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Optimal Mini-grid for Rural Electrification: A Case Study of Sekoukou-Niger

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A B S T R A C T

The electricity access rate in Niger is one of the worst in Sub-Saharan Africa and is an issue of paramount importance to the Government of Niger. This energy insecurity has negatively affected industrialization and developmental plans, making Niger one of the poorest countries in the world. With a large landmass and several pockets of habitation in Niger, mini-grids remain the optimal way of providing electricity to people living in rural areas. Nigerienne Agency for the Promotion of Rural Electrification (ANPER), which is the institute responsible for rural electrification, currently operates about 110 diesel-powered mini-grids in Niger. With global warming looming, the operation of these diesel generators is not only expensive but also has an adverse effect on the environment. This paper seeks to analyze the techno-economic feasibility of a hybrid system for rural electrification in Niger with Sekoukou village as a case study. Load assessment, component technical configuration and component cost are simulated in HOMER software as objective functions to find the optimal size and cost. Results show that the most economical and efficient system for mini-grid operation in Sekoukou in Niger, is the generator-photovoltaic (PV) hybrid mini-grid which produces a levelized cost of energy of $0.271. A load shifting approach is applied to the existing load profile, which further reduces the levelized cost of energy from $0.271 to $0.177. This hybrid mini-grid system coupled with the load shifting approach would help improve the village's ability and willingness to pay for electricity.

INTRODUCTION

About 16.4 million people in Niger lack access to electricity from the national grid, with most households spending a considerable part of their daily income on inefficient energy sources [1, 2]. Around 19.5% of Niger's population have access to one source of electricity, which is very low when compared to the average access rate of 31% in Sub-Saharan Africa [3]. Electricity access from the grid is usually in the major cities, with just a handful of people living in rural areas having access. Even in areas with access to the grid, electricity access is sporadic with many experiencing brownouts and blackouts [4]. Niger has an on-grid electricity capacity of about 175 MW generated by "*Sociéte Nigerienne d'Electricité"* (NIGELEC) and other private companies [5]. This low generation capacity and underdeveloped infrastructure have led to heavy reliance on energy imports and backup solutions, which are mostly diesel generators. The energy system in Niger is fragmented, small and often depends on electricity imports from Nigeria through the West African Power Pool Project (WAPP) [6]. The main power system is made up of two independent grids that are connected to Nigeria because of relatively cheap electricity from Nigeria, coal power plants and many diesel-generator powered mini-grids [7].

80.5% of households in Niger have no access to any medium of stable electric power, with the share of households without electricity reaching 89.1% in rural areas [3]. Due to initiatives and funding from different organizations such as the World Bank, a variety of measures have been considered to promote rural electrification in Niger, with the government focusing on mini-grid deployment for rural areas due to the expensive nature of extending the grid to those areas [8]. The country currently has over 110 mini-grids powered by diesel generators [9]. These diesel generators have been found to run on losses due to high maintenance and operating costs, and rising diesel prices in the country [10]. The country has an enormous underutilized renewable energy potential with an average solar irradiance of 6 kWh/m^2/day and 9 hours of daily insolation throughout the year [11]. However, the installed generation related to renewable energy (solar) only stands at 4.04 MW with telecoms and water

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pumping activities making 32% and 53% of its usage, respectively [12].

Photovoltaic systems have been identified as an effective way of championing mini-grids in Africa because they are pollution-free, maintenance-free, coupled with an abundance of solar energy in the area. The solar potential in Niger for Mini-grid is capable of roughly covering the annual energy needs of the country due to the availability of the sun all year round, but this potential is almost wasted with only 10% harnessed per day [13]. The international Multi-Tier Framework (MTF) is an initiative to define electricity access according to ranges from full access (Tier 5) to no access (Tier 0) [14]. Table 1 shows the MTF tier for urban, rural, and nationwide. About 17.5% of households in Niger are either in Tier 1 or fall above it. 48.8% of this number can be found in urban areas with the share reaching 8.5% in rural areas.

Table 1: MTF Tier distribution in Niger [1,2].

MTF	Nationwide	Urban	Rural
Tier 0	82.50%	51.20%	91.50%
Tier 1	0.60%	0.90%	0.50%
Tier 2	4.40%	9.70%	2.90%
Tier 3	3.80%	9.40%	2.20%
Tier 4	3.90%	12.30%	1.50%
Tier 5	4.80%	16.50%	1.40%

The challenges contributing to the inability of households to gain access to electricity from the grid are largely due to the distance of these households from the grid. As shown in Figure 1, the distance to the grid contributed 87% of the reasons why these households lack electricity access from the grid, with a share of 92.7% for people living in rural areas [12].

