Solar Based Rural Electrification in Liberia

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Abstract

Low income population living in the rural areas suffers from lack of human and economic development. Modern energy access is one of the main drivers to improves health, education, and enhances the quality of life in less developed countries. As the cost of photovoltaic energy and storage systems continues to decrease, decentralized renewable energy base hybrid mini-grids become increasingly attractive options for rural electrification where the grid extension is not feasible. The main goal of this work is to show how solar based hybrid mini-grids can be used to solve the problem of electricity access and constitute a sustainable energy supply option for rural areas. This study focuses on the advantages of rural electrification and describes the design, installation and analysis of solar based hybrid systems in 5 villages in Liberia. The software HOMER is used as a tool for the techno-economic analysis and its mathematical models and the assumptions used are illustrated. An optimization with the software is performed to find the optimal configuration and size for each village. Then, simulations of the final designs are accomplished to predict the performances of the systems. The final configurations, with the description of the components used in the villages in Liberia and the installation procedure are illustrated. The energy production data collected from the mini-grid are analyzed and compared with the results from HOMER simulations. Finally, the costs of the project are reviewed and several considerations about the project are discussed, with possible improvements for similar projects.

Keywords: HOMER, Hybrid system, Off-grid, Photovoltaic, Rural electrification

1. Introduction

Modern energy services are crucial for human well-being and for a sustainable development, yet globally over 1.1 billion people are without access to electricity and 2.8 billion people are without clean cooking facilities [1]. However, significant progresses to promote access to electricity have been made worldwide, in fact since 2012 more than 100 million people per year have gained electricity access [2]. Basically all of the new connections are made through the main grid, however thanks to the declining costs for photovoltaic energy, cheaper and more efficient lighting and new business models, the number of available solutions for renewable access to electricity has increased. Over the last five years, renewable technologies distribution have started to gain ground, especially with off-grid and mini-grid systems, reaching of 30% of new connection's supplying and they are expected to increase in the next years [1]. Distributed energy systems are great solutions for power production in developing countries. Their use can complement or substitute the centralized energy generation systems, providing affordable lighting, communication or education services.

Liberia has one of the most underdeveloped energy sectors worldwide. While having one of the lowest rates of access to public electricity (13.8% in 2018), it has a high costs of electricity (around 0.50 USD/kWh). Liberia was upset by two civil wars, during which most of Liberia's infrastructures had been destroyed, including power plants and electric distribution lines [3]. However, the Government of Liberia presented in 2016 a national Rural Energy Strategy and Master Plan (RESMP), which aims to achieve a rural electrification rate of 35% by 2030, benefitting about 1.3 million people [4].

2. Case Study

In this institutional framework of the RESMP plan, the case study described in this work was realized in 2017. The project is called "Light up Our Futures through Renewable Energy Facility for Rural Isolated Communities in Lofa" in 5 communities. This project was led by the NGO Plan International Liberia and founded by the European Development Fund (EDF). The overall objective of the project is to contribute to poverty reduction in rural communities in Liberia through the installation of five micro-

Table 1: Energy demand of the villages

	Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
Number of Connection	96	156	143	64	101
Total Daily Demand [kWh]	66.8	102.2	81.2	46.2	93.8
Peak Power [kW]	7.4	11.3	9	5.1	10.4

Table 2: System optimization results

	Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
PV Modules [kWp]	22.3	34.3	27.3	15.7	31.3
Generator [kW]	12	24	12	10	24
Battery Bank [Ah]	2792	4271	3396	1938	3917
Inverter [kW]	12.7	19.3	15.3	8.7	18.0
NPC [USD]	124,228	183,980	143,597	84,247	171,182
System Autonomy [hr]	24.1	23.5	24.1	24.2	23.0
Unmet Load [%]	0	0	0	0	0
Renewable Fraction [%]	85.4	87.8	88.7	88.3	87.4

grid for five small rural communities in Lofa county. The villages are in isolated location and connected only through unpaved roads, therefore the connection to the grid is not an available option. 8,412 inhabitants live in the five rural communities and their economy is mainly based on agriculture, with some small scale commercial activities. Five schools, several small health clinics, mills and water pumping systems are present in the villages. Survey and assessment were carried out at each house and community buildings to identify the electricity demand. Different tariff types were then defined in order to classified the daily demand of the facilities. In table 1 are shown the energy and power demand of the 5 villages.

