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RESEARCH ARTICLE

GENETIC ALGORITHMS APPROACH FOR OPTIMIZATION OF HYBRID POWER PLANT SIZING IN SAHELIAN ZONE: CASE STUDY IN BURKINA FASO

Moussa Tissologo¹, Seydou Ouedraogo² and Frédéric Ouattara¹

1. Laboratoire de Recherche en Énergétique et Météorologie de l'Espace (LAREME), Norbert ZONGO University, Koudougou, Burkina Faso.
2. Department of Electrical Engineering, University Institute of Technology, Nazi BONI University, 01 BP 1091 Bobo-Dioulasso 01, Burkina Faso.

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Abstract

Electrification development in rural areas is essential; in order to meet electricity needs at bearable cost, for rural areas population development. This work presents optimization of hybrid electric power plant composed of solar photovoltaic and biogas generators, without electrical energy storage, for low-cost electrification of rural and peri-urban areas, at four sites in Sahel region of Burkina Faso. Simulation results give electricity kilowatt-hour cost about 0.0616 dollar at Gorom-Gorom site, 0.0611 dollar at Dori site, 0.0616 dollar at Djibo site and 0.0616 dollar at Sebba site. Compared to kilowatt-hour cost charged by the national electricity distribution company, who is from 0.1345 dollar, produced electricity cost at these sites is very competitive and accessible for this region population. Use of biogas in addition to solar as an energy source for electrical hybrid power plant has made it possible to reduce significantly polluting and greenhouse gas emissions.

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Introduction:-

Access to modern energy sources being one of first necessary conditions for southern countries development, in particular, from rural area, the need to develop electrification in rural areas is essential, in order to satisfy electricity needs at bearable cost for population. However, announced depletion of conventional energy resources and environmental degradation are main causes which direct research towards renewable energies. Renewable energies are inexhaustible on human scale and their conversion has little impact on environment. They therefore constitute relevant response to current and future energy problem (Alkhalil, 2011). Among many sources of renewable energy, there is biomass gas or biogas. With technologies rapid development, biogas production techniques have reached level of technological maturity and reliability, which minimizes its production cost (Afilal and al., 2031).

Converting biogas to electricity could help address the challenge of depleted fossil resources and greenhouse gas emissions.

For biogas exploitation, knowing sites biomass potential is important. However, biomass quantity necessary for biogas optimal production varies during different seasons (Tahri and al., 2012). In domestic breeding biomass exploitation context, livestock number assessment can help to control seasonal variations in biogas production

Corresponding Author:-Seydou Ouedraogo

Address:-Department of Electrical Engineering, University Institute of Technology, Nazi BONI University, 01 BP 1091 Bobo-Dioulasso 01, Burkina Faso.

potential or anaerobic digestion at site (Ouedraogo and al., 2018). Anaerobic digestion is technical, ecological and social innovation, which makes it possible to recover organic waste, by producing renewable energy and organic products that can be used to improve soil fertility (Beline and al., 2012; Bapat and Bhatia, 2018). Biogas can be converted into electricity by generator, where it is used as gaseous fuel. In solar case, power variations are caused by day-night cycle, by clouds crossing sky or other obstacles between sun and photovoltaic fields. Photovoltaic system optimization depends in part on instantaneous meteorological variables values (Ouedraogo and al., 2017). Extensive studies are carried out in world several regions to assess and model solar radiation potential. Markovian approaches have contributed to modeling solar radiation random fluctuations (Harrouni and Maafi, 2002). They allowed solar radiation models development. Studies that are more recent are interested in solar radiation random fluctuations modeling, using neural networks and fractal analysis (Benatallah and al., 2020). Some works have used sunstroke and others have used daily average relative humidity, maximum and minimum temperature (Despotovic and al., 2015; Almorox, 2011). Other works are also done to assess solar potential. It is worth mentioning work carried out by Ouedraogo and al. (2017), which gave relationship linking diffuse solar irradiation and global solar irradiation on horizontal surface according to different seasons in Sahel zone. However, in addition to their high price, photovoltaic systems are characterized by low efficiency, which further limits their distribution. Renewable energies exploitation still comes up against relatively high cost per kilowatt-hour produced (Bouharchouche and al., 2013). Hybrid electric systems that combine multiple energy sources will maximize electricity production systems, from a technical, economic and environmental point of view (Brihmat, 2012). Hybrid electric systems overcome intermittency, uncertainty and low availability of each renewable energy source, which makes these systems more reliable (Bouharchouche and al., 2014; Kanchev, 2014).