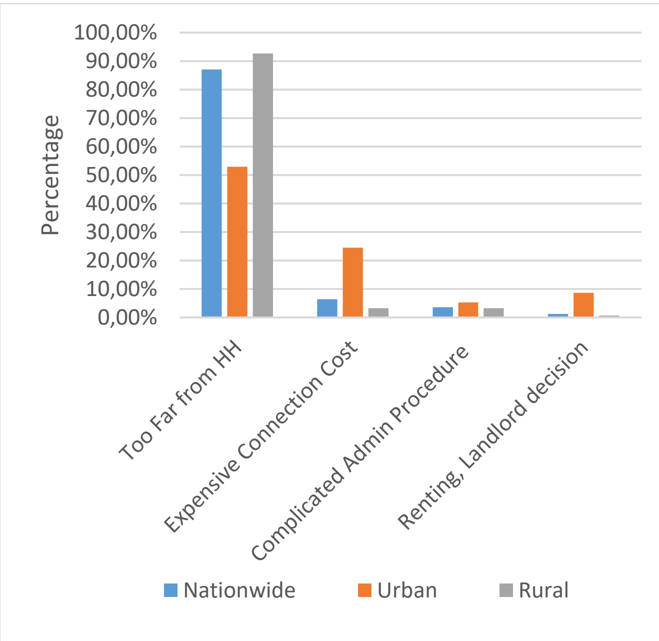

Figure 1. Barriers to Grid Electricity Access in Niger

Mini-grid systems have been employed in Sub-Saharan Africa to promote electricity access in communities that are far from the electricity grid [15, 16]. Mini-grid systems are autonomous systems that can be operated and controlled without connection to the conventional electricity grid [17]. This independent distributed system has the tendency of ensuring a more reliable and stable electricity access because faults and interference with electricity supply can easily be resolved. As an extra factor, having the source of electricity close to consumers helps reduce distribution losses [18]. The deployment of mini-grid systems in Sub-Saharan Africa is often more pronounced and economical in communities that live in villages with houses in proximity [19, 20]. In this light, the benefits of mini-grids can be compared to the national grid with a little distinction of mini-grids being their ability to be deployed independently.

Apart from selecting resources that would be used in a mini-grid, another key problem associated with mini-grids are the sizing of these resources to meet consumer demand [21, 22]. The objective of this research is to analyze the techno-economic feasibility of providing a hybrid standalone system for rural electrification in the village of Sekoukou based on a case study on the village's willingness to pay [23]. An optimization of this simulation results in alternative configurations based on system inputs that would ensure the lowest carbon emission and levelized cost of energy (LCOE). An alternative load profile using a load shifting approach is proposed to further reduce the LCOE. In the design and sizing of this mini-grid, the various systems are considered autonomous systems, which leads to several possible system configurations. Such a constraint leads to an infinite number of possible system configurations.

Literature Review

Optimal mini-grid systems have been proposed in literature for many rural areas, particularly those in Sub-Saharan Africa. In [24], the authors proposed a mini-grid consisting of PV panels, inverter and a battery. The sizing of the system was done using an analytical approach while the financial modelling was done in Homer software. However, analytical approaches make use of approximations and thus lack calculation precision. The authors also failed to address if the proposed system was the most optimal system possible. In [25], a containerized mini-grid system was proposed for developing countries in Sub-Saharan Africa. The authors designed a solar hybrid system with battery as the sole back up option. The effects of this design on the levelized cost of energy were however not considered. The optimality of the system was also based on only the azimuth and tilt angle of the panels.

To find the optimal levelized cost of energy, the authors in [26] designed a solar hybrid mini-grid system by considering all available options. This approach however failed to address the technical design and connection point of the system. Approaches to reduce the LCOE was not taken into consideration. Optimal hybrid system was considered by the author in [21] to determine the most feasible LCOE. The simulation was done in Homer and load data collected through survey. This approach did not consider options to reduce the LCOE nor design for the technical configuration. In [27], the authors proposed a load profile formulation approach to help with the design of energy technologies. This proposal focused on how energy is consumed in various communities and how best to model energy systems to meet such needs. This paper did not examine optimal design systems based on the respective loads. Considering the review of

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relevant literature and to the best of the authors', no literature exists that involves combining design of optimal hybrid mini-grid system, technical design for installation and a demand side management approach to reduce LCOE.

