# A novel approach for sizing and optimization of hybrid solar-PV, biogas-generator, and batteries system for rural electrification: case study


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**Article Info**

***Article history:***

Received Se 13, 2022
Revised Dec 2, 2022
Accepted Dec 16, 2022

*Keywords:*

Biogas
Electrification
HOMER Pro®
Hybrid system
Optimization
Photovoltaic
Renewable energy



**ABSTRACT**

A new approach for sizing a hybrid solar-PV-battery and biogas generator for power generation was suggested in this study, based on the variation of energy resources and the load profile. Biogas has enormous potential and numerous economic and social advantages. In this respect, the monthly solar radiation, temperature, and biogas produced from biomass resources were used as model inputs. This study considers the total annualized of the components for the feasibility analysis. HOMER Pro® software-based outcomes in the proposed methodology revealed that the proposed solar biogas hybrid system was sufficient to meet the load requirements of the village (Ain Farba village in the Hodh El Gharbi area located in the northeast of the Mauritania country) with a net present cost over the 25-year lifespan of 61,144 $ and the energy cost was determined to be 0.0473 $/kWh.



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## 1. INTRODUCTION

Population growth, rising living standards, mobility, and globalization dynamics have all contributed to rapid increase in energy demand in recent years [1]. As a result, about 15% of the world's population lacks access to electricity [2], [3]. Further, approximately 600 million people in Africa do not have access to electricity. Problems with limited fossil fuel reserves and the negative consequences of traditional energy sources that contribute to global warming, as well as the negative consequences of traditional energy sources, have prompted the search for more sustainable energy technologies [4], [5]. As a result, renewable power technologies such as solar, wind, hydro, bioenergy, and their hybridization have become common electricity generation alternatives [6], [7]. Therefore, it is interesting to take into account hydrogen positioned as the accelerator of the energy transition.

The rate of access to electrification in Mauritania was around 45% in 2019 [8]. In fact, Mauritania has significant renewable energy sources that include wind [9], solar [10], biomass [11], and even small-scale hydroelectricity [12]. Further, Mauritania was one of the first countries in Sub-Saharan Africa to have installed large renewable energy projects, including 15 MW and 50 MW solar PV power plant in two different locations, in Nouakchott, 4.4 MW solar PV plant installed by National Industrial and Mining Company of Mauritania (SNIM), 30 MW wind farm in Nouakchott [13], and 100 MW wind power plant in progress at Boulanoir. Stand-alone and mini-grid systems are currently viewed as among the most cost-effective alternative energy options required to expand and accelerate access to electricity in many rural communities [14]. Further, in remote areas, combining renewable energy sources (photovoltaic, wind, and biomass) with conventional energy sources (internal combustion engines) or hybrid installations is a more cost-effective option than grid connection [15], [16]. In addition, supplying electricity to remote areas mostly through grid extension can be costly and frequently necessitates long-term planning [17]. Renewable energy can also benefit villages with unreliable power grids due to frequent blackouts, particularly during peak hours or in off-grid areas [18]. The hybrid system is primarily intended to generate electricity from renewable energy sources, while the traditional source, which serves as an auxiliary source, is the best compromise capable of producing enough energy to meet the needs of small villages and rural areas [19].

