International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 6 Issue 2, January-February 2022 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Comparative Study of Electricity Production Cost of Renewable Energy Power Plants: Case of Photovoltaic Plant and Biogas Generators Power Plant in Sahel Area

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ABSTRACT

The massive use of renewable energies for electricity production still comes up against a very high production cost per kilowatt-hour. Although renewable energies are free and inexhaustible at human scale, most of time the high cost value of producing electricity from these renewable energies is related to the conversion equipments cost. For this reason, the purpose of this research is to choose the most suitable conversion system for a given site, taking into account the system implementing costs and the cost of electricity produced per kilowatt-hour. For a given electrical load, the project carrying out costs and the electricity cost per kilowatt-hour are calculated for Photovoltaic-lithium battery storage, Photovoltaic-AGM battery storage, Photovoltaic-Gel battery storage, Photovoltaic-lead battery storage and plant consisting of generators running on biogas. The different costs comparison made it possible to designate PV-Gel battery storage power plant as the best suited model for the studied site. The Photovoltaic-Gel battery power plant gave the lowest project costs, bearable by users in Sahelian zone in which the electrification project is planned.

KEYWORDS: *Photovoltaic, battery storage, biogas, electricity, kilowatt-hour cost*

How to cite this paper: Seydou Ouedraogo | Moussa Tissologo | Arnaud R. A. A. Valea | Adekunlé A. Salami | Ayité. S. A. Ajavon "Comparative Study of Electricity Production Cost of Renewable Energy Power Plants: Case of Photovoltaic Plant and Biogas Generators Power Plant in Sahel Area" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-6 | Issue-2, February 2022, pp.1346-1355, URL: www.ijtsrd.com/papers/ijtsrd49434.pdf

IJTSRD49434

I. INTRODUCTION

Access to modern sources of energies is one of necessary conditions for development of South countries, in particular rural area, which is generally isolated and not connected to traditional electricity networks [1]. Sectors listed in poverty reduction strategy: agriculture, education, health, industry, water, etc., cannot develop sustainably without adequate supply of appropriate energy service. For sustainable development, recourse to energy systems with renewable energy sources has therefore become essential for electrical energy production [2]. The use of renewable energies, like solar photovoltaic or biogas is an appropriate solution in some contexts to satisfy electrical energy needs of populations at bearable cost for user, especially in rural areas [3].

Photovoltaic systems must be connected with other energy source, so that load can be satisfied at night or in cloudy weather. Storage is sometimes ideal, battery bank, electrolyzer with hydrogen tank or a combination of two different storage devices such as electrolyzer and battery or electrolyzer and super capacitor [4], [5], [6], [7], [8]. Photovoltaic systems are currently economical for low power installations. For off-line power systems, storage cost represents the greatest constraint on system overall cost for large power installations.

As for biogas, it can be converted into electricity through generators, where it is used as gaseous fuel. Part of research work is directed towards design of new systems for converting biogas into electricity [9]. In this structure, there is no storage of electrical energy. Biogas generators production ensures continuity of electricity supply. In France, at Borde-Matin power station, biogas is converted into electricity by seven (7) generators, which produce a total nominal electrical power of 6.2 MW at 20 kV [10], [11]. Biogas from Barycz storage facility in Poland, is converted into electrical and thermal energy in three energy blocks in containers, with total nominal electrical output of 873 kW. The output electricity is delivered to the company of energy network distribution [12], [13].

However, electricity production from renewable energies still faces relatively high cost per kilowatt-hour. A serious problem with increasing installed capacity of renewable energy power systems is high initial investment required due to materials used high cost. For off-line electrical systems, storage cost represents the greatest constraint on overall cost of electrical system for large and medium-power installations [14]. To minimize producing electricity cost, renewable energy choice for conversion at a given site is important [15]. This is why this study concerns cost of producing electricity from photovoltaic power plant with battery storage and power plant made up of biogas generators.

This study objective is to find, between photovoltaic plant with battery storage and power plant composed of biogas generators, the best power plant for a given site with regard to low cost of investment, operation, maintenance, as well as the cheapest cost of electricity kilowatt-hour.

II. MATERIAL AND METHOD

It is about here, to find and compare optimal production cost per kilowatt-hour (kWh) of electricity from photovoltaic power plant composed of photovoltaic field, battery storage, inverter and the optimal production cost per kilowatt-hour of power plant composed of biogas generators.

2.1. Solar energy modeling

The global solar radiation is sum of direct radiation and diffuse radiation. The solar direct radiation on a horizontal plane is given:

$$S_{DR} = 1370\exp\left[-\frac{\mathrm{T_L}}{0.9+9.4\sin(\mathrm{h})}\right]\sin(h) \qquad (1)$$

S_{DR} being solar direct radiation, T_L is Link disorder factor, h is sun height, 1370 is conversion factor.

The solar diffuse radiation is calculated by equation below:

$$S_{DifR} = 54.8\sqrt{\sin(h)}\left(T_L - 0.5 - \sqrt{\sin(h)}\right) \qquad (2)$$

S_{DifR} is solar diffuse radiation, T_L is Link disorder factor, h is sun height in sky.