Study Approach

The village of Sekoukou has a population of about 2000 with 300 households and is about 50 km from the capital of Niger, Niamey. The main sources of livelihood are agriculture, fishing, and irrigation. As of 2020, the village had not been electrified with no known plans of being electrified. In earlier research to determine the ability and willingness of the residents of Sekoukou to pay for electricity, data on the consumption of electricity in Niamey was collected specifically from (NIGELEC), the utility responsible for power generation and transmission in Niger, and analyzed to determine the consumption patterns throughout the year [23].

Figure 2. Sekoukou village in Niger

To develop an electrification scenario for a load profile, a survey to determine the perceived electrical needs of the population was conducted. This included a questionnaire based on the services households wanted, compared to their financial status and in priority order [23]. The power rating of each electrical gadget is used to extrapolate the conceptual demand for electricity for Sekoukou village. The most feasible load profile is that of the mixed scenario ownership, which is a mixture of individual and community loads. Thermal loads were not considered due to their unavailability.

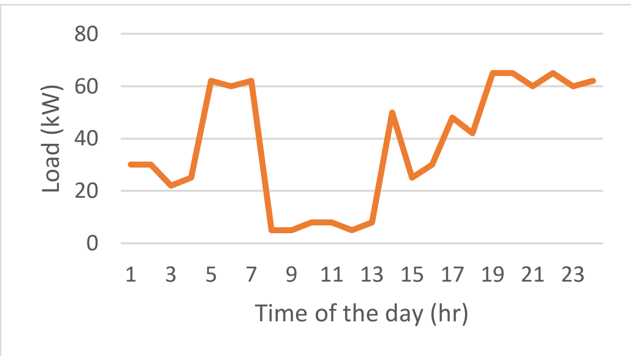

Figure 3. Daily Load Profile of Sekoukou

Sekoukou is a predominantly farming village with the same activities carried out every day of the week. This makes the load profile over the weekday like that of the weekend. The final load profile is the average load consumption throughout the week. Found in the Tillaberi region of Niger, a solar resource assessment of Sekoukou was obtained from the National Aeronautics and Space Administration (NASA) database found in HOMER Pro software. The website provides data for over 22 years; from 1983 to 2005. The scaled annual average was found to be 6.17kWh/m^2/day with the highest daily irradiation during the year being April and May, which is also essentially among the hottest days in Niger as shown in Figure 4. The clearness index of the village varies between 0.691 and 0.656 as the highest experienced during the dry season. However, the lowest clearness index is 0.542 in August. This is because the region experiences peak rainfall during August, which causes an overcast of heavy rain clouds, hence the lower clearness index and average daily irradiation of 6.17kWh/m^2/day [28].

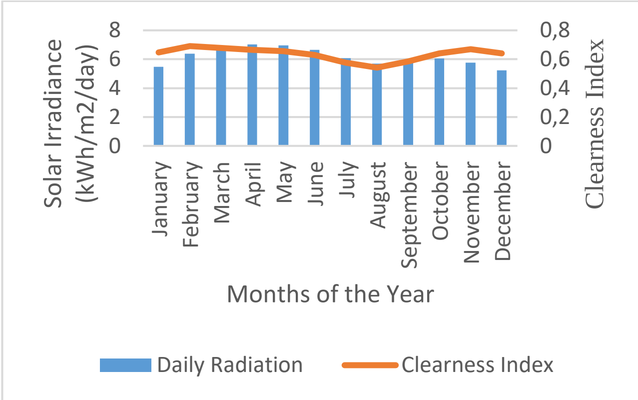

Figure 4. Solar Irradiance and Clearness Index for Sekoukou

METHODOLOGY

The techno-economic analysis is performed using HOMER software tool. HOMER is widely used in many literatures worldwide for designing optimal technologies for off-grid rural electrification because of its wide scope of resource input and optimal combination [29]. This helps in a wide range of selection of system configuration and power dispatch based on consumer needs. To obtain the most optimized design for the mini-grid, three tasks of simulation, optimization, and sensitivity analysis are carried out to obtain the most suitable system desire. Achieving this requires data of load assessment, component technical characteristics, economics associated with the project, and the sensitivity parameters.