Hybrid system us is attractive solution for areas where electricity grid extension is not feasible, or requires relatively high cost. Hybrid electric systems development requires them to become more economically attractive. Dipama J. (2010), in his thesis, shows that industrial systems energy optimization offers enormous advantages, whether from economic or environmental point of view. Therefore, detailed techno-economic analysis, based on real observations (Belanger-Gravel, 2011), or on cost trends predictions of hybrid system various components is essential (Fathima and Palanisamy, 2015). Many studies have been carried out on hybrid power systems optimal sizing. Belatel and al. (2014) carried out hybrid wind-photovoltaic system with fuel cell technical and economic analysis. Chen and al. (2015) have in turn proposed optimal configuration for micro-grid system using diesel as main source. Bao and al. (2013), on the optimal capacity of an autonomous wind-photovoltaic-diesel-battery system based on genetic algorithm, have carried out research. Olatomiwa and al. (2014) studied hybrid power system optimization for isolated site for telecommunication relay station in Nigeria. Li and al. (2015) carried out studies on mini distribution network optimal configuration, considering diesel generator as the main source. They made comparison between results obtained with Homer software and those obtained using genetic algorithm. It turns out that it is advantageous to use diesel generator as main source. For autonomous power, micro gas turbines are preferred over diesel generators because of their better dynamic performance and lower greenhouse gas emissions (Kanchev and al., 2015). The optimal definition of hybrid electric system generating elements includes steps of modeling available energy resources, optimization methodology definition, system each element modeling taking into account methodology objective and constraints definition (Kouam and Tchuen, 2015). Different criteria are used for hybrid electric system optimization, depending on installation site: electrical load loss probability, combination of minimal system cost and minimum harmful emissions, to which is added minimum unsatisfied load (Kaabeche and al., 2010; Ismail and al., 2012). Optimization procedures use either genetic algorithms, heuristic methods or commercial software such as Homer, DimHybrid or PVsyst (Ko and al., 2015; Kumar, 2016; Zhou and al., 2010). Ouedraogo (2018), in his thesis used genetic algorithm for multi-objective optimization of hybrid power plant, composed of solar photovoltaic, wind turbine and biogas generator.

The main objective of this work is to increase access to electricity supply and thus contribute to population development in rural and peri-urban areas in sahelian zone. Optimizing the sizing of hybrid power plant, composed of photovoltaic generator and biogas generator, will make it possible to offer produced electricity kilowatt hour cost cheapest and bearable by population

Studied sites:

Sahel region of Burkina Faso extends between 13th and 15th parallel of north latitude and covers area approximately 35,000 km². Sahel region in Burkina Faso includes provinces of Oudalan, Seno, Soum and Yagha. These provinces administrative centers are respectively Gorom-Gorom, Dori, Djibo, and Sebba.



Figure 1:- Studied sites geographical location (Source: Geographical Institute of Burkina)

According to general population census of Burkina in 2006, Sahel region had 903,084 inhabitants (INSD, 2008). This population would reach 1,481,543 people in 2020.

Table 1:- Geographic coordinates and inhabitants number at studied sites.

sites	Coordinates		Area (km ²)	Inhabitant number (-)	Density (Inhab/km ²)
	Latitude	Longitude			
Gorom-Gorom	14°27'N	0°14'O	9 797	298 344	30
Dori	14°02'N	0°02'O	6 863	400 557	58
Djibo	14°06'N	1°38'O	12 222	526 898	43
Sebba	13°26'N	0°32'E	6 468	241 236	37

The Sahel region is characterized by Sahelian-type climate, alternation dry season and rainy season of 3 to 4 months. Annual rainfall is less than 600 millimeters, with variability in precipitation distribution, strong evapo-transpiration around 3 meters per year, significant variations in daily and annual temperatures. Breeding is the main socio-economic activity. It is income source for more than 80% of population and contributes 10% to Gross Domestic Product (MRA, 2018). Cattle, goats, sheep, donkeys, pigs, horses and poultry are essentially raised in Burkina Faso Sahelian region. Ministry of Animal Resources statistics give livestock number in 2020.

Table 2:- Livestock numbers at studied sites.

Sites	Species							
	Donkey	Cattle	Camels	Goats	Equines	Sheep	Pigs	Poultry
Gorom-Gorom	40470	318997	13135	499705	2234	334247	46	307762
Dori	20293	1149894	1408	1259787	8503	610896	4355	581466

Djibo	24468	371799	2709	590083	1579	461577	85	775355
Sebba	4537	263207	0	431750	185	147151	0	255464

Material and methods:-

In this work, technical and economic optimization of hybrid electric power plant sizing is carried out by genetic algorithm, at four sites in Sahel region of Burkina Faso. For the hybrid power plant analysis, Matlab software is used.

Matlab presentation:

Matlab is an abbreviation of Matrix Laboratory. Matlab is an environment for scientific computing, which has several mathematical, scientific and technical functions. Matlab toolboxes solve problems in signal processing, automation, optimization, and more. Matlab has following particularities: easy programming, continuity among whole, real and complex values, the wide range of numbers and their precisions, very comprehensive mathematical library, graphical tool which includes graphical interface functions and utilities. Matlab allows links with other conventional programming languages (Zhang and al., 2019). In Matlab, no declaration of numbers is made. This feature makes the programming mode very easy and very fast.

Optimization methods:

There are several optimization methods for multicriteria problems (Bokovi, 2013). It is question here of finding optimal solutions, which must be compromises between objective functions. Among these methods, genetic algorithms are widely used as optimization method. Genetic algorithms were proposed by Holland J. (1975) and then developed by other researchers (Fang and al., 2010). It is method based on Pareto approaches. For problem containing parameters with strong interactions resolution, genetic algorithms method was able to get closer to real front (Deb and al., 2002). Genetic algorithms method is chosen in this study. This method is also used by Ko and al. (2015) to minimize life cycle cost of electricity generation facility. Genetic algorithms structure used in this work is given.