Several studies on hybrid renewable energy systems for rural electrification, in remote and isolated communities have been conducted. For example, Odoi *et al.* [20] investigated the use of a hybrid solar PV/biogas/battery power system to provide electricity to remote communities in Ghana. They used the HOMER software to model and investigate the hybrid energy system's technical, economic, and environmental aspects. They found that the PV/biogas/battery hybrid system outperformed the PV/diesel/battery and diesel systems. In a different study, Podder *et al.* [21] proposed an energy-based method for charging electric vehicles (EVs) using solar photovoltaic (PV) and biogas as two sustainable energy sources. They employed HOMER software to examine the power generated while considering solar photovoltaic and biogas charging stations for electric vehicles. Since the NPC and COE were 93,530 $ and 0.181 $/kWh, respectively, they decided on a 4.5 kW solar PV installation. Further, the authors described a method to design the best hybrid diesel/ PV/wind/battery (HRES) for the electrification of residential structures in rural areas [22]. A standard geographic information system program (ArcGIS 10.2) was used in this study to create a map of Algeria's potential for renewable energy. In addition, a constraint approach and a particle swarm optimization algorithm were used to address the multi-objective design of the hybrid renewable energy system. According to this study, the optimal design for Adrar and Tindouf was determined to be PV/wind/diesel/battery, while the best configuration for the other locations was determined to be PV/diesel/battery. Murugaperumal *et al.* [23] presented a hybrid renewable energy system (HRES) with an optimal design and technical-economic feasibility for applications involving rural electrification. By using Homer software, multiple approaches were used to determine the best hybrid renewable energy (HRE) configurations for optimum performance, and it was determined that the company's suggested efficient strategy. In a different inquiry, Teferra [24] presented a study of the potential for renewable energy applications, feasibility analysis of the hybrid PV generator using biogas and biodiesel, and a comparison of the obtained solutions to the existing networks to feed a rural community. Kumar and Saini [25] investigated an integrated, grid-independent hybrid renewable energy system to provide electricity and fresh water to a numerous of unconnected villages in the Indian state of Odisha. In another study, Baruah *et al.* [26] provides a technical and economic feasibility of a standalone hybrid renewable energy system for generating power to meet the needs of an Indian university. Solar radiation, wind speed, biogas, syngas, and hydrokinetic power were the resources taken into account for this study. HOMER Pro® software was used for the feasibility study. Based on the net present cost (NPC), levelized cost of energy (LCOE), battery storage, emissions, space needs, and employment potential, 31 distinct alternative combinations of the various technologies were examined. The analytical hierarchy process (AHP), a well-known method for multi-criteria decision support, was used to find the best combination. With an NPC of 5 million dollars and a COE of 0.095 $/kWh, the hybrid PV-wind-biogas-syngas-hydrokinetic-battery renewable energy system was the best configuration. In the [27], [28], the authors evaluated the feasibility of three different systems (a non-renewable system, a stand-alone renewable system, and a hybrid renewable system) to provide energy to a rural hamlet in Borneo, Malaysia. They discovered that the hybrid PV/diesel/batteries system, the stand-alone PV system, the hybrid PV/hydrokinetic system, and the non-renewable system all had the lowest NPC. Significantly, it was possible to power the isolated communities in Malaysian Borneo using renewable energy sources (photovoltaic/hydrokinetic). Another Italian study [29] examined the best system layout for three remote area without grid access in different climate zones of Peru: Campo Serio, El Potrero, and Silicucho. The analysis took into account seven different configurations, including single-component (solar, wind, and diesel) and hybrid systems. The HOMER software was used to determine the best system configuration. The hybrid solar-wind-diesel system was the most economically viable option for all of the communities studied. The authors in the study [30] developed an optimization approach for the feasibility study of a hybrid renewable energy system, as well as to determine the optimal size of different renewable energy technologies and to assist decision-makers in their performance survey. To solve the multi-objective optimization problem, a simulation-based optimization method combined with a constraint technique was developed. The developed algorithm's performance was evaluated and validated using the HOMER software. Oladigbolu *et al.* [31] used HOMER software to investigate the technical-economic feasibility and optimization of a micro-hydro hybrid photovoltaic-diesel-battery-wind system designed to power a typical remote village in southern Nigeria. According to the results of the experiments and benchmark tests, the hybrid water/PV/wind/diesel/battery system was the most appealing option for off-grid rural electrification. According to the study, the optimal system had an NPC and COE of 1.01 million $ and 0.106 $/kWh, respectively, with a renewable energy rate of 77.4% and an environmental pollutant emission of 228,945 kg/year. Furthermore, Odou *et al.* [32] presented a technical-economic feasibility study of a hybrid renewable energy system (HRES) for long-term rural electrification in Benin. The hybrid PV/diesel generator/battery was determined to be the best configuration with the lowest NPC. Abaye and Haro [33] also used the Homer to carry out study on the evaluation of the energy resource potential and the feasibility of a hybrid PV-wind-biogas system with backup battery storage. They found that the best configuration for supplying the village includes the renewable energy technologies. Further, Ronad and Jangamshetti [34] performed the optimal cost of a wind-PV hybrid system connected to DC and AC irrigation pumps. The authors concludes that the annual electricity production of the two systems was nearly equal. However, the comparison between the costs of AC and DC loads showed that AC pumps could lead to uneconomical results and overproduction for small irrigation systems powered by renewable energy, while the DC pumps were proven more economical and reliable.

The above literature reveals that a lot of works have been reported around the world on improving the uses of the renewable energy. However, although 65% of Mauritanians do not have access to electricity and the country has significant potential for solar energy and biogas, very little work has been done in Mauritania on the electrification of rural areas far from the grid using a hybrid PV-biogas system. Considering this apparent literature gap, in the present study, it was aimed to develop a novel approach for sizing and optimization of a hybrid renewable energy system solar-PV, batteries, generator biogas for the electrification of rural areas valorizing the animal manure through. Furthermore, the feasibility of a hybrid power plant PV/biogas/batteries was studied for the case of Ain Farba in Mauritania based on the proposed methodology.

The remainder of this paper is organized as follows. Section 2 describes the sources of the energy used for sizing the hybrid system. Section 3 presents the concept of the hybrid PV-batteries-biogas system for the decentralized application. Moreover, section 4 presents the modeling of the different device of this system and discusses the results. Finally, section 5 concludes the present study.

## 2. METHOD

### 2.1. Solar energy source

The location of this study is El Medina shown in Figure 1, located at 15°45.2' north latitude and 10° 18.1' east longitude, in the commune of Ain Farba (Hodh el Gharbi) in the northeast from Mauritania. For this study, HOMER Pro® was used to calculate global horizontal solar radiation through coordinates. According to data obtained from the NASA Surface Weather and Solar Energy website, the annual average solar radiation (SR) at El Medina Village was approximately 5.82 kWh/m$^2$/day. Figure 2 illustrates the monthly average of the global horizontal solar radiation of the village El Medina, Location: WJQ4+VC Ain Farba (H, Mauritania (15°56.4'N, 10°23.6'W). The highest solar radiation (SR > to 6 kWh/m²/day) is observed for the period from March to July (dray season). The lowest is observed for the December with SR=4.5 kWh/m²/day. The all cleared index is between 0.5 and 0.60, that means the site is located in region which correspond to the moderate sky.