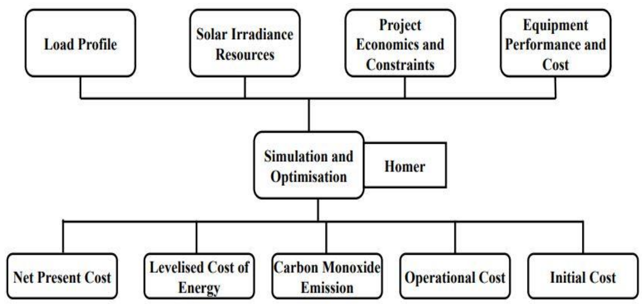

Figure 5. Flow chart for Methodology

This simulation and optimization would help identify the most optimal electricity generation configuration in terms of size, and number of equipment required. The environmental impact would also be assessed to analyze the effect of each system configuration on the environment. Pollutant emissions of SO_2, CO, NO, CO_2, unburnt hydrocarbons from combustion of fuel in Homer is defined using the factor of emission and fuel consumption per year. The factor of emissions per pollutant is calculated as the grams of pollutant emission per unit fuel consumption. Only CO emissions will be considered in this paper. The optimization simulation is used to determine the most optimal method of electricity generation configuration with the best generation technology, size and number of materials needed.

The simulation of the running electrical system is done by finding the annual energy remains on an hourly basis. Using this hourly-by-hour basis all year round, the electricity needed by the village and the electricity that can be provided by the designed system is determined. Juxtaposing the energy demand and supply, the viability of the configuration to supply the needed electrical power is determined. Considering all feasible configurations determined by the optimization, the most economical and environmentally configurations would be retained for analysis. As shown in Figure 6, the peak load for the load profile of Sekoukou is 65.09 kW with a daily load of 516.50 kWh/day.

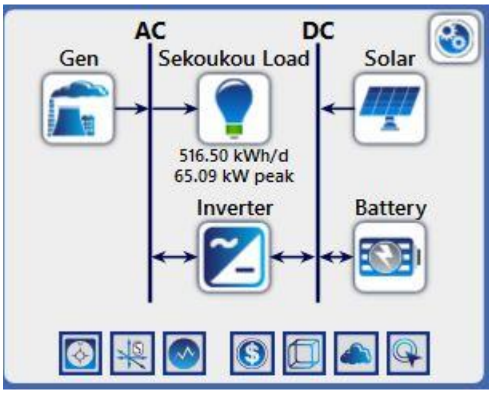

Figure 6. Schematics of Connection in Homer

Fraction of Renewable Energy

The fraction of renewable energy is the proportion of electrical power that would be supplied to the people of Sekoukou from sources of renewable energy which is the solar panel here. Figure 7 shows the I-V characteristics of the panel

$$F_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \quad (1)$$

where,

E_{nonren}= nonrenewable electrical production (kWh/yr)
H_{nonren} = nonrenewable thermal production (kWh/yr)
E_{served} = total electric load served (kWh/yr)
H_{served} = total thermal load served (kWh/yr)

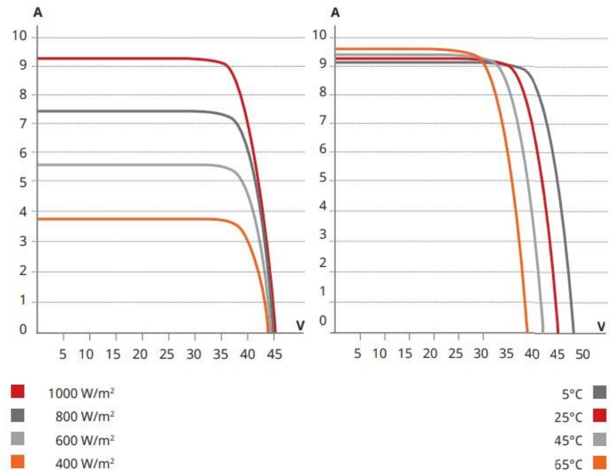

Figure 7. I-V Curve for PV (Irradiance and Temperature)

Net Present Cost (NPC)

The net present cost is the current cost of the entire financials involved in fixing and running the system throughout the 25-year life span without the current worth of income it earned over the project life span. A discount rate of 7.4% is used to make up for the time value of the revenue over the years. To achieve this, the cash flow of each system is computed at the end of the 25th year without including the salvage value.

$$NPC = \sum \left(\frac{CFn}{(1+i)^n}\right) - \text{Initial Investment} \quad (2)$$

where,

N = period which takes values from 0 to the nth period until the cash flow ending period

CF_n = cash flow in the 25th year

i = Discount rate

Levelized Cost of Energy (LCOE)

This LCOE is the mean cost per kWh of efficient electricity generated by each generation system. The price of generating electric power (annualized cost of producing electricity without the cost involved in serving loads that are thermal) is divided by the overall electric load served. Equation (3) shows the mathematical formula for finding the levelized cost of energy.

$$COE = \frac{C_{ann,tot} - C_{boiler}H_{served}}{E_{served}} \quad (3)$$

where,

$C_{ann,tot}$ = total annualized cost of the system \$/yr
C_{boiler} = boiler marginal cost(\$/kWh)
H_{served} = total thermal load served (kWh/yr)
E_{served} = total electric load served (kWh/yr)

Taking into consideration the fact that the component of PV does not serve any thermal load, the portion of H_{served} would be neglected.