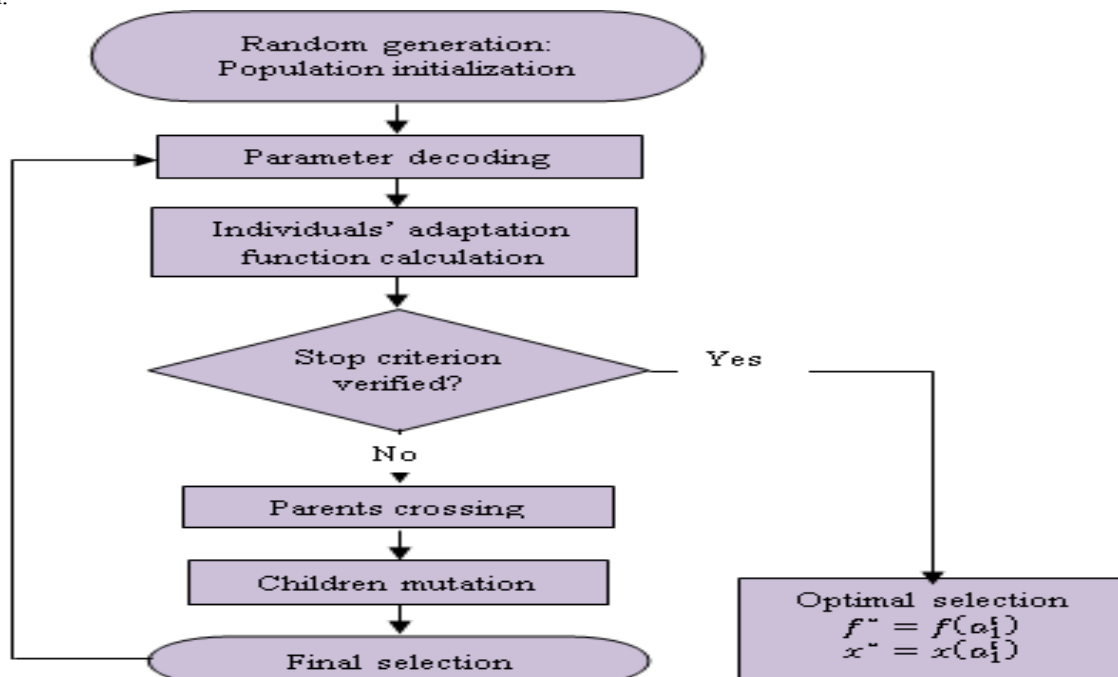


Figure 2:- Genetic algorithms structure.

Hybrid power plant architecture and modeling:

Hybrid electric power plant to size includes electrical energy production part, from renewable energies and electrical load part. This electric power plant is composed of photovoltaic generator and biogas generator. Hybrid electric power plant parts are directly connected to alternative (AC) bus for biogas generator and through inverters for photovoltaic field.

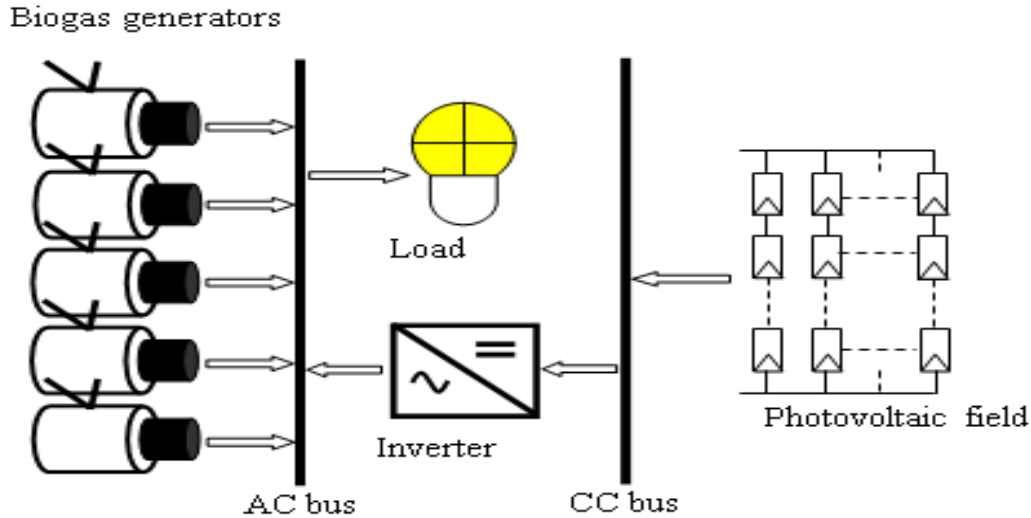


Figure 3:- Studied system architecture.

Biogas production modeling:

Five (05) types of livestock waste are considered in this study (Weiland, 2013). These are pigs, cattle, goats, sheep and poultry. Digester sizing is made on basis of livestock number present at site. Depending on animal species, livestock number required for one (1) m³ biogas production per day is given (Kamalan and al., 2011).