Figure 1. Geographical location of the site

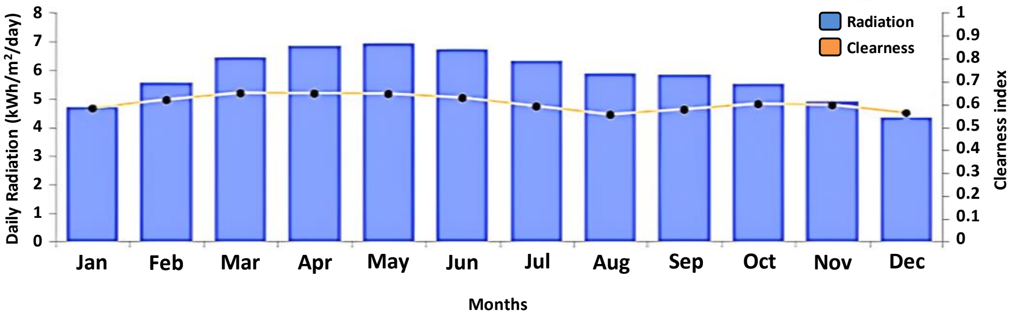


Figure 2. Monthly variation of the solar radiation and clarity index of the site

## 2.1. Biomass sources

The raw material needed for the formation of biogas was the manure of live animals in the village of El-Medina. The village contains 100 families each owning about 120-160 sheep and goats, 40-50 cows, 1-2 camels, 2-3 horses, and 3-4 donkeys. This study assumes that the animals of this village are distributed as follows: 47 large ruminants (cows, donkeys, camels, and horses) and 120 small ruminants (sheep and goats). This distribution gives a potential of 1.25 tons of animal waste/day. This assumption was used as one of the constraints of the HOMER Pro® model. The percentage of $CH_4$ in this study was assumed to be 60%) [34], [35]. In addition, the daily quantity of waste according to the type of animal in Mauritania according to 2016 data [36] is given in Table 1, and the range of biogas production according to livestock waste and solid content corresponding totals (TS) is presented in Table 2 [36], [37]. On the other hand, 1 m$^3$ of $CH_4$ corresponds to 36 MJ, corresponding to equal to 10 kWh [37], [38]. Figure 3 presents the biomass resources used for our study.

Table 1. Quantity of live animal manure for different ruminants

| Live animal | Weight of the body (kg) | Manure (kg/day) | Blood (kg/day) | Rumen (kg/day) |
|---|---|---|---|---|
| Ruminants of great size | 250 | 22.5 | 21 | 30 |
| Poultry small ruminants | 40 | 1.6 | 1.2 | 10 |
| Poultry small ruminants | 1.5 | 0.045 | 0.03 | 0.3 |

Table 2. Range of biogas production according to livestock waste and corresponding total solids (TS) content [38], [39]

| Livestock waste | TS (%) | Biogas ($m^3 * kg^{-1} * TS$) |
|---|---|---|
| Camels | 30 – 45 | 0.3 – 0.4 |
| Cows | 25 – 30 | 0.6 – 0.8 |
| Goats and Sheep | 18 – 25 | 0.3 – 0.4 |
| Poultry | 10 – 29 | 0.3 – 0.8 |
| Blood | 18 | 0.3 – 0.6 |
| Rumen | 12 – 16 | 0.3 – 0.6 |

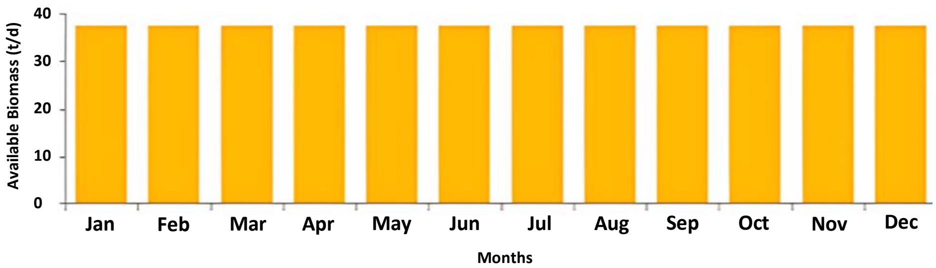


Figure 3. Monthly variation of the biomass resource

## 2.2. Location of the site

Ain Farba is one of the eight municipalities of the department of Tintane, located in the region of Hodh El Gharbi in Mauritania. At the 2000 census, it had a population of 7,677 and included several villages such as El Medina located at 5 km north of Ain Farba city center. The village consists of 100 families of 4-5 people. In addition, there are a two-room (1st and 2nd grade) elementary school and a mosque in the village.

Currently, this village does not have access to electricity, and the only solution is to install an autonomous system because the center of Ain Farba municipality has only one generator, which does not meet the needs of the center, and it is economically feasible to connect to the national grid.

### 2.3. Demand load profile

The village consists of 100 families, a school and a mosque. The daily electrical load profile is estimated based on basic service demands such as lighting, communications, and other appliances. The total electricity village consumption is 402.28 kWh/day with the maximum power of 57.1 kW per day. The estimated daily load profile for the village is displayed in Table 3, and Figure 4 illustrates the load profile.