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System Sizing

The system size focuses on the relationship between the inverter and the solar panels. The minimum and maximum strings needed to connect to the inverter must be taken into consideration to prevent underperformance of the system. Equation 4 and Equation 6 show formulae for finding the minimum and maximum strings. This is calculated using the minimum module voltage from Equation 5 and the maximum module voltage from Equation 7.

$$\text{Min string size} = \frac{\text{Inverter } V_{min}}{\text{Module } Vmp_{min}} \quad (4)$$

where,

Module Vmp_{min} = minimum module voltage expected when the temperature at site is high
Inverter V_{min} = the inverter minimum MPPT voltage (V)

$$\text{Module } Vmp_{min} = Vmp \times \{+((T_{max} + T_{add} - T_{STC}) \times (\frac{Tk_{Vmp}}{100}))\} \quad (5)$$

where,

Vmp = rated module max power voltage (V)
Tmax = ambient high temperature of installation site
T_{add} = temperature adjustment for installation method
T_{STC} = temperature at standard test conditions, 25° C
Tk_{Vmp} = module temperature coefficient of Vmp(%/C)

$$\text{Max string size} = \frac{\text{Inverter } V_{max}}{\text{Module } Voc_{max}} \quad (6)$$

where,

Module Voc_{max} = maximum module voltage corrected for the site's lowest ambient
Inverter Vmax = the maximum allowable voltage for the inverter.

$$\text{Module } Voc_{max} = Voc \times \{1 + (T_{min} - T_{STC}) \times (\frac{Tk_{Voc}}{100}) \quad (7)$$

where,

Voc = module rated open current voltage (V)
T_{min} = lowest expected ambient temperature for site °C
T_STC =temperature at standard test conditions (25°C)
Tk_{Voc} = module open current voltage temperature coefficient (%/°C)

RESULTS AND DISCUSSION

After simulation and optimization, five possible configurations that resulted in a Tier 5 access for the village of Sekoukou were obtained. The five possible configurations are given in Table 2. The various configurations give different possible outcomes for net present cost, LCOE, carbon emissions, operational cost, and initial cost.

Table 2: System Configurations with the lowest LCOE

Type of System	Inverter (kW)	PV panel (kWp)	Battery (Units)	Diesel Gen (kW)
A	59.1	143	689	72
B	67	369	676	0
C	15.1	91.6	0	72
D	0.0319	0	13	72
E	0	0	0	72