Table 3:- Animals number for 1 m³ biogas production per day.

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

With livestock number at site, makes it possible to calculate slurry quantity per day (Ouedraogo and al., 2019).

$$Q_{Slurry}(kg/d) = 30 \left(N_{cat} + \frac{1}{3} N_{Pig} + \frac{1}{11} N_{She} + \frac{1}{11} N_{Goa} + \frac{1}{93} N_{Pou} \right) \quad (1)$$

Where Q_{Slurry} is slurry available quantity per day; N_{Cat} is cattle number; N_{pig} is pigs number; N_{She} is sheep number; N_{Goa} is goats number; N_{Pou} is poultry number.

If livestock number at a site is known, biogas volume produced per day at this site is calculated (Ouedraogo and al., 2019).

$$V_{Biogas}(m^3/d) = N_{cat} + 3N_{Pig} + 11N_{She} + 11N_{Goa} + 93N_{Pou} \quad (2)$$

where V_{Biogas} is biogas volume per day; N_{Cat} is cattle number; N_{pig} is pigs number; N_{She} is sheep number; N_{Goa} is goats number; N_{Pou} is poultry number.

The digester power is calculated according to methane content in biogas and this biogas calorific value (Levasseur and al., 2011). 100% methane in biogas has calorific value of 12.67 kWh/m³. Biogas calorific value at methane content t is given (Beline and al., 2012).

$$LCP_t(kWh/m^3) = t \cdot LCP_{100} \quad (3)$$

where LCP_t is biogas lower calorific power value at methane content t ; t is methane content of biogas; LCP_{100} is biogas lower calorific power value at 100% methane content.

Electrical energy produced from biogas at methane content t is calculated (Beline and al., 2012).

$$E_{Biogas}(kWh) = LCP_t \times V_{Biogas} \quad (4)$$

where E_{Biogas} is digester electrical energy; LCP_t is biogas lower calorific power value at methane content t ; V_{Biogas} is biogas volume per day.

Digester electrical power is calculated (Beline and al., 2012).

$$P_{Dig}(kW) = \frac{LCP_t \times V_{Biogas}}{24} \quad (5)$$

where P_{Dig} is digester power; LCP_t is biogas calorific value at methane content t ; V_{Biogas} biogas volume per day.

Biogas generator modeling:

Several parameters are used to describe biogas engines performance, including specific consumption and overall or effective efficiency.

Specific consumption:

Specific consumption (SC) is equal to consumed gas quantity during one hour to produce one kW electrical power. For biogas generator, specific consumption is expressed (Yamegueu NGuewo, 2012).

$$SC = a'P^2(t) + b'P(t) + c' \quad (6)$$

where a' , b' and c' are generator characteristic constants, $P(t)$ is power generated at given time by generator.

Generator overall efficiency:

The generator overall efficiency expresses the conversion efficiency of biogas chemical energy into electrical energy. It is directly linked to specific consumption (Yamegueu NGuewo, 2012).

$$\eta_{GBio} = \frac{3600}{LCP \times SC} \quad (7)$$

where LCP (MJ/kg) is lower calorific power value of biogas; SC (g/kWh) is generator specific consumption.

Relation (8) gives biogas generator total power.

$$P_{T-GBio} = \frac{L_{max}}{X_{GBio}} \quad (8)$$

Where P_{T-GBio} is biogas generator total power, L_{max} is load peak, X_{GBio} is generator load rate.

Photovoltaic field modeling:

Photovoltaic field performance depends on solar radiation, temperature and load to supply. Photovoltaic field maximum output power is calculated (Bouharchouche and al., 2014).

$$P_{mp} = \eta_{PV} A_{PV} G_S \quad (9)$$

where P_{mp} is photovoltaic field maximum output power, A_{PV} (m^2) is photovoltaic field area; G_S (W/m^2) is solar irradiance; and η_{PV} is photovoltaic modules efficiency.

Photovoltaic modules efficiency is given by equation (10).

$$\eta_{PV} = \eta_{ref} \left[1 - \alpha \left(\frac{G_s}{18} + T_a - 20 \right) \right] \quad (10)$$

where α is temperature coefficient for power correction ($\alpha = 0.0042$), η_{ref} is photovoltaic module reference efficiency and T_a is ambient temperature.

Inverter modeling:

Inverter input power is photovoltaic field maximum output power. Inverter output power can be expressed from his input power and his efficiency according.

$$P_{in} = \eta_{inv} P_{out} \quad (11)$$

with:

$$\eta_{inv} = \frac{p}{p + p_0 + kp^2} \quad (12)$$

and:

$$p = \frac{P_{out}}{P_n} \quad (13)$$

where η_{inv} is inverter efficiency; p_0 and k are coefficients calculated from data supplied by manufacturer; p is reduced power.

Technical-economic analysis:

In techno-economic analysis process, investment, maintenance, operation and renewal costs, as well as generating elements residual value of hybrid plant are considered in produced electricity kilowatt-hour (kWh) cost calculation (Belatel and Ouazeta, 2014). It is proposed here, cost equation minimization expressed as function of each generating element optimal size (digester, biogas generator, photovoltaic field, inverters), while respecting hybrid power plant energy constraints (Bouharchouche and al., 2013).