3. Design

An optimization of the each of the 5 systems was performed using the software HOMER (Hybrid Optimization Model for Multiple Energy Resources), in order to find the optimal size for each village. Due to the high availability of solar resources, solar based hybrid renewable energy systems (HRESs) have been designed for this project (scheme in figure 1). During the day, when the sun is shining, the photovoltaic modules generate electricity that directly powers the AC load or can be stored in the battery bank. At night or during days without sunshine the stored energy can be used. A supplementary Diesel generator makes the system reliable, offering the possibility of producing power at any time. The MPPT solar charge controller manages the power going into the battery bank from the solar array. It constantly monitors the voltage and current output of the PV panels in order to ensure the maximum power output working point and it controls that the deep cycle batteries are not overcharged.The coupling between the DC and AC bus is achieved by a bidirectional inverter, which converts DC power from the modules and the batteries to usable AC power and also converts AC power from the diesel generator to charge the storage system.

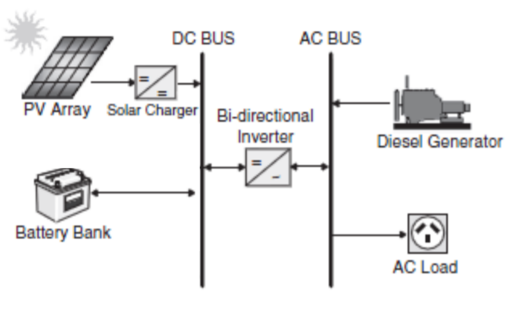

Figure 1: System configuration

HOMER software is a powerful tool for the optimal designing, sizing and planning of hybrid renewable energy systems, that can carry out techno-economic analysis for off-grid and grid connected power systems. The software takes as input the electric loads and the natural resources to perform simulations based on different system's configurations or the hybrid combinations of components and generates the optimized system configurations sorted in term of NPC (Net Present Cost) or COE (Cost of Energy). The optimization process is performed by minimizing the objective function to the constraints [5]. The objective function in this analysis is NPC, and the selected constraints are the system autonomy (1 day) and a null unmet load. The electrical loads for the simulations were built with HOMER from the energy daily demands and power peaks summarized in table 1, using two perturbation parameters: a daily noise (δ_d) of 10% and an hourly noise (δ_{ts}) of 20%. Theses perturbation parameters allow to add randomness to the load data to make it more realistic.

The resource data were obtained from the NASA Surface Meteorology and Solar Energy web site [6], specifying the longitude and latitude for each village. The annual scaled average solar radiations were found to be 5.15 kWh/m2/day. HOMER synthesizes hourly solar radiation data using an algorithm based on the work of V.A. Graham [7]. This algorithm produces realistic hourly data, requiring only the latitude and the twelve monthly average values. The algorithm creates synthetic solar data with certain statistical properties that reflect global averages. Then, HOMER calculates the global solar irradiance incident on the surface of the PV array using the HDKR model and with the incident irradiance it calculate the performance of the system. The results of the optimizations are shown in table 2. It is possible to noticed that each system has a predicted autonomy about 24 hours and the unmet load is zero, as required by the imposed constrains. The renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources and in these optimal configurations has an average value of 87%. HOMER calculates it according to the following equation [5]:

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}} \tag{1}$$

where:
f_{ren} = renewable factor
E_{nonren} = Non-renewable production [kWh/yr]
E_{served} = Total electrical load served [kWh/yr]

3.1. Final configuration

A first configuration of the project was created according the optimal sizes of the systems. However, due to budget limitation, Plan international decided, after the submission of this initial design, to modified the requirements, decreasing the amount of renewable energy contribution, therefore the capital cost, and relying more on the back up generators. The final design is summarized in the first part of table 3. In the second part of the table are shown the results of the simulations of this final configurations performed with HOMER. This simulations were accomplished to predict to performance of the 5 systems. As expected, in these results the PV productions are slightly lower that the optimization results, due to the lower PV sizes (lower renewable fractions). Despite the lower PV power, the predicted unmet load is null, which means that these designs allow the systems to work without any power shortage over the entire year. However, the autonomy of the systems are lower than 1 day, with value around 20 hours.