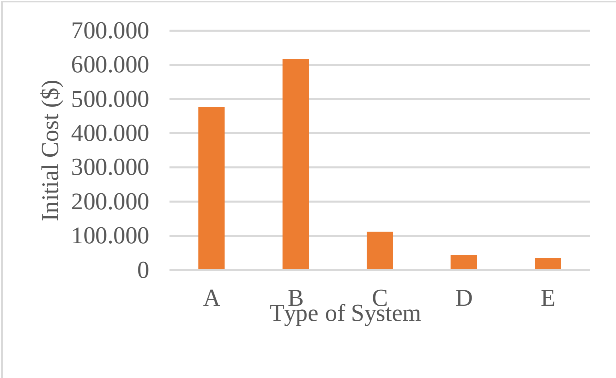

Figure 8. Initial Cost for the different configuration

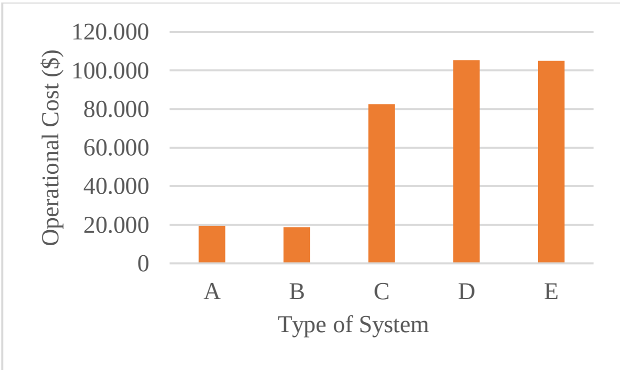

Figure 9. Operational Cost for the different configuration

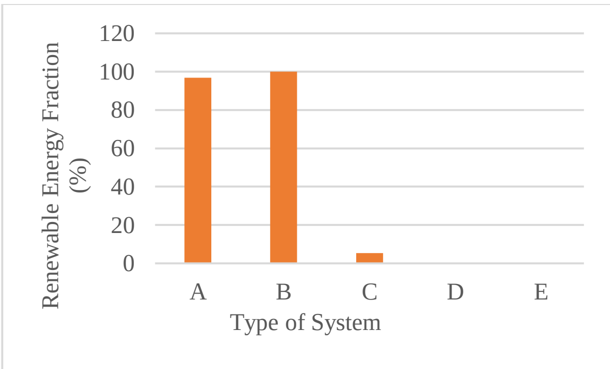

Figure 10. Renewable Energy Fraction

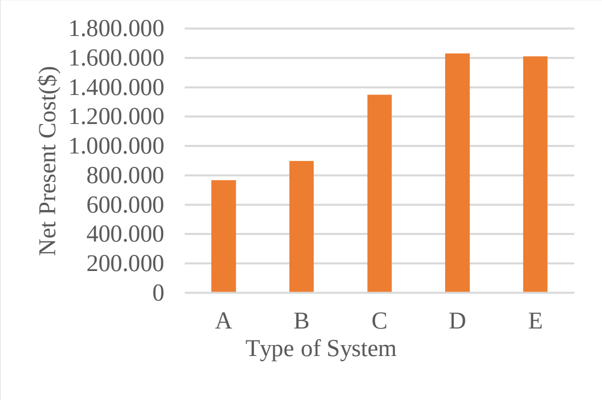

Figure 11. Net Present Cost of System

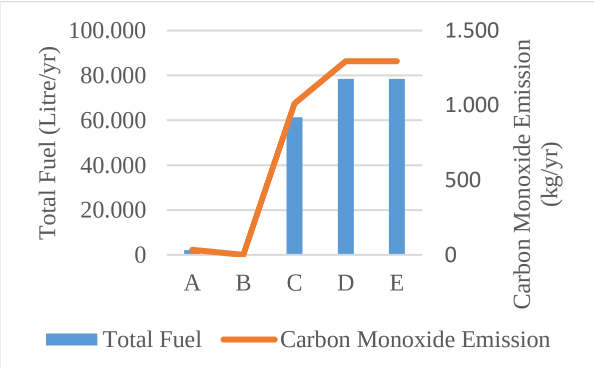

Figure 12. Carbon Monoxide emission

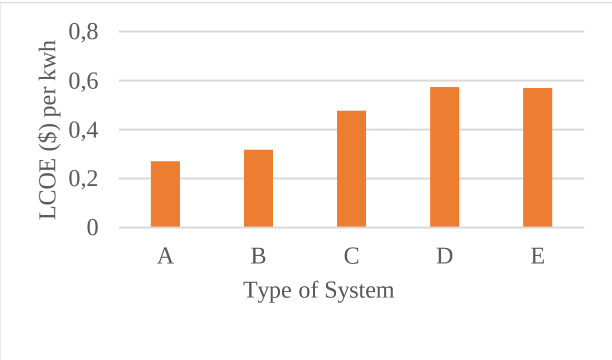

Figure 13. Levelized Cost of Energy

The initial capital as shown in figure 8 for the various systems is the entire installed value of the components in the set-up at the beginning of the project. As indicated, system B has the highest initial cost of $617,137 while system E has the lowest initial cost of implementation of $34,641. This initial cost of implementation is the biggest reason why there are several system E types of Mini-grids in Niger. While it is important to consider the initial cost of implementation, the long-term benefits must be compared to the initial cost to make a good choice.

Maintenance and Operation Cost

The maintenance and operation cost of the system is the cost of maintaining and operating the individual components in the project set-up. The maintenance and operation costs of the various equipment in this system are generally calculated on an annual basis. However, the maintenance and operation cost of the generator is entered as an hourly value which is multiplied by the annual hours of operation to determine the cost of maintenance and operation per year. System B has the lowest operational cost of $105 per annum while system D has the highest operational value of $18,635 per annum. System D has the highest operational value because of the rising cost of diesel needed to run this system. This drawback of system D, which is also evident in system E, makes it generally unattractive to run in the long term. The generally low maintenance cost of PV components in systems A and B makes their overall operational cost relatively cheaper.

Renewable Energy Fraction

The renewable energy fraction in system B is 100% followed by system A with 97%. Systems D and E have a renewable fraction which is almost 0% of their total generation. This is shown in figure10.