Model formulation:

Developed model is based on objective "cost" function definition. This function takes into account all expenses incurred by hybrid power plant, during its lifetime. This function definition goes through classic stages of engineering projects financial analysis. Objective function takes into account of investment, operation, maintenance and renewal costs, as well as residual value of hybrid plant generating elements.

$$f(x) = C_I + C_M + C_{Op} + C_R + V_R \quad (19)$$

where $f(x)$ is objective function, C_I is investment cost, C_M is maintenance cost, C_{Op} is operation cost, C_R is renewal cost, V_R is residual value.

Investment cost is express according to:

$$C_I = a_1 x_1^{1-b_1} + \frac{L_{max}}{X_{GBio}} a_2 x_2^{-b_2} + a_3 x_3^{1-b_3} + a_4 x_3 x_4^{-b_4} \quad (20)$$

where a_1 is the digester acquisition coefficient 1, a_2 is biogas generators investment coefficient 1, a_3 is PV field investment coefficient 1, a_4 is inverters investment coefficient 1, b_1 is digester investment coefficient 2, b_2 is biogas generators investment coefficient 2, b_3 is PV field investment coefficient 2, b_4 is inverters investment coefficient 2,

x_1 is digester peak power, x_2 is biogas generators peak power, x_3 is PV field peak power, x_4 is inverters peak power, L_{\max} is load maximum value, X_{GBio} is biogas generators load rate.

Hybrid power plant maintenance cost equation is determined by:

$$C_M = m_{Dig} PW(i, a, d) A(a, n_{Dig}) a_1 x_1^{1-b_1} + N(a_0 + b_0 x_2) PW(i, a, d) \sum_{t=1}^{24} X_{t+4} + m_{PV} A(a, n_{PV}) a_3 x_3^{1-b_3} \quad (21)$$

where a_0 is biogas generators maintenance coefficient 1, b_0 is biogas generators maintenance coefficient 2, m_{Dig} is digester maintenance cost coefficient, m_{GBio} is biogas generator maintenance cost coefficient, m_{PV} is PV field maintenance cost coefficient, N biogas generators number, $A(a, n_{Dig})$ is digester investment annualization factor, $A(a, n_{PV})$ is PV field investment annualization factor, $P(i, a, d)$ is investment discounting factor, X_{t+4} is biogas generators number operating at time t , C_{L-PV} is PV field investment cost, x_1 is digester peak power, x_2 is biogas generators peak power.

Hybrid power plant operating cost is giving by:

$$C_{Op} = E_{Dig} PW(i, a, d) A(a, n_{Dig}) a_1 x_1^{1-b_1} + C_0 x_2 N(a_5 X_{GBio} + b_5) PW(i, a, d) \sum_{t=1}^{24} X_{t+4} \quad (22)$$

where C_0 is 1 m³ biogas cost, a_5 and b_5 are biogas generator consumption parameters, E_{Dig} is digester operating cost coefficient, $A(a, n_{Dig})$ is digester investment cost annualization factor, $PW(i, a, d)$ is investment discounting factor, x_1 is digester peak power, x_2 is biogas generators peak power.

The hybrid power plant components renewal cost is given by:

$$C_R = PW(i, \bar{a}_1, d) a_2 \frac{L_{\max}}{X_{GBio}} x_2^{-b_2} + PW(i, \bar{a}_2, d) a_4 x_3 x_4^{-b_4} \quad (23)$$

where $PW(i, \bar{a}_1, d)$ is adjusted discount rate for biogas generators replacement and $PW(i, \bar{a}_2, d)$ adjusted discount rate for inverters replacement, L_{\max} is maximum load, X_{GBio} is biogas generators load rate, x_2 is biogas generators peak power, x_3 is PV field peak power, x_4 is inverters peak power, L_{\max} is load maximum value, X_{GBio} is biogas generators load rate.

Hybrid plant residual value equation at project end is:

$$V_R = S(a, d) \frac{nr_{Dig}}{n_{Dig}} a_1 x_1^{1-b_1} + S(a, d) \frac{nr_{GBio}}{n_{GBio}} \frac{L_{\max}}{X_{GBio}} a_2 x_2^{-b_2} + S(a, d) \frac{nr_{PV}}{n_{PV}} a_3 x_3^{1-b_3} + S(a, d) \frac{nr_{Inv}}{n_{Inv}} x_3 a_4 x_4^{1-b_4} \quad (24)$$

where 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, nr_{PV} is photovoltaic modules remaining lifetime, n_{PV} is photovoltaic modules total lifetime, nr_{Inv} is inverters remaining lifetime, n_{Inv} is inverters total lifetime, L_{\max} is maximum load, X_{GBio} is load

rate, x_1 is digester peak power, x_2 is biogas generators peak power, x_3 is PV field peak power, x_4 is inverters peak power.