Table 3. Daily energy demand for the village

| Village | Devices | Unity | Watt | Operating hour (h) | Total energy demand per 100 families (kWh/d) |
|---|---|---|---|---|---|
| 100 families | lamp | 4 | 40 | 8 | 128 |
| | Fan | 2 | 60 | 9 | 108 |
| | TV | 1 | 100 | 6 | 60 |
| | portable | 4 | 2 | 8 | 6.4 |
| | Pump | 4 | 4,776 | 4 | 76,416 |
| | | | | | 378,816 |
| | Lamp | 4 | 40 | 6 | 0.96 |
| School | Fan | 2 | 60 | 9 | 1.08 |
| | PC | 1 | 200 | 4 | 0.8 |
| | portable | 2 | 2 | 6 | 0.024 |
| | Pump | 1 | 4,776 | 2 | 9,552 |
| | | | | | 12,414 |
| | Lampe | 2 | 40 | 6 | 0.96 |
| Mosque | Fan | 1 | 60 | 9 | 0.54 |
| | Pump | 1 | 4,776 | 2 | 9,552 |
| | | | | | 402.28 |

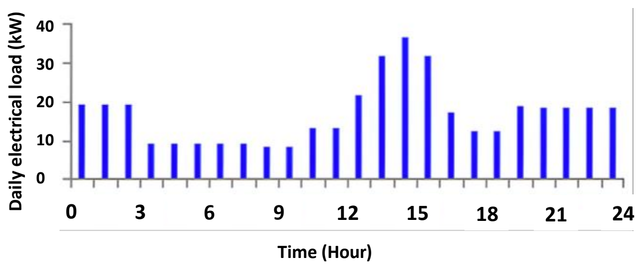


Figure 4. Daily electrical load profile

## 3. SYSTEM COMPONENTS

Photovoltaic panels, a biogas engine generator, a converter, and storage batteries are all part of the proposed power system. As shown in Figure 5, the PV panels and battery system are connected to the DC bus, while the biogas generator is connected to the AC bus. The communication between the two buses is served by a bi-directional converter.

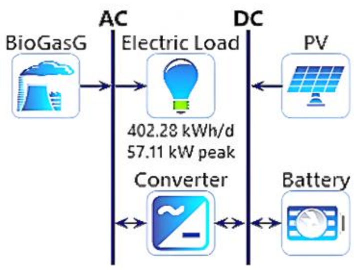


Figure 5. Block diagram of the hybrid PV-BiogasG-Batteries system

### 3.1. Solar PV system

To determine the power generated by a photovoltaic solar panel, it is necessary to determine the meteorological parameters such as solar radiation shown in Figure 2, cell temperature, monthly average temperature and wind speed. The expected energy output of the system is expressed in (1) [40].

$$E(t)_{pv} = R(t) * \eta_{pv} * S \quad (1)$$

Where $R(t)$ is the hourly solar radiation in W/m$^2$, $\eta_{PV}$ is the yield of the PV panel, and $S$ is the area of the PV modules.

In Mauritania, the cost per watt of photovoltaic panels manufactured about 1 $/watt while the cost per watt of panels manufactured in China is about 0,28 $/watt, with a power greater than 220 W [41]. The characteristics of the solar panels chosen and the different types of costs are presented in the Table 4, and the photovoltaic production is given by [40], [41].

$$\mathrm{P_p} = \mathrm{P_{pn}} * \mathrm{f_d} * \left(\frac{\mathrm{I_s}}{\mathrm{S_I}}\right) * \left(1 + \alpha_c * \left(\mathrm{T_p} - \mathrm{T_{pn}}\right)\right) \quad (2)$$

Where $P_p$ is the PV power-output (W), $P_{pn}$ is the nominal power under standard PV conditions (kW), $f_d$ is the PV derating factor (%), $I_s$ is the incident solar radiation on a horizontal plane (W/m$^2$), $S_I$ is the maximum solar radiation (1000 W/m$^2$), $\alpha_c$ is the thermal power coefficient (%/°C), $T_p$ is the temperature of the operation PV cell (°C) at the current time step, and $T_{pn}$ is the nominal operating cell temperature of the PV cell under standard test conditions (at 25 °C).

Table 4. Characteristics and cost of a solar panel

| Description | Value/explanation |
|---|---|
| Monitoring system | Fixed |
| Nominal operating temperature of the cell | 47 °C |
| The coefficient of temperature | 0.4%/°C |
| Efficiency under standard test conditions | 18% [42],[43] |
| Derating factor | 80% |
| Capital cost of operation and maintenance | 640 $/kw |
| Replacement cost | 640 $/kW |
| Lifetime | 25 years |

### 3.2. Battery

In this study, the main source of energy was the biogas/solar PV generators. An additional storage system was proposed to store the excess energy from the renewable sources. A charge control system was used to prevent overcharging and deep discharging of the batteries. The nominal capacity of the battery is given in (4) [42], [43].

$$E_b = \frac{E_d * d_a}{\eta_i * \eta_b * b_d} \quad (3)$$

Where $E_d$ is the total energy demand, $d_a$ is the day number of the autonomy, $b_d$ is the depth of discharge of the battery, $\eta_i$ is the efficiency of the inverter, and $\eta_b$ is the efficiency of the battery. The characteristics and costs of the battery are presented in Table 5.