Net Present Cost

The net present cost of system D of $1.6 million dollars after 25 years is the highest while that of system A is the lowest with a net present cost of $767,911. This is largely due to the high operation and maintenance cost of system D as well as the high cost of fuel needed to keep system D in operation.

Carbon Monoxide Emission

The total liters of fuel used per year is linked to the carbon monoxide emission into the atmosphere. The source of pollutants is from the generator's use of fuel. Carbon dioxide, carbon monoxide, unburned hydrocarbons, and particulate matter make up the pollutants. Data for carbon monoxide is computed in Figure 12. The emission of carbon monoxide into the atmosphere increases the level of greenhouse gases in the atmosphere, which causes global warming and climate change. Inhaling these carbon monoxides is also linked to several health conditions. Systems D and E both have the highest level of carbon monoxide emission into the atmosphere. System B has no emission of carbon monoxide due to the absence of a generator component.

Levelized Cost of Energy

The levelized cost of energy is the most important aspect of the simulation and would determine the financial feasibility of a system for financial investment purposes. The lowest LCOE is the most sought configuration. As shown in Figure 13, System D has the highest levelized cost of energy of $0.574, while system A has the lowest of $0.271, followed by system B with $0.317. System A is therefore, the most optimal mini-grid configuration for the community of Sekoukou.

Technical Design

The technical design for system A focuses on the connection between the inverter and the solar panels. The minimum and maximum strings needed to connect to the inverter must be taken into consideration to prevent underperformance of the system. The minimum number of strings required is 100 and the maximum strings required to run the system is 120. The system configuration is shown in Figure 14. Two inverters are recommended to improve the performance of the system.

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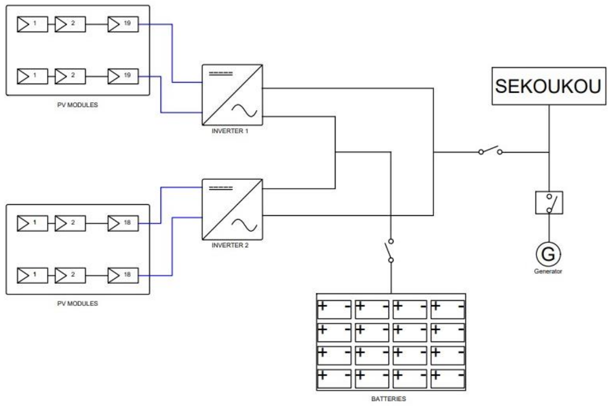

Figure 14. Technical Design for System

Demand Side Management

While this paper has shown that the community of Sekoukou can enjoy the lowest cost of energy, a demand side management can be implemented to further reduce the LCOE. This demand side management simply means shifting demands to times of higher renewable resource availability. Activities that require lots of energy can be shifted from night hours to day hours. A typical load shifting approach is applied to the load profile of Sekoukou. All heavy loads are shifted to daytime with the light loads shifted to nighttime. Operations like pumping water for irrigation or domestic use and milling of grains which are usually done early in the morning can be shifted to noon. Load A represents the initial load profile that was analyzed. Load B represents the proposed load shifting approach that is aimed at reducing the levelized cost of energy.