2.2. Biogas production modeling

Biogas production makes it possible to recover organic waste by producing renewable energy [16], [17]. Five (05) types of animal droppings are considered in this study [18]. This is waste from pigs, cattle, goats, sheep and poultry. The digester sizing is done basis on livestock numbers present at the site. Depending on animal species, animal's number required to produce organic material quantity to produce one (1) m^3 of biogas per day is known [19].

Table 1 Animals number for one m^3 of biogas production per day

Specie	Cattle	Pig	Sheep	Goat	Poultry
Number	1	3	11	11	93

With livestock number at site, slurry quantity per day is calculated with relationship below [20]:

$$Q_{\mathrm{slur}} = 30\left(n_{ca} + \frac{1}{3}n_{pi} + \frac{1}{11}n_{sh} + \frac{1}{11}n_{ga} + \frac{1}{93}n_{po}\right) \qquad (3)$$

Q_{slur} is slurry available per day quantity, n_{Ca} cattle number, n_{pi} pig number, n_{sh} sheep number, n_{go} goat number, n_{po} poultry number.

If the livestock numbers at a given site are known, the biogas volume produced per day is evaluated according to the following relationship [21]:

$$V_{Biogas} = n_{ca} + 3n_{pi} + 11n_{sh} + 11n_{go} + 93n_{po} \qquad (4)$$

V_{Biogas} is biogas available volume per day, n_{Ca} is cattle number, n_{pi} is pig number, n_{sh} is sheep number, n_{go} is goat number, n_{po} is poultry number.

2.3. Photovoltaic module modeling

A photovoltaic system directly converts sunlight into electricity. The main device of a photovoltaic system is a solar cell. Cells may be grouped to form panels or arrays. In order to maximize the extracted output power from a photovoltaic power plant, the understanding and modeling of photovoltaic cell is necessary.

The single-diode equivalent circuit model is arguably the most popular used photovoltaic cell model thanks to its relatively appropriate trade-off between accuracy and simplicity [22]. This model has been confirmed to be more accurate than other model [23].

Although single-diode equivalent circuit model imitates the behavior of physical photovoltaic cells better than ideal photovoltaic cell model, it can also lack accuracy, especially in the situations where the photovoltaic cell presents many defects and/or important temperature variation [24]. The configuration of the simulated ideal solar cell with single-diode, shunt resistance and series resistance is shown in Figure 1.

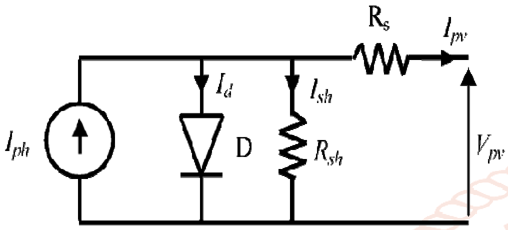

Figure 1 Single Diode Equivalent Circuit Model of photovoltaic cell.

In Figure 1, I_{ph} is the photo generated current, I_d is the diode current, I_{sh} is the shunt resistance current, I_{pv} is the output current, and V_{pv} is the terminal voltage.

According to the existing literature, the presence of this shunt resistance represents the construction defects that cause leakage currents within the PV cell, i.e., any parallel high-conductivity paths (shunts) free carriers produced by the solar irradiation across the photovoltaic cell P-N junction or on the photovoltaic cell edges [25], [26].

A high shunt resistance means that the clear majority of these carriers generate power, whereas a low resistance indicates large losses [27]. The magnitude of the shunt resistance varies with different fabrication methods since it is intimately related to the construction defects. The I-V characteristics of the solar cell with single-diode, shunt resistance and series resistance are given by:

$$I_{pv} = I_{ph} - I_s\left[\exp\left(\frac{q\left(V_{pv} + R_s I_{pv}\right)}{akT}\right) - 1\right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (5)$$

I_S represents the saturation current, a is the ideality factor of the diode. Constant k is the Boltzmann's constant ($1.380653*10^{-23}$ J/°K), q is the absolute value of electron's charge ($1.60217646*10^{-19}$ C), T is the temperature of the junction (°K).

The output power is given by:

$$P = I_{pv} V_{pv} \quad (6)$$

Photovoltaic generator performance depends on illumination, temperature and on the load to be supplied.

2.4. Inverter modeling

An inverter input power is power produced by photovoltaic field. Output power can be expressed from input power and efficiency [28].

$$P_{out} = \eta_{inv} P_{in} \quad (7)$$

P_{out} is inverter output power, P_{in} is inverter input power, η_{inv} is inverter efficiency.

with:

$$\eta_{inv} = \frac{p}{p + p_0 + kp^2} \quad (8)$$

$$p = \frac{P_{out}}{P_n} \quad (9)$$

η_{inv} is inverter efficiency, p_0 and k are coefficients calculated from data provided by manufacturer, p is reduced power, P_n is inverter peak power.

2.5. Digester modeling

The digester power is calculated based on methane content in biogas and calorific value of this biogas [29]. 100% methane content in biogas has 12.67 kWh/m^{3}calorific value. The digester electrical power is given by following relationship [30].

$$P_{Dig} = \frac{tP_{CI100} V_{Biogas}}{24} \quad (10)$$

P_{Dig} is digester power, t is methane content in biogas, P_{CI100} is 100% methane content calorific value in biogas, V_{Biogas} is biogas volume per day, *24* is one day hour number.

