. Kader, B. Bais, R. Sirwan, "Economic Analysis of a Stand-Alone PV System to Electrify a Residential Home in Malaysia," *10th IASME/WSEAS Int. Conf. Heat Transf. Therm. Eng. Environ. (HTE'12). Istanbul, Turkey*, pp. 169–174, 2012.

[19] A. El-Shafy A. Nafeh, "Design and Economic Analysis of a Stand-Alone PV System to Electrify a Remote Area Household in Egypt," *Open Renew. Energy J.*, vol. 2, no. 1, pp. 33–37, 2009.

[20] B. Afif, A. Chaker, and A. Benhamou, "Sizing of optimal case of standalone hybrid power system using homer software," *Int. Rev. Autom. Control*, vol. 10, no. 1, pp. 23–32, 2017.

[21] R. Rawat and S. S. Chandel, "Simulation and Optimization of Solar Photovoltaic- Wind stand alone Hybrid system in Hilly Terrain of India," vol. 3, no. 3, 2013.

[22] I. Prasetyaningsari, A. Setiawan, and A. A. Setiawan, "Design optimization of solar powered aeration system for fish pond in Sleman Regency , Yogyakarta by HOMER software," *Phys. Procedia*, vol. 32, pp. 90–98, 2013.

[23] G. G. Kidegho, "Design of a Grid Connected Photovoltaic System for Enhancement of Electrical Power Supply in Kenya : A Case Study of Nairobi Embakasi," *Jomo Kenyatta Univ. Agric. Technol.*, 2013.

[24] A. N. Al-shamani *et al.*, "Design & Sizing of Stand-alone Solar Power Systems A house Iraq," pp. 145–150, 2017.