Hybrid power plant must be able to meet electric load power at all times. Problem formulation therefore boils down to constrained optimization problem, which can be expressed.

$$\begin{cases} \text{Min}(f(x)) \\ x_1 + x_2 X_t + q_0 G(t) x_3 + \eta_{inv} x_4 = L(t), t = 1 : 24 \end{cases} \quad (25)$$

where x_1 is digester power, x_2 is biogas generators peak power, x_3 is photovoltaic field nominal power, x_4 is inverter nominal power, X_t is biogas generators number in operation at time t , $G(t)$ is solar radiation, $L(t)$ is load power every hour, η_{inv} is inverter efficiency.

Carbon dioxide emissions analysis:

Photovoltaic generator, in its operation does not produce greenhouse gases. In our study, carbon dioxide (CO_2) equivalent quantity is calculated by considering only biogas consumed and gases emitted after combustion in biogas generators, taking into account their global warming potential. CO_2 equivalent quantity is calculated (Kanchev and al., 2015).

$$m_{\text{CO}_2_equivalent_i} = m_{\text{CO}_2_i} + 3m_{\text{CO}_i} + 25m_{\text{CH}_4} + 298m_{\text{NO}_x_i} \quad (26)$$

where $m_{\text{CO}_2_i}$ is carbon dioxide mass; m_{CO_i} is carbon monoxide mass; m_{CH_4} methane mass; $m_{\text{NO}_x_i}$ is nitrogen oxide mass.

Genetic algorithm setting in Matlab environment:

Technical and economic sizing optimization program written in Matlab environment consists of series of files (Javadi and al., 2011).

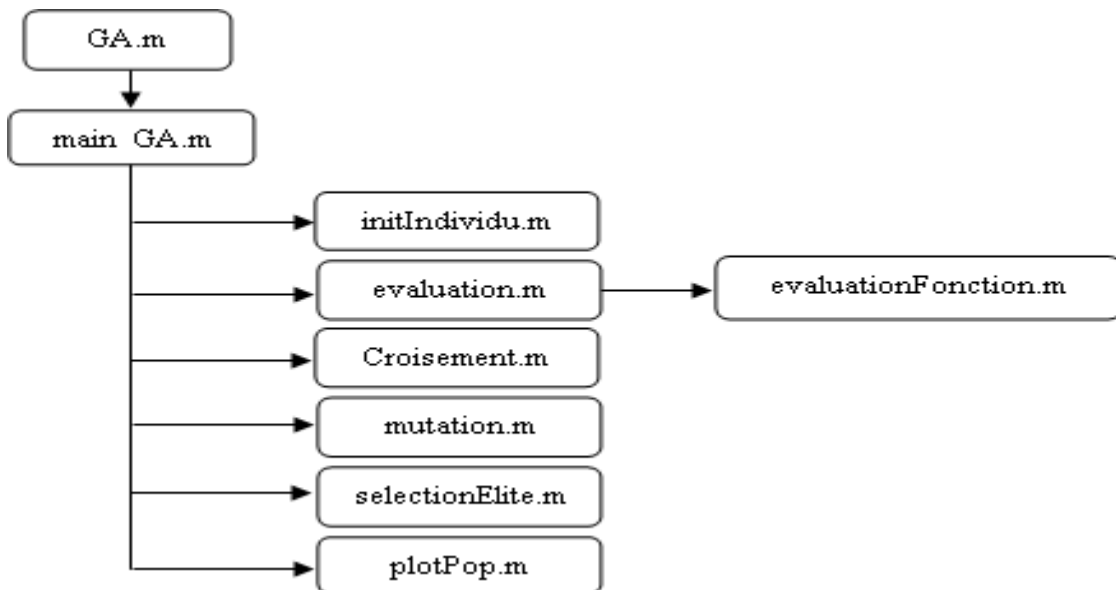


Figure 4:- Genetic algorithm program structure.

Parameters configuration file (GA.m) and evaluation file (evaluationFonction.m) must be modified for program easy use. Setting only two files allows obtaining very good results with reasonable computing time. Hybrid power plant model developed at each site, in this study has as input parameters solar radiation daily values, biogas quantity produced per day and load profile at each site.

Results and Discussions:-

Chosen sites for this study are those of Gorom-Gorom, Dori, Djibo and Sebba located in the Sahel region of Burkina Faso. The aim is to increase access to electricity supply in this zone, by exploiting endogenous renewable resources, in particular solar photovoltaic and biogas. Study is carried out for 25 years project lifetime.

Electricity load profile at studied sites:

According to population growth forecasts at studied sites, electricity load profile to be satisfied by hybrid power plants is estimated.