2.6. Storage battery modeling

Batteries or accumulators are electrochemical systems, which store energy in chemical form and release it in electrical form. Modeling batteries is a very important task both in their development and in certain applications requiring battery state modeling in real time [31]. There are several methods for modeling batteries behavior. The equivalent electric circuit model, known under Thevenin model name is the most used model for different types of batteries in various applications [32], [33]. Figure 2 gives this type of model diagram.

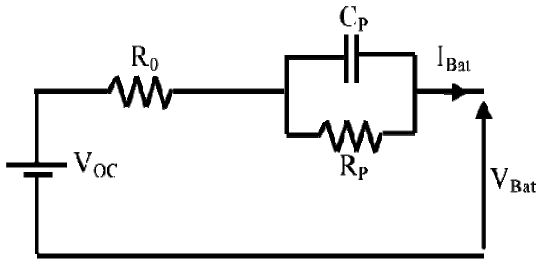

Figure 2 Thevenin model of battery

In figure 2, R_0 is the ohmic resistance, V_{OC} is the no-load voltage, C_P the double layer capacitance, R_P is the charge transfer resistance at electrode-electrolyte interface and I_{Bat} is the battery current intensity

The Thevenin's electric model equation takes following equation form [33].

$$V_{Bat}(s)=V_{oc}(s)-I_{Bat}(s)\left(\frac{R_0}{1+R_pC_p(s)}\right) \qquad (11)$$

V_{OC} is open circuit voltage, R_0 is battery resistance, V_{Bat}(S) is battery voltage corresponds to battery charge state S, I_{Bat} is battery current intensity, C_p is polarization capacitance, R_p is polarization resistance.

2.7. Biogas generator modeling

Biogas can be valorized in electricity by generators, where it is used as gaseous fuel [34]. Several parameters allow describing the performance of biogas engines, among which are specific consumption and efficiency. The specific consumption (CS) is equal to gas consumed quantity during one hour to produce 1 kW of electrical power [35]. For biogas generators, it is expressed in g/kWh or Nm^3/kWh [36].

$$CS = aP^2(t)+bP(t)+c \qquad (12)$$

CS is generator specific consumption, *a*, *b* and *c* are generator constants characteristic, *P(t)* is generated power by generator at time *t*.

Biogas generator overall efficiency is biogas chemical energy conversion efficiency into electrical energy. It is directly related to specific consumption [36].

$$\eta_{GBio}=\frac{3600}{PCI\cdot CS} \qquad (13)$$

η_{GBio} is biogas generator overall efficiency, *CS* is generator specific consumption, *PCI* is biogas lower calorific value.

2.8. Technical and economic analysis

In technical-economic analysis, investment, maintenance, operating and renewal costs as well as residual value of biogas generators and photovoltaic generator are considered to calculate cost per kilowatt-hour electricity produced by each electric system [37]. We propose here minimization of cost equation expressed as optimal size function of each generator, while respecting load energy constraints [38].

The "objective function" takes into account costs of acquisition, operation, maintenance and renewal of photovoltaic generator.

$$\begin{cases} OF_{PV}=C_{I-PV}+C_{I-Inv}+C_{I-Bat} \\ +C_{M-PV}+C_{M-Inv}+C_{M-Bat} \\ +C_{Op-PV}+C_{Op-Inv}+C_{Op-Bat} \\ +C_{R-PV}+C_{R-Inv}+C_{R-Bat} \\ +V_{R-PV}+V_{R-Inv}+V_{R-Bat} \end{cases} \qquad (14)$$

OF_{PV} is objective function of photovoltaic generator, C_{I-PV} is photovoltaic field investment cost, C_{I-Inv} is inverter investment cost, C_{I-Bat} is battery investment cost, C_{M-PV} is photovoltaic field maintenance cost, C_{M-Inv} is inverter maintenance cost, C_{M-Bat} is battery maintenance cost, C_{Op-PV} is photovoltaic field operation cost, C_{Op-Inv} is inverter operation cost, C_{Op-Bat} is battery operation cost, C_{R-PV} is photovoltaic field renewal cost, C_{R-Inv} is inverter renewal cost, C_{R-Bat} is battery renewal cost, V_{R-PV} is photovoltaic field residual value, V_{R-Inv} is inverter residual value, V_{R-Bat} is battery renewable cost.

Thus, for photovoltaic generator, following relation is used.

$$F_{PV}(x)=a_{PV}\left[1+m_{PV}ED(i,a,d)A(a,n_{PV})-S(a,d)\frac{nr_{PV}}{n_{PV}}\right]x_{PV}^{1-b_{PV}} + a_{Inv}\left[1+ED(i,\bar{a},d)-S(a,d)\frac{nr_{Inv}}{n_{Inv}}\right]x_{PV}\,x_{Inv}^{-b_{Inv}} \qquad (15)$$

x_{pv} is photovoltaic field power, x_{Inv} is inverter power, a_{PV} is photovoltaic field acquisition coefficient 1, b_{PV} is photovoltaic field acquisition coefficient 2, a_{Inv} is inverter acquisition coefficient 1, b_{Inv} is inverter acquisition coefficient 2, m_{PV} is photovoltaic field percentage corresponding to maintenance cost, $A(a,n_{PV})$ is annualization factor of photovoltaic field investment cost, $ED(i,a,d)$ is current expenditure discount factor, $ED(i,\bar{a},d)$ non-current expenditure discount factor, $S(a,d)$ discount factor, nr_{PV} is photovoltaic field remaining lifetime, n_{PV} is photovoltaic field lifetime, nr_{Inv} is inverter remaining lifetime, n_{Inv} is inverter lifetime.