3.2. Implementation

The system was realized in 2017 by Sunlabob Renewable Energy. The installation started on 13th of April and was concluded after two month at the beginning of June. The installations were realized in all the villages with the same procedure and simultaneously. All the system components, except the PV array and the PV combiner boxes, are located inside a power house. The solar modules are installed on a Pergola type mounting structure above the powerhouse and inclined with a tilt angle of 10 and facing south. The selected photovoltaic panels are 260Wp poly-crystalline Sunmodule Plus from SolarWorld. The battery bank consists of 24 2V Hoppecke OPzS Solar lead-acid batteries with a maximum depth of discharge of 80%. The solar charge controllers, bi-directlional inverters, remote controllers and system monitors were selected from the brand Studer. Elcos Diesel Generators were installed to work in conjunction with the bidirectional inverter and thus ensure that the battery bank is sufficiently charged to prevent prolonged low state-of-charge and accelerated battery damage. All the components were sized according the final design illustrated in table 3. In each village the connection between the different buildings were realized. Electrical cables connected the powerhouse to each user through overhead electrical lines. Moreover, five outdoor lights were installed in strategic positions in each village in order to provide street illumination.

Table 3: Final configuration and simulation results

	Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
No. PV modules	63	90	87	45	87
Total PV Capacity	16.38 kW	23.4 kW	22.62 kW	11.7 kW	22.62 kW
Genset Power	12 kW	24 kW	12 kW	10 kW	24 kW
Battery Capacity	2328 Ah	3108 Ah	3108 Ah	1608 Ah	3108 Ah
Charge Controller	4x 5 kW	5x 5 kW	5x 5 kW	3x 5kW	5x 5 kW
Inverters	2x 8 kVA	3x 8 kVA	2x 8 kVA	1x 8 kVA	2x 8 kVA
NPC [USD]	139,424	217,445	151,904	93,210	192,198
Capital Cost [USD]	48,250	71,638	59,119	32,489	65,359
Load Consumption [kWh/yr]	24,378	37,303	37,303	16,863	34,712
PV Production [kWh/yr]	23,686	33,838	32,710	16,919	32,710
Genset Production [kWh/yr]	6,313	11,986	5,460	4,203	9,883
Renewable Fraction [%]	74.1	67.8	81.6	75.1	71.1
Autonomy [hours]	20.1	17.6	22.2	20.0	19.2
Unmet Load [%]	0	0	0	0	0

In each building connected to the mini-grids, a single-phase meter with an electric energy dispensing function to control the demand. The energy dispensers provide a smart control of the available electricity to the users depending on their energy tariff. The users can charge a RFID card in a central station and then they can activate the dispenser in the house and consume the amount of energy that was charged.

4. Analysis

After the realization of the micro-grids, the data from the monitoring system have been collected and graphically analyzed with the Xtender Analysis Tool in order to evaluate the performance of the systems. The monitoring devices collected data for nine months, from July 2017 to April 2018. These data have then been compared with the theoretical production data simulated with HOMER (summarized in table 3). The comparison is shown in table 4, where the measured are the data collected by the grid analyzer (Xtender), while the expected are the production data from the simulations over the same period (from July 2017 to April 2018). The absence of Lengbamah's data is due to failure of the system caused by lighting strikes, while for Taninahum, the lack is due to delays in collecting of the data. It is easy to see as the real value are way lower than the expected ones. Both the PV production and the load consumption are lower, with different ranges depending on the village, while the backup generators is almost never used. For Koiyama the data are closer to the expected values. In order to better understand these differences, in figures 2 are shown the monthly averaged daily PV productions from the HOMER simulation (in red) and from the Xtender analyzer (in blue) for Nyengbelahun. The production in the first months of use (July) is compared with the production in the final period of analysis (March).