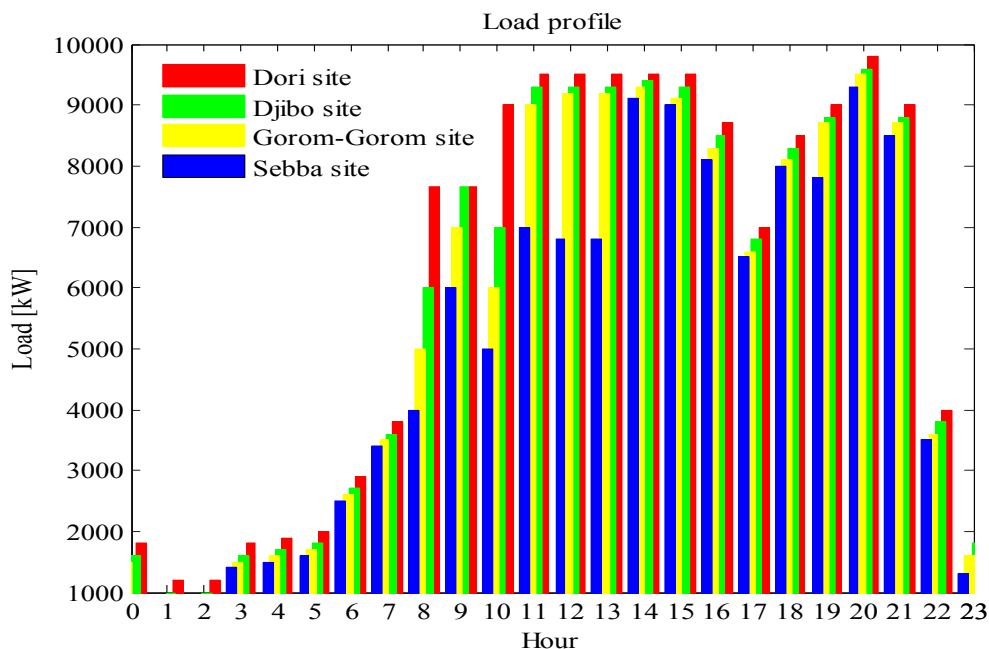


Figure 5:- Hourly load profile at studied sites

Biogas production assessment at studied sites:

Livestock number at each site makes it possible to determine biogas daily quantity that be produced at each site.

Table 4:- Biogas production potential at four sites.

Digesteur parameters	Site			
	Gorom-Gorom	Dori	Djibo	Sebba
Volume (m ³ /d)	38114473	75816810	84048329	30389270
Weight (t/d)	44213	87947	97496	35252
Daily electrical energy (MWh/d)	231800	461090	511150	184820
Electric power (MW)	9658	19212	21298	7701

High livestock number at these four sites means that biogas production potential is enormous. Studied sites have very high potential for biogas production. However, it is at Djibo site that the highest biogas production potential is observed. This is due to animals' total number at this site, which is higher than in other sites.

Solar radiation profile at four studied sites:

Solar radiation profile at four studied sites is represented.

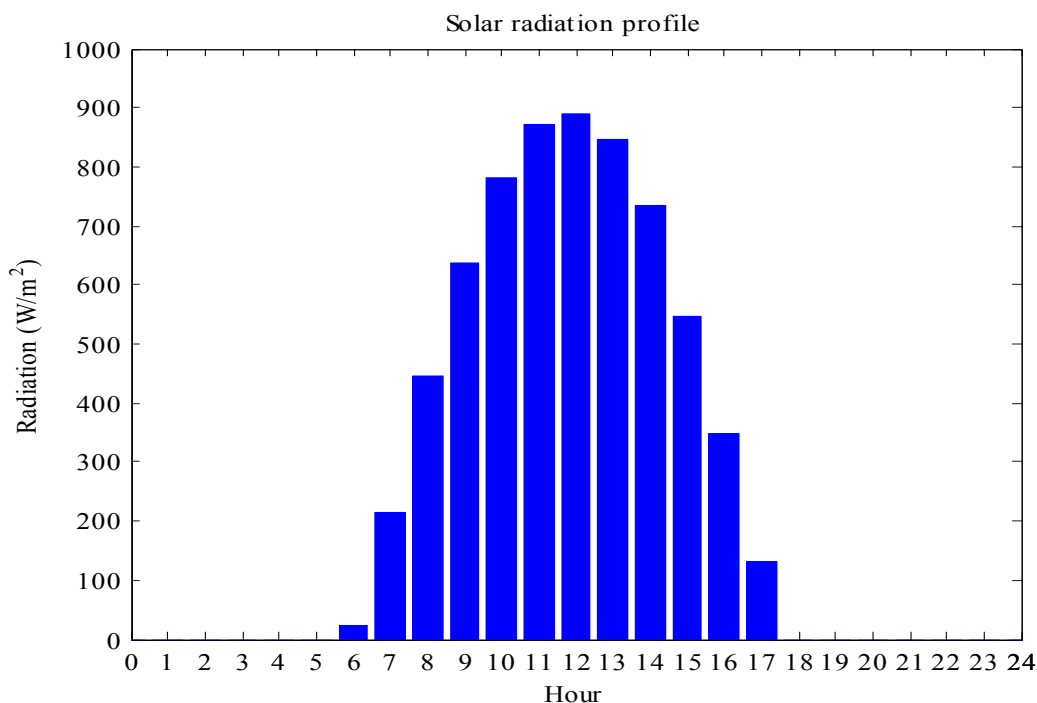


Figure 6:-Solar radiation profile at studied sites

The best solar radiation curve at studied sites is that March month. This solar radiation is used in this study to better understand hybrid power plants dynamics. Solar energy is the most abundant endogenous renewable resource at study sites. Daily average solar radiation is 5.5 kWh/d, for 3,000 to 3,500 hours per year and average production estimated at 1,620 kWh per kWp installed (PNDES, 2016).