The photovoltaic generator must be able to satisfy the load power at all times. This constitutes constraint, which results in following equation.

$$\frac{\eta_{Inv} F_{PV}}{1000} G(t) x_{PV} + \eta_{Inv} x_{Inv} = D(t) \qquad (16)$$

$G(t)$ is solar radiation, η_{Inv} is inverter efficiency, x_{Inv} is inverter power, F_{PV} is various losses factor recorded on photovoltaic field, $D(t)$ is load power at every hour, x_{PV} is photovoltaic field power.

Formulation of optimization problem of photovoltaic generator sizing therefore boils down to constrained optimization problem.

$$\begin{cases} Min[F_{PV}(x)] \\ \frac{\eta_{Inv} F_{PV}}{1000} G(t) x_{PV} + \eta_{Inv} x_{Inv} = D(t) \end{cases} \qquad (17)$$

$Min[F_{pv}(x)]$ is minimum value of function $Fpv(x)$, x_{pv} is nominal photovoltaic field power, $G(t)$ is solar radiation, η_{Inv} is inverter efficiency, x_{Inv} is an inverter power, $D(t)$ is load power at each hour t.

In case of biogas generators, the "objective function" takes into account costs of acquisition, operation, maintenance and renewal of each biogas generator.

$$\begin{cases} OF_{Bio} = C_{I-Dig} + C_{I-GBio} \\ + C_{M-Dig} + C_{M-GBio} \\ + C_{Op-Dig} + C_{Op-GBio} \\ + C_{R-Dig} + C_{R-GBio} \\ + V_{R-Dig} + V_{R-GBio} \end{cases} \qquad (18)$$

OF_{Bio} is objective function of biogas generator, C_{I-Dig} is digester investment cost, C_{I-GBio} is biogas generator investment cost, C_{M-Dig} is digester maintenance cost, C_{M-GBio} is biogas generator maintenance cost, C_{Op-Dig} is digester operation cost, $C_{Op-GBio}$ is biogas generator operation cost, C_{R-Dig} is digester renewal cost, C_{R-GBio} is biogas generator renewal cost, V_{R-Dig} is digester residual value, V_{R-GBio} is biogas generator residual value.

The objective function of our problem is deduced from the preceding developments. Thus, for biogas generators:

$$F_{Bio}(x) = a_{Dig}\left[1 + 2m_{Dig} ED(i,a,d) A(a,n_{Dig}) - S(a,d)\frac{nr_{Dig}}{n_{Dig}}\right] x_{Dig}^{1-b_{Dig}}$$
$$+ a_2 \beta D_{\max}\left[1 + ED(i,\bar{a},d) - S(a,d)\frac{nr_{GBio}}{n_{GBio}}\right] x_{GBio}^{-b_{GBio}}$$
$$+ nED(i,a,d)[C_0(a_1\beta + b_1) + b_0] x_{GBio} \sum_{t=1}^{24} X_{t+2} + nED(i,a,d) a_0 \sum_{t=1}^{24} X_{t+2} \qquad (19)$$

a_{Dig} is digester acquisition coefficient 1, b_{Dig} is digester acquisition coefficient 2, a_{GBio} is generator acquisition coefficient 1, b_{GBio} is generator acquisition coefficient 2, C_0 is1 Nm^3 biogas cost, b_0 is biogas generators maintenance coefficient 2, a_1 and b_1 are consumption parameters of each biogas generator, $A(a,n_{Dig})$ is digester factor of investment cost annualization, D_{max} is maximum load value, β is load rate, m_{Dig} is digester unit percentage corresponding to maintenance cost, nr_{Dig} is biogas plant remaining lifetime, $n_{Dig}$is biogas plant total lifetime, nr_{GBio} is biogas generators lifetime, n_{GBio} is biogas generators total lifetime, X_{t+2} is biogas generator number in operation at each hour of day, n is biogas generators number, $ED(i,a,d)$ is current expenditure discount factor, $ED(i, \bar{a},d)$ non-current expenditure discount factor, $S(a,d)$ discount factor.

Biogas power plant must be able to satisfy load power at all times. This constitutes constraint which results in following equation.

$$x_{GBio} X_{t+2} = D(t) \qquad (20)$$

x_{GBio} is biogas generator power, X_{t+2} is biogas generator number in operation at each hour of day, $D(t)$ is load power at each hour t.

The problem formulation therefore boils down to constrained optimization problem.

$$\begin{cases} Min[F_{Bio}(x)] \\ x_{GBio} X_{t+2} = D(t) \end{cases} \qquad (21)$$

$Min[F_{Bio}(x)]$ is minimum value of $F_{Bio}(x)$ function, x_{GBio} is biogas generator nominal power, X_{t+2} is biogas generator number in operation at each hour of day, $D(t)$ is load power at each hour t.