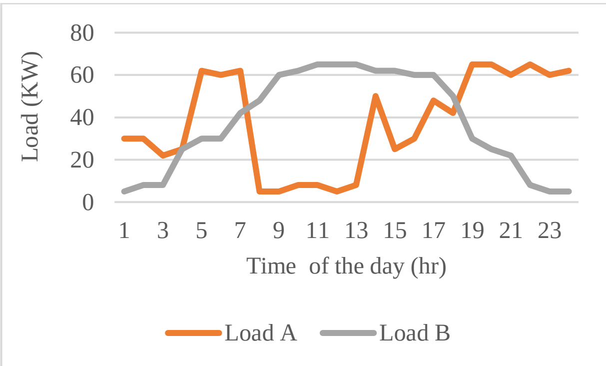

Figure 15. Load Profile for Load A and Load B

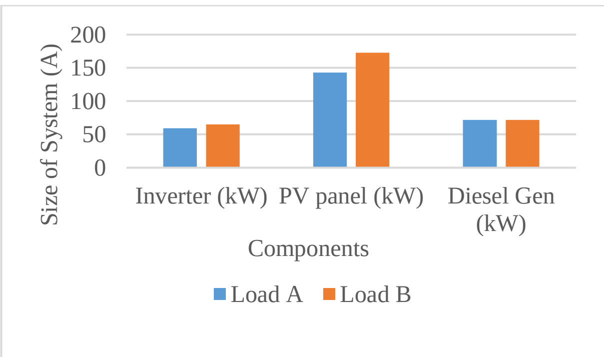

Figure 16. System Size for Load A and Load

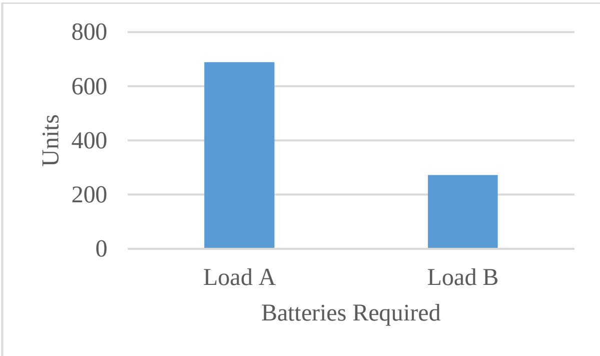

Figure 17. Batteries Required for Load A and Load B

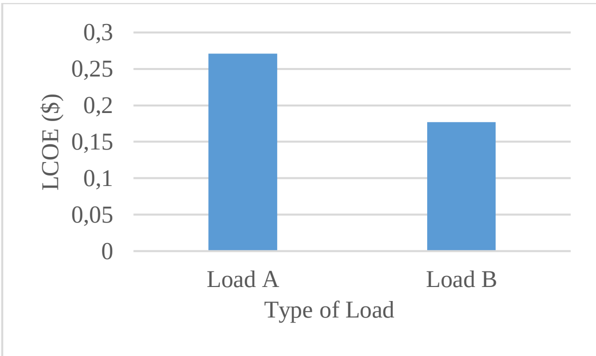

Figure 18. Levelized Cost of Energy

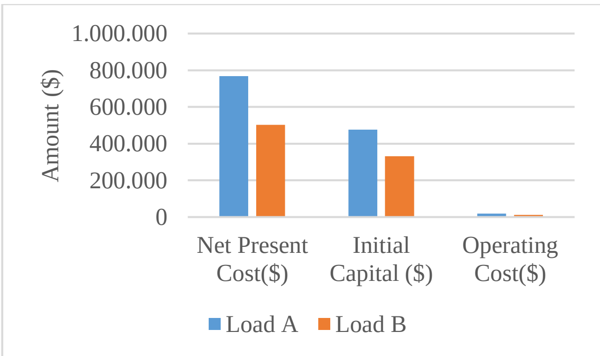

Figure 19. Cost of Implementation

Discussion of Demand Side Management

The sizes needed to ensure a Tier 5 access for the two loads are shown in Figure 16. The inverter and panel size for load B were a little higher than that of load A. The most peculiar change is in the size of the batteries which shows the new load profile with battery 273 units compared to load A of 689 units. This difference is so because relatively less electricity is needed to be stored for use in the evening. This single change in the number of batteries has the tendency of reducing the overall cost of serving the two different loads. The size of the generator remains unchanged in the two load options. The net present cost of serving Load A is $767,911, while that of Load B is $503,107. The initial capital needed to serve load A is $476,581 while that of load B is $331,117. The difference in the operational cost was not much. The levelized cost of energy for serving load A is $0.271 and that of load B is $0.177. This means households in the village of Sekoukou would spend less on electricity if they adopt a load shifting approach. The ability and willingness of a community to pay for electricity largely depends on the cost of energy sold to them. If the levelized cost of energy is high, there is a low ability and willingness to pay.

CONCLUSION

In this paper, a techno-economic feasibility analysis has been carried out with different configurations for a tier 5 mini-grid system. This work has shown that a mini-grid system using PV, inverter, generator, and battery is an optimal way of providing tier 5 electricity access to the village of Sekoukou in Niger. This supports the objective of the research which is to find the techno-economic viability of a hybrid mini-grid system for rural electrification. The system was simulated using HOMER Pro software to find an optimal system configuration that is both affordable and results in less carbon monoxide emissions. This system is an efficient alternative to the diesel generator mini-grids that have been deployed. The proposed system has a relatively low operation and maintenance cost, net present cost, and levelized cost of energy. This work also proposes a load shifting to further reduce the levelized cost of energy from $0.271 to $0.177. The ability and willingness of households in rural areas to pay for electricity largely depends on the affordability of electricity. Designing an economical system and proposing approaches to help households reduce the cost of electricity, like has been done in this paper would make it easier for households to access electricity. This approach can be replicated in remote villages in Niger which cannot be connected to the grid due to their distance from the grid.

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