Table 5. Characteristics of the studied battery

| Battery | Iron Edison Nickel Iron | References |
|---|---|---|
| Nominal capacity | 200 Amp-Hours (Ah) (0.24 kWh) | [44] |
| Nominal voltage | 1.2 V | |
| Nominal capital cost of operation and maintenance | 130 $ | |
| Replacement cost | 100 $ | |
| Lifetime | 5.57 | |

### 3.3. Converter

A converter containing an inverter-rectifier system was intended to connect the DC bus to the AC bus. The characteristics and costs of the selected converter are given in Table 6, and the energy of the system output is given by the following expressions [44]:

$$\mathrm{E_{in}(t) = \eta_c * E_{bl}(t)} \quad (4)$$

$$\mathrm{E_{ou}(t) = \eta_r * E_{bi}(t)} \quad (5)$$

where $E_{in}(t)$ and $E_{ou}(t)$ are the hourly energies at the input and output of the inverter respectively, $\eta_r$ and $\eta_c$ are the rectifier and inverter efficiencies respectively, $E_{bl}(t)$ is the hourly energy of the battery to supply the load, and $E_{bi}(t)$, the hourly value of the energy surplus of the biogas generator.

Table 6. Characteristics and costs of the chosen converter

| Description | Value /explanation | References |
|---|---|---|
| Efficiency | 90% | [44], [45] |
| Cost of capital | 550$/Kw | |
| Capital and replacement cost | 450 $/kW | |
| Cost of operating | 5 $/kW/year | |
| Lifetime | 15 years | |

### 3.4. Biogas generator

Assuming the same amount of water (1370 liters), the potential waste available (mainly manure) was estimated as 1.25 tons/day. Therefore, the digester required a capacity of 2.74 $m^3$/day of substrate. It is noted that this potential can ensure a continuous supply of biogas to meet the electricity needs of the village. The costs of digesters and biogas generators are presented in Table 7.

Table 7. Costs of the digester

| Nominal capacity | 6 kW | References |
|---|---|---|
| Yield | 95% | [45], [46] |
| Investment and replacement cost | 742 $/kW | |
| Operation and maintenance cost | 0.015 $/kWh | |
| Lifetime | 20 years | |

The electrical energy generated from biogas is given by (6) [46].

$$\mathrm{e_{bio} = E_{bio} * \eta_{be}} \quad (6)$$

Where $e_{bio}$ is the amount of electricity produced, $E_{bio}$ is the raw unconverted energy of biogas and $\eta_{be}$ indicates demonstrates the general effectiveness conversion of biogas into energy.

### 3.5. Economic parameters

The interest rate and the project's lifetime are the economic model's input parameters. In this study, the interest rate and lifetime were assumed to be equal to 10% and 20 years, respectively. The NPC and cost of energy (COE) are given by (7) and (10) [46]:

$$\mathrm{NPC} = \frac{\mathrm{C_{ann,total}}}{\mathrm{CRF(i,n)}} \quad (7)$$

$CRF$ is the capital recovery factor, it is given by the following equation:

$$\mathrm{CRF(i,n)} = \frac{\mathrm{i*(1+i)^n}}{\mathrm{(1+i)^n-1}} \quad (8)$$

where $C_{ann,total}$ is the total annualized cost, *n* is the interest rate, and *i* is the lifetime of the project in years.

$$i = \frac{i'-f}{1+f} \quad (9)$$

where *i* is the nominal interest rate is $i'$, and *f* is the annual inflation rate. The value of the energy cost is computed by the (10):

$$COE = \frac{C_{ann,total}}{E_{served}} \quad (10)$$

where $E_{served}$ is the total electric load served by the system.

## 4. RESULTS AND DISCUSSION

In this section, the obtained results from the model are presented in fallowing. In the first part, the optimization results are described, then the comparison with the electricity network and other international networks is analyzed.

### 4.1. Optimization results

The input parameters defined for each component in the system component specification section were used with HOMER Pro® to analyze the feasibility of the PV-BiogasG-Batteries system necessary to meet the electrical load. The six viable configurations optimized based on increasing the net present cost (NPC) are given in the Table 8. It should be noted that the best configuration is the one corresponding to the lowest NPC value [47]. In addition, this system configuration consisted of a 20 kW biogas engine, a 15 kW photovoltaic generator, 44 batteries, capacity 200 Ah/battery, and nominal voltage 12 V and an inverter with nominal capacity of 10 kW. Moreover, it corresponded to an initial capital of 26,126 $, operating cost of 3,858 $/year, NPC of 61,144 $, and a COE of 0.0473 $/kWh. These results are similar to those in the [48]. The initial capital costs, replacement cost, and the operating cost of each system component is shown in Figure 6. This figure shows that the capital costs of the digester and biogas generator, batteries, PV generator, and converter represent 51.9%, 24.3%, 17.9%, and 5.9% respectively.