III. RESULTS AND DISCUSSION

This study is carried out for 20 years project duration. It is question of finding optimal production costs per kilowatt-hour of electricity of each power plant at a given site and then compares electricity production costs per kilowatt-hour to determine the most suitable plant for the site. The technical-economic optimization is carried out by

Homer software. The Homer software will be configured with the simulation parameters for each electric system element.

3.1. Demand profile

The electrical load profile to be satisfied at the site by each power plant is given in figure 3.

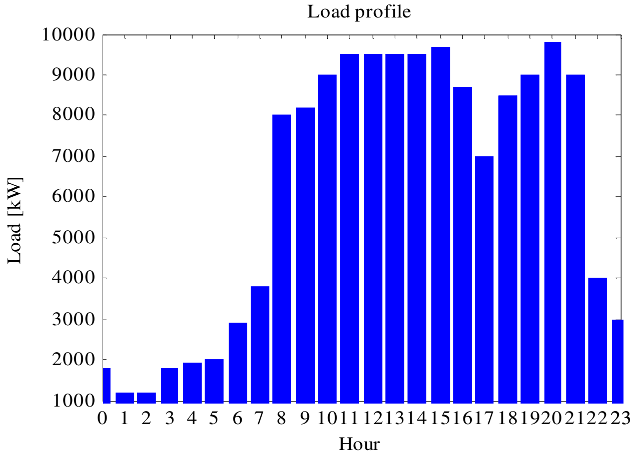

Figure 3 Electrical load profile.

3.2. Solar radiation assessment

Due to site geographic location, there is a huge solar deposit. The best curve radiation at studied site is on March. This curve is used in this study to understand better photovoltaic power plant dynamics. The solar radiation profile at the site is determined for this month.

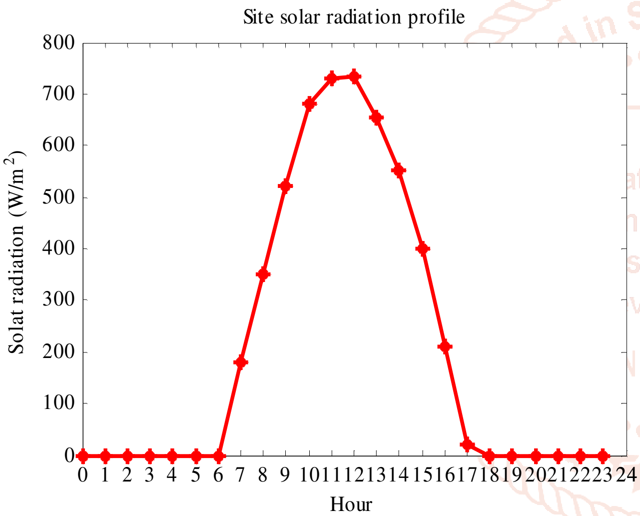

Figure 4 Solar radiation profile at the site

The site daily solar radiation average is 5.5 kWh/m^2/d. The isolation time is 3000 to 3500 hours per year, with average producible estimated at 1620 kWh. The chosen site has very high potential for sunshine.

3.3. Site's biogas production estimation

Biogas production potential at study site is given in Table 2.

Table 2 Biogas energy available at the site

Production	Quantity
Slurry quantity (tons/day)	9370.98
Biogas volume (m^3/day)	312365
Biogas weight (tons/day)	224.90
Daily electrical energy (kWh)	1920000
Electric power (kW)	80000

The studied site has very high potential for biogas production. The biogas production at this site reaches 312365 m^3 per day. Generators operate with biogas at 48% methane content. With biogas volume from Table 2, digester electrical power is determined. The electricity generated with generators from this biogas quantity is 80000 kW.

3.4. Optimal sizes of power plants elements

The study is carried out for 20 years project duration and 9800 kW of load peak. Table 3 shows different biogas power plant elements lifetime and costs.

Table 3 Optimal size of biogas generators power plant

Element	Size (kW)	Life time (Year)
Digester	25128	25
Biogas generator	12250	10

Load satisfaction at all times including the load peak, which is 9800 kW by the power plant composed of generator sets running on biogas, requires a digester power of 25128 kW, which will produce the biogas necessary to operate biogas generators with total power of 12250 KW. The digester lifetime of 25 years, which is higher than the project lifetime (20 years), is an advantage in the digester residual value calculation. However, biogas generators lifetime (10 years) is half of the project lifetime. This means that the generators will be renewed once before the project end. This will increase the cost of renewing the generators.

Table 4 shows different photovoltaic power plant elements lifetime and size.

Table 4 Optimal size of photovoltaic power plant

PV power plant elements	Size (kW)	Life time (Year)
PV field	65333	25
Inverter	66000	20
Lithium battery	235200	10
AGM battery	235200	3
Gel batteries	235200	7
Lead acidbattery	235200	4

The satisfaction of the load at any time including the peak of the load that is 9800 kW by photovoltaic plant with electrochemical storage requires photovoltaic power plant composed of photovoltaic field with 65333 kW, an inverter with power of 66000 kW and an electrochemical storage of 235200 kWh. The photovoltaic field and the inverter lifetimes respectively 25 and 20 years, compared to project lifetime are advantageous for the calculation of renewal costs and residual value of these elements. With regard to the storage life, excluding lithium batteries lifetime (10 years) which are renewed only once during the project life, the other batteries are renewed twice for Gel batteries, six times for AGM batteries and four times for lead acid batteries. This will lead to very high storage renewal costs and low residual values.