First, it is possible to notice that both the Xtender and the HOMER data have a tendency to growth in peak value and shape over this period. The increase in peak values of the PV production in the winter period is due to the end of the rainy season, therefore to higher solar irradiance. Moreover, the data from the real PV productions (Xtender) tend to increase over that period, assuming the same shape and size of the predicted production. This trend is due to a growth in the energy demand of the villages. In fact, in the first period the electricity consumptions were still low and after some months the use of the mini-grids increased, thanks to the familiarization of the villagers with the systems and their higher electricity needs (e.g. new electric devices). Due to this low energy consumption, the solar energy is enough to maintain the state of charge of the batteries in the optimal range and to supply the demand. This behaviour is easier to noticed in figure 3 where the PV production is compared with the AC power output (load demand), the AC power input (Backup generation) and the State of Charge (SoC) of the battery bank. The PV production reaches its peak around 9 a.m., this happen because the battery bank is fully charged (SoC=100%). Therefore, the PV production is stopped and then it stabilizes on low generation values, used only to keep the battery charged. The AC power demand is in fact really low, around 200 W, and the energy is consumed only during the nighttime, caused only by the street lights.

4.1. Economical Analysis

In this section the costs of the project are discussed. First, the cost of the different components have been analyzed and summarized in table 5. The total cost of the components account for 691,761.1 USD. A total of 373 PV panels were installed, with an unitary price of 225 USD. The battery banks, traditionally the most expensive component of an off-grid system, constitute 13% of the

Table 4: Production analysis results and comparison

		Koiyama	Mamikonedu	Nyengbelahun
Load Consumption	Measured [kWh]	10,671	5,048	2,844
	Expected [kWh]	18,284	27,977	12,647
	Difference [%]	42%	82%	78%
PV Production	Measured [kWh]	13,336	9,633	5,189
	Expected [kWh]	17,765	24,533	12,689
	Difference [%]	25%	61%	59%
Genset Production	Measured [kWh]	851	0	0
	Expected [kWh]	4,735	4,095	3,152
	Difference [%]	82%	100%	100%
Renewable Fraction	Measured [kWh]	92%	100%	100%
	Expected [kWh]	74%	85%	75%