Table 8. Different configurations of the hybrid PV-BiogasG-Batteries

| Configurations | PV (kW) | Biogas (kW) | Battery (kWh) | Converter (kW) | COE ($/kWh) | NPC ($) | Operating cost ($/yr) | Initial capital ($) | Fuel cost ($/yr) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 15 | 20 | 44 | 108 | $61,144 | $0.0473 | $3,858 | $26,126 | 0 |
| 2 | 15 | 20 | 42 | 112 | $61,220 | $0.0473 | $3,829 | $26,007 | 0 |
| 3 | 15 | 20 | 45 | 108 | $61,336 | $0.0475 | $3,865 | $26,256 | 0 |
| 4 | 15 | 20 | 44 | 110 | $61,384 | $0.0475 | $3,876 | $26,197 | 0 |
| 5 | 15 | 20 | 43 | 112 | $61,422 | $0.0474 | $3,887 | $26,137 | 0 |
| 6 | 15 | 20 | 46 | 108 | $61,524 | $0.0476 | $3,871 | $26,386 | 0 |

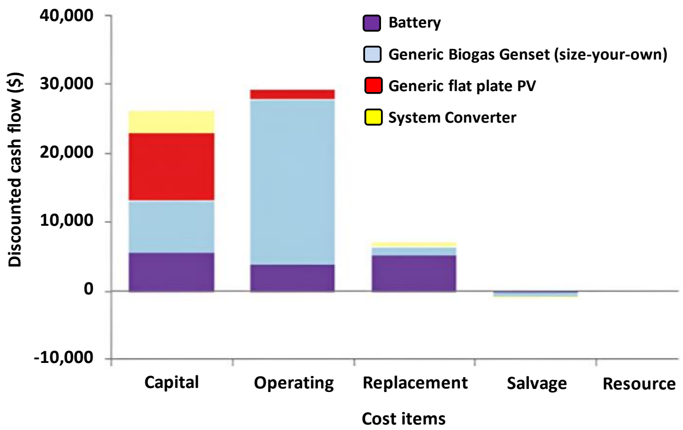


Figure 6. The cash flow by type of the optimal PV-BiogasG-Batteries system

Figure 7 shows that the biogas generator and batteries system continue to incur the total recurring annual maintenance cost of 6,763 $. Further, analysis indicates that the biogas generator, batteries, and converter have the 20 years, 5.7 years, and the 20 years lifetime, respectively. This means that the batteries will be replaced at least twice during the lifetime of the project, according to the results obtained by Sanni *et al* [48]. In addition, Table 9 presents the annual electricity production for each component. It shows that electricity produced is 130,208 kWh/year for the biogas generator and 26,147 kWh/year for the PV generator. The annual energy produced for the renewable energy sources is 156,355 kWh/year.

Figure 8 shows that the total annual electricity generated is 156,355 kWh/year. In addition, it is clear that the electricity produced covers the load profile. Figure 9 depicts the demand evolution of the village over seven days (28-30 June and 1-4 July) in the presence of the 10.8 kW converter, 40 batteries. Table 10 shows that the biogas generator operates 8,719 h/year with fuel consumption of 397 tons/year, minimum electrical output of 10 kW electrical efficiency of 30.7% and produces 130,208 kWh/year.

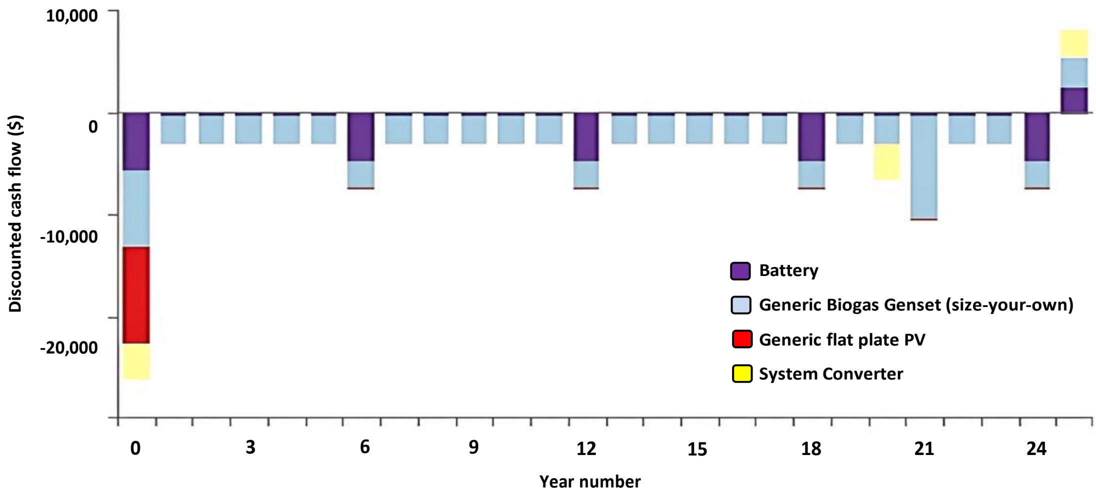


Figure 7. Cash flows of the PV-BiogasG-Batteries system

Table 9. Annual electricity produced from the PV generator and the BiogasG

| Component | Production (kWh/yr) | Percent (%) |
|---|---|---|
| Generic flat PV | 26,147 | 16.7 |
| Generic biogas genset | 130,208 | 83.3 |
| Total | 156,355 | 100 |