3.5. Power plants economic analysis

The sizing optimization with Homer software of power plant composed of generators running on biogas gave results recorded in Table 5.

Table 5 Optimal costs of biogas generators plant

Initial capital ($)	Operation cost ($)	Maintenance cost($)	Renewal cost ($)	Residual value ($)	kWh cost ($)
432530000	135930000	136340000	648900000	26241000	0.7731

Sizing optimization with Homer software of photovoltaic power plants with different storage battery technologies gave results recorded in Table 6 to 10.

Table 6 Optimal costs of photovoltaic power plant with lithium battery storage

Initial capital ($)	Operation cost ($)	Maintenance cost ($)	Renewal cost ($)	Residual value ($)	kWh cost ($)
362040000	514689	4393300	1122400000	4924700	0.7513

Table 7 Optimal costs of photovoltaic power plant with AGM battery storage

Initial capital ($)	Operation cost ($)	Maintenance cost ($)	Renewal cost ($)	Residual value ($)	kWh cost ($)
181400000	514689	4393300	827380000	19883000	0.4655

Table 8 Optimal costs of photovoltaic power plant with gel battery storage

Initial capital ($)	Operation cost ($)	Maintenance cost ($)	Renewal cost ($)	Residual value ($)	kWh cost ($)
189550000	514689	4393300	597190000	8502100	0.3276

Table 9 Optimal costs of photovoltaic power plant with lead acid battery storage

Initial capital ($)	Operation cost ($)	Maintenance cost ($)	Renewal cost ($)	Residual value ($)	kWh cost ($)
173870000	13134000	13134000	689360000	4924700	0.5152

3.6. Each power plant optimal costs comparison

Table 10 summarizes discounted costs of investment, operation, maintenance, renewal, as well as residual value of each power plant.

Table 10 Photovoltaic power plants and biogas power plant optimal costs

Costs	Photovoltaic power plant				Biogas generators power plant
	PV-Lithium battery	PV-AGM battery	PV-Gel battery	PV-Lead acid battery	
Initial capital ($)	362040000	181400000	189550000	173870000	432530000
Operation cost ($)	514689	514689	514689	13134000	135930000
Maintenance cost ($)	4393300	4393300	4393300	13134000	136340000
Renewal cost ($)	1122400000	827380000	597190000	689360000	648900000
Residual value ($)	4924700	19883000	8502100	4924700	26241000

The photovoltaic-lithium battery power plant initial capital ($362040000) is practically the double of initial investments of photovoltaic power plants using other battery technologies (around $180000000 each). This is due to lithium batteries acquisition cost, which is very high, compared to purchase cost of other types of batteries. However, biogas generators plant investment cost ($432530000) is higher than photovoltaic power plants investment cost, regardless of storage battery technology used. This is explained by the fact that biogas must first be produced and biogas production cost is added to generators acquisition cost. The biogas power plant operation costs ($135930000) and maintenance costs ($136340000) are also significant compared to photovoltaic plants operating and maintenance costs. These massive operation and maintenance costs of biogas power plant will contribute to increasing electricity kWh cost of this power plant and create financial difficulties for financing biogas power plant project.

Taking into account only investment, operation and maintenance costs, the most appropriate power plant for this site is photovoltaic power plant with Gel battery storage.

3.7. Electricty kilowatt-hour cost comparison

Optimal costs of electricity kilowatt-hour of photovoltaic power plants and biogas generators power plant are shown on Table 11.

Table 11 Electricity kilowatt-hour optimal costs

Costs	Photovoltaic power plant				Biogas generators power plant
	PV-Lithium battery	PV-AGM battery	PV-Gel battery	PV-Lead acid battery	
kWh cost ($)	0.7513	0.4655	0.3276	0.5152	0.7731

The cost of electricity kilowatt-hour produced by photovoltaic-lithium battery plant ($0.7513) is practically the same as kilowatt-hour cost of biogas generator plant ($0.7731). Apart from photovoltaic-lithium battery plant, electricity kilowatt-hour cost of other plants is lower than cost of electricity produced by biogas generators power plant. The cost of kilowatt-hour of electricity produced by photovoltaic-Gel battery power plant ($0.3276) is the lowest compared to kilowatt-hour cost of photovoltaic plants and biogas generators power plant. Taking into account only electricity kilowatt-hour cost, photovoltaic-Gel battery power plant is the best choice for this site.

IV. CONCLUSION

The objective of this study is to find among PV-battery power plants and power plant composed of generators running on biogas, which is the most suitable, in terms of implementation costs on a given site. The study consisted, for each power plant, in calculating and comparing the optimal costs of investment, maintenance, operation, renewal, residual value, as well as per kWh cost of electricity for peak load of 9800 kW and 20 years project duration. The simulations are carried out in the commercial software Homer, with data from a site located in the semi-arid zone of Burkina Faso in West Africa. Simulation results showed that, for studied, PV power plants with battery electrochemical storage have lower project costs than generator power plant running on biogas. Biogas generators power plant investment costs are heavy because of biogas generators power plant equipment importation. Biogas production cost and maintenance cost make kilowatt-hour electricity cost of biogas generators power plant to be around $0.7731. Recovery biogas from domestic livestock waste into electricity is very expensive. However, for power plants with generator sets running on biogas, the cost per kWh of electricity produced becomes very competitive, because generators purchase and maintenance costs are considerably reduced. Thus, the most suitable power plant for the study site is that of photovoltaic-gel battery, with investment cost of $189550000, operation cost of $514689, maintenance cost of $4393300, renewal cost of $597190000 and kWh cost of $0.3276.