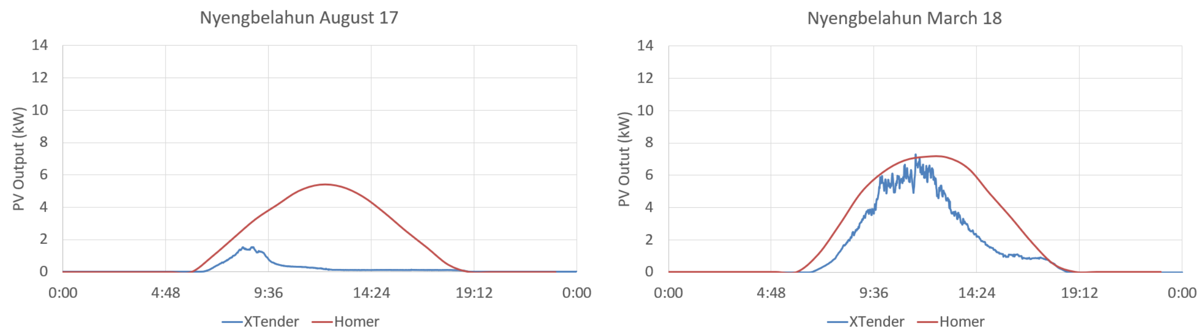

Figure 2: Production comparison for Nyengbelahun

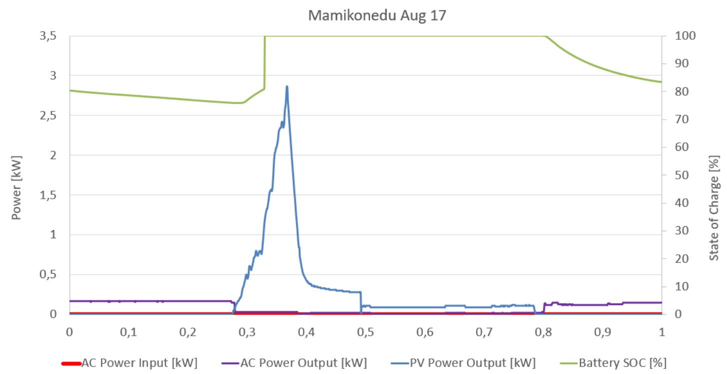

Figure 3: Production analysis for Nyengbelahun in August 2017

total cost, thanks to the low price of the lead acid batteries of 130 USD/kWh. The dispenser systems are the most expensive component of the project (14%). This because one dispenser has been installed in every household (590 dispensers), each with a unitary price of 150 USD. The last big share (12%) is the cost of the accessories. The budget cut to the final design generated a total saving that account to 100,622 USD. This change allowed to save almost 15% of the total components cost.

In table 6, the total cost of the system is shown. The components cost described in the previous table account for 69% of the total system cost, while the civil work and installation costs are 20%. The cost of the shipping and transportation of the components to the sites are 3% of the total. Finally, the engineering cost is 8% of the total and the last 1% are import taxes. The total cost of the system is 1,007,953.9 USD, for a PV peak power of 96.72 kWp, which means a cost of 10,465 USD/kWp.

5. Conclusions

During the realization of this project, several difficulties have been observed. One of the first barrier is the remote location of the sites. In fact, the villages are located at several hours from the main cities and accessible only through by four-wheel-drive pickup truck. This situation influences all the aspects in the installation and maintenance of a mini-grid. First of all, the delivery of the equipment to the sites, that can involve complex logistic, delays and, therefore, additional costs. Moreover, the systems were designed to be controlled remotely through the control and communication components. However, in the villages no internet connections are available, which creates several disadvantages. For the collection of the production data, for example, the remote control system has to save the data on a SD card, since the communication set can not work. The SD cards must be periodically collected by a technician, before being elaborated and analyzed. This problematic is the cause of the absence of the production data for Taninahum. The absence of internet connection created also difficulties in the security of the systems. In fact, the remote location of the grid together with the lack of control, make room for improper use of the systems. For example, in some villages have been reported illegal electrical connections to the mini-grid or bypassing of the dispenser. This problematic, not only generates an economic loss, but also a safety issue due to eventual electric shocks or damages to the mini-grid.

After the economical and implementation analysis of this work, it is certainly that grid centralized grid systems are easier to install, more efficient and cost-effective systems compared to decentralized electricity provision. Especially due to the high cost of investment of the mini-grid, which the rural com-

Table 5: Distribution of the Components Cost

	Costs	
	USD	Percentage
PV Modules	83,995.9	12%
Mounting Structure	43,414.8	6%
Diesel Generators	44,404.6	6%
Battery Banks	88,058.2	13%
Inverters	59,025.4	9%
Charge Controllers	23,062.6	3%
Dispenser Systems	99,256.5	14%
Cables	71,536.4	10%
Distribution Boxes & Rails	37,515.7	5%
Grounding	31,691.8	5%
Electrical Protections	25,899.2	4%
Accessories	83,900.0	12%
Total Components Cost	691,761.1	

Table 6: Distribution of the Project Total Cost

	Costs	
	USD	Percentage
Total Equipment Cost	691,761.1	69%
Civil Work & Installation	196,620.9	20%
Design Cost	82,938.3	8%
Shipping Cost	27,543.4	3%
Administrative Charge	9,090.2	1%
Total Cost	1,007,953.9$	

munities cannot afford. However, hybrid mini-grid systems, when properly designed and supported by international funds, can be a powerful technology for achieving rapid rural electrification, improving at the same time the living conditions of the local population and supporting the socioeconomic development of rural communities.

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