Hybrid power plant technical and economic optimization:

Optimization simulation is done with program developed with genetic algorithm, in Matlab 8 environment. Several trials were necessary to arrive at overall optimum. Four optimal values of decision variables: x_1 , x_2 , x_3 and x_4 , corresponding respectively to digester power, biogas generator nominal power, photovoltaic field peak power and inverters nominal power are calculated.

Table 5:- Hybrid power plant elements optimal sizes.

Sites	Digesters power (kW)	Biogas power (kW)	generators	Photovoltaic power (kW)	field	Inverters power (kW)
Gorom-Gorom	15,010	9,500		1,900		2,000
Dori	15,484	9,800		1,960		2,100
Djibo	15,168	9,600		1,920		2,020
Sebba	14,852	9,400		1,880		1,980

The highest digester power is at Dori site, with power of 15,484 kW, while the smallest is at Sebba site, which records 14,852 kW power. The same is true for hybrid system other generating elements at all sites. Dori site records the largest hybrid power plant power. Animals' number at Dori site explains this, which is higher than at other sites. Optimal value of f_{val} , obtained by implementing objective function over project lifetime (25 years), corresponding to electricity produced kWh cost at each site is determined by simulation in program developed with genetic algorithm.

Table 6:-Hybrid power plant optimal costs at each site.

Sites	Initial capital (\$)	Annual operating cost (\$)	Annual maintenance cost (\$)	Renewal cost (\$)	Residual value (\$)	kWh cost (\$)
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Gorom-Gorom	135940647	4598021	16798741	129683	8814748	0.0616
Dori	140250000	4743165	16127877	136169	29728417	0.0611
Djibo	137370503	4646402	16975539	130980	29116906	0.0616
Sebba	134510791	4549640	16621942	128386	28510791	0.0616

Simulation results give electricity kWh cost at four studied sites: 0.0616 \$ at Gorom-Gorom site, 0.0611 \$ at Dori site, 0.0616 \$ at Djibo site and 0.0616 \$ at Sebba site. The lowest kWh cost is observed at Dori site, which is 0.0611 \$. Initial capital, operating cost and renewal cost are the highest at Dori site, but, maintenance cost (16,127,877 \$) is the lowest at this site. In addition, the highest residual value of hybrid power plant (29,728,417 \$) is at Dori site. Lower maintenance cost and high residual value justify the cheapest kWh cost at Dori site.

Carbon dioxide emissions analysis:

Biogas combustion in generator engines produces carbon dioxide, carbon monoxide, nitrogen oxides, unburned biogas and particulate matter. These gases carbon dioxide (CO₂) equivalent quantity is calculated by considering each gas effect on global warming. Consumed biogas and emitted gases by generators quantities as well as CO₂ equivalent quantity avoided at each site are calculated.

Table 7:- Biogas consumed and gases emitted by biogas generators quantities.

Sites	Biogas consumed equivalent (tons)	CO ₂	Rejected gases equivalent (tons)	CO ₂	CO ₂ avoided quantity (tons)
Gorom-Gorom	2,4218,480		10,398		24,208,082
Dori	62,747,880		26,940		62,720,939
Djibo	29,722,680		12,761		29,709,919
Sebba	17,613,440		7,562		17,605,878
Total	134,302,480		57,663		134,244,818

Consumed biogas total CO₂ equivalent for biogas generators operation at four sites is one hundred and thirty-four million three hundred and two thousand four hundred and eighty (134,302,480) tons per year. This CO₂ quantity could be emitted into atmosphere, if it was not converted into electricity. CO₂ equivalent avoided is then one hundred and thirty-four million two hundred and forty-four thousand eight hundred and eighteen (134,244,818) tons per year.

Conclusion:-

This study main objective is to increase access to electricity supply, at lower cost, for daily electricity needs at four sites in the Sahel region of Burkina Faso, thus contributing to improvement of populations living conditions. The simulation results give electricity kWh cost at four studied sites: 0.0616 \$ at Gorom-Gorom site, 0.0611 \$ at Dori site, 0.0616 \$ at Djibo site and 0.0616 \$ at Sebba site. Compared to per kilowatt-hour cost practiced by national electricity distribution company, which is on average 0.1345 \$, hybrid power plants sizing optimization has resulted in very competitive kWh costs. Electricity production from these low-cost hybrid power plants will thus sustainably boost socio-economic development in Sahel region. Upgrading animals waste into biogas, used as gaseous fuel, has significantly reduced producing electricity cost and producing fertilizer for crops. Use of biogas in addition to solar energy for hybrid power plants has reduced polluting and greenhouse gas emissions very significantly. Developed model with genetic algorithm is model which, in addition to giving system overall configuration, also simulate system dynamics. This model can be used as decision support tool for decentralized electrification operators. This project expected socio-economic impact is jobs creation and local wealth. Parameters similarity of studied sites which are located in Liptako-Gourma zone, orders that this study results be applicable to Liptako-Gourma zone, which covers large part of North-East Mali, North-East and East Burkina Faso, and South Niger, as well as to entire Africa Sahelian zone.

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