For decentralized electrification project, photovoltaic-Gel battery power plant can serve as power plant model for sunny rural areas, as is the case of our study site, because this system has the cheaper electricity production cost, bearable for users of this area.

Références

[1] Virginie Escudié. Evaluation et capitalisation de microprojets: L'accès à l'énergie photovoltaïque dans les microprojets d'aide au développement. Pertinence, exigences et alternatives. Etude commanditée par la Guilde Européenne du Raid Décembre 2014.

[2] PNDES: Plan National de Développement Economique et Social 2016-2020. Gouvernement du Burkina Faso 2016.

[3] D. J. Grinmshaw and S. Lewis. L'énergie solaire pour les pauvres, faits et chiffres. Science et développement 2010. https://www.scidev.net/afrique-sub-saharienne.

[4] Mulder G., De Ridder F., Six D. Electricity storage for grid-connected household dwellings with PV panels. Solar Energy 2010; 84(7):1284-1293.

[5] Oluwarotimi Delano Thierry Odou, Ramchandra Bhandari, Rabani Adamou. Hybrid off-grid renewable power system for sustainable rural electrification in Benin. Renewable Energy 2020; 145:1266-1279. https://doi.org/10.1016/j.renene.2019.06.032.

[6] Chaouki Ghenai, Maamar Bettayeb. Modelling and performance analysis of a stand-alone hybrid solar PV/Fuel Cell/Diesel Generator power system for university building. Energy 2019; 171:180-189. https://doi.org/10.1016/j.energy.2019.01.019.

[7] Anthony Roy, Jean-Christophe Olivier, François Auger, Bruno Auvity, Emmanuel Schaeffer, Salvy Bourguet, Jonathan Schiebel, Jacques Perret. A combined optimization of the sizing and the energy

management of an industrial multi-energy microgrid: Application to a harbour area. Energy Conversion and Management2020; X 12:100107. https://doi.org/10.1016/j.ecmx.2021.100107.

[8] N'guessan S. Attemene, Krehi S. Agbli, Siaka Fofana, Daniel Hissel. Optimal sizing of a wind, fuel cell, electrolyzer, battery and supercapacitor system for off-grid applications. International Journal of Hydrogen Energy 2020; 45(8): 5512-5525. https://doi.org/10.1016/j.ijhydene.2019.05.212.

[9] Ahmed Belila, Yassine Amirat, Mohamed Benbouzid, El Madjid Berkouk, Gang Yao. Virtual synchronous generators for voltage synchronization of a hybrid PV-diesel power system. International Journal of Electrical Power & Energy Systems 2020; 117:105677. https://doi.org/10.1016/j.ijepes.2019.105677.

[10] S Ouedraogo, A.S.A. Ajavon, A.A. Salami, M.K. Kodjo, K.S. Bedja. Modèle optimal de conversion en électricité du biogaz de déchets de l'élevage domestique. J. Rech. Sci. Univ. Lomé (Togo) 2019; 21(1):135-146.

[11] Site internet de Waukesha Engine. Groupes électrogènes au biogaz. http://www.waukeshaengine.com. Consulté le 13 Janvier2022.

[12] Nicolae Scarlat, Jean-François Dallemand, Fernando Fahl. Biogas: Developments and perspectives in Europe. Renewable Energy 2018; 129(Part A):457-472. https://doi.org/10.1016/j.renene.2018.03.006.

[13] INSTRUKCJA OBSŁUGI STACJI BIOGAZU IGNiG. Instruction de service de la station du biogaz pour l'installation de la production de l'électricité et de la chaleur du brulage du biogaz sur le Centre de Stockage Barycz). Instytut Górnictwa Naftowegoi Gazownictwa, Kraków, Polska, 1999.

[14] Oliver Schmidt, Sylvain Melchior, Adam Hawkes, Iain Staffell. Projecting the Future Levelized Cost of Electricity Storage Technologies. Elsevier 2019; 3(1):81-100. https://doi.org/10.1016/j.joule.2018.12.008.

[15] Omar Ellabban, Haitham Abu-Rub, Frede Blaabjerg Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews 2014; 39:748-764. https://doi.org/10.1016/j.rser.2014.07.113.

[16] Spyridon Achinas, Vasileios Achinas, Gerrit Jan Willem Euverink. A Technological Overview of Biogas Production from Biowaste. Engineering 2017;3(3):299-307. https://doi.org/10.1016/J.ENG.2017.03.002

[17] Michel Torrijos. State of Development of Biogas Production in Europe. Procedia Environmental Sciences 2016; 35:881-889. https://doi.org/10.1016/j.proenv.2016.07.043.