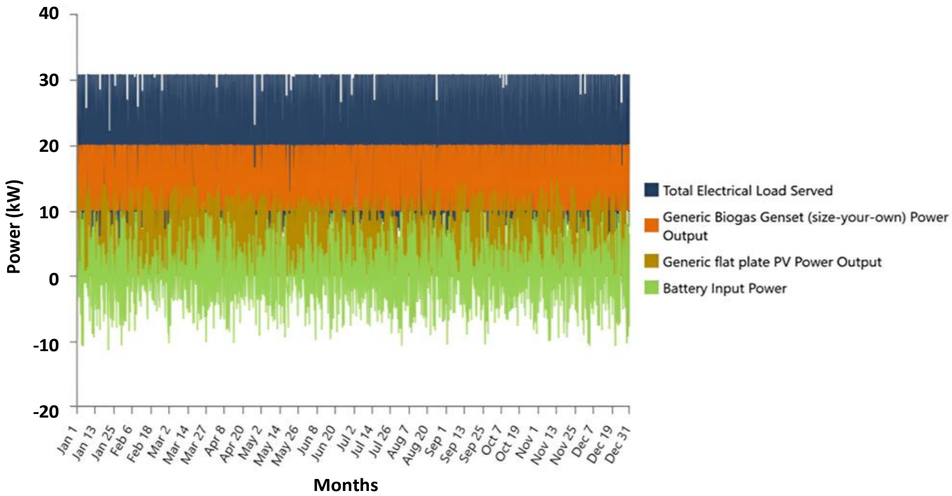


Figure 8. Total annual electricity generated during the year

From the Table 11, it could be noted that the solar PV generator has a capacity factor of 19.9%, average output-power of 2.98 kW, the maximum output of 14.8 kW and produces 26,147 kWh/year. Table 12 presents that the unsatisfied load and the excess of the energy for this configuration are, respectively, 4,467 kWh/year and 11,296 kWh/year (2.81% and 7.22% of the total production). The percentage of unsatisfied load is a user-defined parameter, which in this case is assumed to be a maximum of 3%. Excess power has to be dumped into this system, which can be considered a negative factor. However, it also shows the ability of the system to meet future demand growth.

The battery lifetime and the maximum number of the batteries are 1.58 h and 44, respectively. In addition, the results show that the battery input and output energy are 6,831 kWh/year and the 5,470 kWh/year, respectively. In addition, the difference between battery input and output was due to the charge and discharge losses (1,367 kWh/year) and storage depletion (5.7 kWh/year). The expected battery lifetime is 5.76 years shown in Table 13. The output power of the inverter during this period is shown in Table 14. Table 14 shows that the converter operates 4,029 hours per year, with a capacity of 10.8 kW.

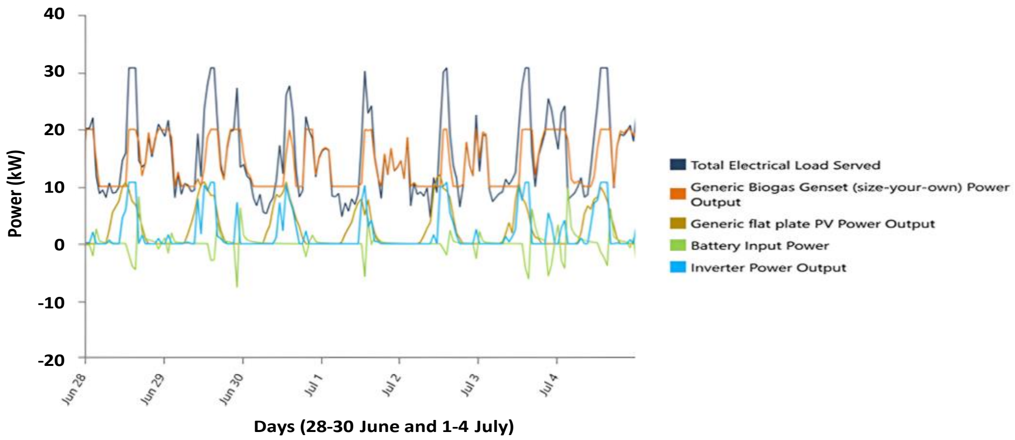


Figure 9. Demand evolution of the village over seven days

Table 10. Generic biogas genset (size-your-own) (biogas)

| Quantity | Value | Units |
|---|---|---|
| Average of the production | 130,208 | kWh/yr |
| Minimum output | 10.0 | kW |
| Fuel consumption | 397 | tons/yr |
| Specific fuel consumption | 2.13 | kg/kWh |
| Fuel energy input | 424,499 | kWh/yr |
| Average of the electrical efficiency | 30.7 | % |
| Number of the operation hours | 8,719 | hrs/yr |
| Operational lifetime | 20.1 | yr |
| Factor of the capacity | 74.3 | % |
| Fixed generation cost | 0.342 | $/hr |
| Marginal generation cost | 0 | $/kWh |

Table 11. Generic flat plate PV

| Quantity | Value | Units |
|---|---|---|
| Minimum output | 0 | kW |
| Maximum output | 14.8 | kW |
| PV penetration | 17.8 | % |
| Hours of operation | 4,379 | hrs/yr |
| Levelized cost | 0.0462 | $/kWh |
| Rated capacity | 15.0 | kW |
| Average output | 2.98 | kW |
| Average output | 71.6 | kWh/d |
| Factor of the capacity | 19.9 | % |
| Total production | 26,147 | kWh/yr |

Table 12. Excess and unsatisfied electricity

| Quantity | Value | Units |
|---|---|---|
| Excess of the energy | 11,296 | kWh/yr |
| Unmet load | 4,467 | kWh/yr |
| Capacity shortage | 7,477 | kWh/yr |