[18] Weiland P. Production de biogaz par les exploitations agricoles en Allemagne. Sciences Eaux & Territoires 2013; 3(12):14-23.

[19] Kamalan H., Sabour M., N. Shariatmadari. A review on Available Landfill Gas Mode. Journal of Environmental Science and Technology 2011; 4(2):79-92.Ref. 26.

[20] Ansoumane Sakouvogui, Younoussa Moussa Balde, Mamadou Foula Barry, Cellou KANTE, et Mamby KEITA. Évaluation du potentiel en biogaz de la bouse de vache, de la fiente de poule et en codigestion à Mamou, République de Guinée. Afrique SCIENCE 2018; 14(5):147 – 157.

[21] Dinh Duc Nguyen, Byong-Hun Jeon, Jae Hoon Jeung, Eldon R. Rene, J. Rajesh Banu, Balasubramani Ravindran, Cuong ManhVu, Huu Hao Ngo, Wenshan Guo, Soon Woong Chang.Thermophilic anaerobic digestion of model organicwastes: Evaluation of biomethane production and multiple kinetic models analysis. Bioresource Technology 2019; 280:269-276. https://doi.org/10.1016/j.biortech.2019.02.033

[22] [Jord] Jordehi AR. Parameter estimation of solar photovoltaic (PV) cells: A review. Renew Sustain Energy Rev 2016; 61: 354–71.

[23] [Lobr] Lo Brano V, Orioli A, Ciulla G. On the experimental validation of an improved five parameter model for silicon photovoltaic modules. Sol Energy Mat Sol C 2012; 105:27–39.

[24] [Mare] Mares, O., Paulescu, M., Badescu, V., 2015. A simple but accurate procedure for solving the five parameter model. Energy Convers. Manage. 105, 139–48.

[25] [Bout] Boutana N, Mellit A, Haddada S, Rabhi A, Massi Pavan A. An explicit I-V

model for photovoltaic module technologies. Energy Convers Manage 2017; 138:400-12.

[26] [Khan] Khan F, Baek SH, Park Y, Kim JH. Extraction of diode parameters of silicon solar cells under high illumination conditions. Energy Converse Manage 2013; 76:421–9.

[27] [Rusc] Ruschel C.S., Gasparin F.P., Costa E.R., Krenzinger A. Assessment of PV modules shunt resistance dependence on solar irradiance, Sol Energy 2016. 133:35-43.

[28] Bouharchouche A., Bouabdallah A., Berkouk E. M., Diaf S. et Belmili H.Conception et réalisation d'un logiciel de dimensionnement d'un système d'énergie hybride éolien-photovoltaïque. Revue des Energies Renouvelables 2014; 17(3):359–376.

[29] Levasseur P., Aubert P., Berger S., Charpiot A., Damiano A., Meier V., Quideau, P. Développement d'un calculateur pour déterminer l'intérêt technico-économique de la méthanisation dans les différents systèmes de productions animales: Méthasim. Innovations agronomiques, INRAE 2011; 17(17): 241-253. ⟨hal-02647447⟩.

[30] Beline F., Girault R., Peu P., Tremier A.,Teglia C. et Dabert P. Enjeux et perspectives pour le développement de la méthanisation agricole en France. Sciences Eaux & Territoires 2012; 2(7):34-43.

[31] Abdollahi, X. Han, N.Raghunathan, B. Pattipati, B. Balasingam, K. R. Pattipati, Y. Bar-Shalom, B. Card. Optimal charging for general equivalent electrical battery model, and battery life management .J. Energy Storage 2017; 9: 47–58. https://doi.org/10.1016/j.est.2016.11.002.

[32] D. Grazioli, M. Magri, and A. Salvadori. Computational modeling of Li-ion batteries. Comput. Mech. 2016; 58(6):889–909.

[33] Fotouhi, D. J. Auger, K.Propp, S. Longo, and M. Wild. A review on electric vehicle battery modelling: From Lithium-ion toward Lithium-Sulphur. Renew. Sustain. Energy Rev 2016; 56:1008–1021. https://doi.org/10.1016/j.rser.2015.12.009.

[34] MAAAR: Ministère de l'agriculture, de l'alimentation et des affaires rurales. Conversion des véhicules au gaz naturel et au biogaz. Gouvernement du Canada, Ontario, 2015.

[35] Gao Ruiling, Cheng Shikun, Li Zifu. Research progress of siloxane removal from biogas. Int J Agric & Biol Eng 2017; 10(1): 30–39. DOI:10.3965/j.ijabe.20171001.3043.

[36] Diniz, P., da Costa L., da Silveira J., Barroso G. & Barcellos W. Performance evaluation of controllers applied to power generator set operating with waste water biogas. Electr Eng 2021; 103:753–768. https://doi.org/10.1007/s00202-020-01113-4.

[37] Sunanda Sinha, S. S. Chandel. Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems. Renewable and Sustainable Energy Reviews 2015; 50:755-769. https://doi.org/10.1016/j.rser.2015.05.040.

[38] Bouharchouche A., Berkouk E. M. and Ghennam T. Control and Energy Management of a Grid Connected Hybrid Energy System PV-Wind with Battery Energy Storage for Residential Applications. Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies, EVER'13. Monte-Carlo, Monaco, 27–30 March 2013.