Table 13. Battery properties

| Quantity | Value | Units |
|---|---|---|
| Energy input | 6,831 | kWh/yr |
| Energy output | 5,470 | kWh/yr |
| Storage depletion | 5.70 | kWh/yr |
| Autonomy | 1.58 | hour |
| Storage wear cost | 0.140 | $/kWh |
| Nominal capacity | 44.0 | kWh |
| Usable nominal capacity | 26.4 | kWh |
| Lifetime throughput | 35.200 | kWh |
| Expected lifetime | 5.76 | year |
| Losses | 1,367 | kWh/r |

Table 14. System converter

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 4,029 | hours/year |
| Energy output | 20,306 | kWh/year |
| Energy input | 21,374 | kWh/year |
| Losses | 1,069 | kWh/year |
| Capacity | 10.8 | kW |
| Average output | 2.32 | kW |
| Minimum output | 0 | kW |
| Maximum output | 10.8 | kW |
| Factor of the capacity | 21.6 | % |
| Average output | 2.32 | kW |

### 4.2. Comparison of this study to others works

Table 15 presents a comparison of the hybrid renewable energy system for autonomous electricity demand. It shows that the hybrid PV-BiogasG-batteries system has lowest cost of the energy, while the hybrid PV-wind-battery system is most expensive. It could be observed in Table 4 that present study using HOMER Pro software is more advantageous in terms of energy cost (COE), net present cost (NPC) and fraction of renewable energy (100% which means no greenhouse gas emissions). However, during the summer season, the amount of the available substrate is lower, which directly affects the amount of the biogas produced and the electricity production.

Table 15. Hybrid PV-Wind-BiogasG-diesel generator from different studies in the world

| Year | Country | Hybrid system | Software | COE ($/kWh) | NPC ($) | FR (%) | Ref |
|---|---|---|---|---|---|---|---|
| 2022 | Egypt | PV/wind/battery/DG | HOMER | 0.157 | 533,654 | 78% | [1] |
| 2022 | Ghana | PV/biogas/battery | HOMER | 0.256 | 506,629 | 100% | [20] |
| 2016 | Ethiopia | PV/biogas/biodiesel | HOMER | 0.175 | 273,887 | 64% | [24] |
| 2021 | Pero | PV/wind/diesel | HOMER | 0.478 | 227,335 | 94% | [29] |
| 2020 | Nigeria | PV/diesel/wind/battery | HOMER | 0.106 | 1 million | 77.4% | [31] |
| 2015 | Kenya | PV/wind/battery | HOMER | 0.258 | 66,650 | 100% | [49] |
| 2022 | Mauritania | PV/biogas/battery | HOMER Pro® | 0.0473 | 61,144 | 100% | Present study |

### 4.3. Comparison of the hybrid solution to the national electricity grid

The Mauritanian electricity company (SOMELEC) charges 1$ for every kWh of electrical energy sold or supplied to a consumer [50]. The price of a kWh of electrical energy sold by the diesel power plants (generators) that supply the city center is 1.3 $/kWh. On the other hand, the proposed hybrid PV-BiogasG-Batteries system provides energy for 0.0473 $/kWh. Currently, the government provides massive subsidies in the electricity sector in order to provide consumers with affordable electricity prices [51], [52]. The cost of the kWh produced by the proposed system is half of the SOMELEC's energy price [53], [54]. As the proposed hybrid system met the load demand with the lowest cost, the installation of this system will be the most efficient and advantageous.

## 5. CONCLUSION

This study aimed to propose a novel approach for sizing and optimization of the hybrid solar PV-batteries-biogas generator based on the biogas resources. The developed technique was applied for the case of the Ain Farba in Tintane, located in the region of Hodh El Gharbi in Mauritania. In this study, we explored feasibility economic of an autonomous solar-biogas-battery hybrid system to electrify a rural area (El Medina village) that does not have access to electricity.

The study was done using the HOMER Pro® software, and the proposed solution provided very clean and emission-free electricity powered by renewable energy system. The optimal configuration was composed of a 20-kW biogas engine, a 15-kW photovoltaic generator, 44 batteries, and an inverter with a nominal capacity of 10 kW. Moreover, it had an initial capital of 26,126 $, annual operating cost of 3,858 $/year, NPC of 61,144 $ and COE of 0.0473 $/kWh. The annual electricity production was determined as 156,355 kWh/year, 83.3% was produced from biogas generator and 16.7% from photovoltaic system. Although the cost of the biogas fuel was assumed to be zero, according to the life cycle analysis. It was identified that the biogas generator and converter would need to be replaced once throughout the project and the battery would need to be replaced every 4.4 years. This has shown that the use of these electrical systems has great potential to meet the energy demands of existing and similar systems in the long run, thus ensuring the sustainability of the energy supply.

Developing countries experiencing severe power outages on the grid or African countries with many villages without access to electricity and producing a lot of animal waste which could be benefit for the autonomous electrification (solar supply and biogas) in these specialized facilities. The performance of the hybrid PV-solar, battery, and GB system is highly dependent on the actual further studies, to consider the components system health base on the diagnosis and identification of default. Also, the implementation of a system performance prediction model considering the influence of the climatic parameters variation and the characteristics of the system components makes it possible to better analyze the feasibility economic of the system.

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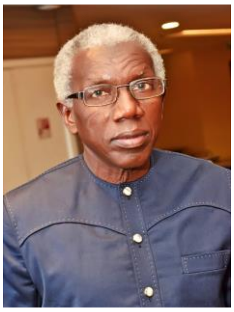

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