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ENDOGENOUS RENEWABLE ENERGIES CONVERSION INTO ELECTRICITY FOR OPTIMAL PUMPING OF AQUIFERS GROUNDWATER IN THE SAHELIAN AREA: CASE STUDY IN BURKINA FASO

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ABSTRACT

The water lack is a major obstacle to socio-economic development in the Sahel of southern countries. Water resources access being one of necessary conditions for the Sahelian space development, only water control is a lasting solution to Sahel development problem. Surface water being very ephemeral in the Sahel area, groundwater exploitation is essential for satisfying daily water needs, especially in rural areas. However, dewatering at optimal cost of groundwater faces the access to electricity problem, which is essential for pumping water. This work presents the optimization of a pumping system for groundwater stored in aquifers, to increase the offer of water resources access in Sahelian area, at a lower cost per cubic meter. The required electrical energy for pumping is produced from a hybrid electrical system, composed of photovoltaic solar and generator sets running on biogas, produced from animal droppings. The technical and economic optimization is done by Homer software. The simulation is carried out with four sites characteristics, located in the Sahel region of Burkina Faso, in West Africa. Simulation results gave water costs at the four sites: 0.152 $/m^3 for Oudalan site, 0.184 $/m^3 for Seno site, 0.151 $/m^3 for Soum site and 0.152 $/m^3 for Yagha site. This pumping system integrates environmental consecrations by calculating equivalent CO_2 before and after conversion of biogas into electricity. CO_2 quantity avoided is 134,244,818 tons per year. Biogas use in addition to solar photovoltaic as sources of energy for hybrid electric system has made it possible to lessen pumped water m^3 cost and reduce significantly polluting and greenhouse gas emissions.

KEYWORDS: Groundwater, Renewable energies, Electricity, Pumping, Optimization.

1. INTRODUCTION

Sustainable access to water resources is a major concern of Sahel region in sub-Saharan Africa. Water lack is an obstacle to socio-economic development of Sahel region. In such context, a paradigm shift is essential in solutions search to Sahel development problems. It is no longer a question of trying to solve Sahel vulnerability problem by tackling the symptoms, which are fight against desertification, famine, drinking water access difficulties and rural exodus, but rather find lasting solutions to Sahel water control problem.

Five major transboundary aquifer systems constitute Sahel region groundwater resources. These are Lake Chad basin, Iullemeden aquifer system, Taoudéni basin, Senegalo-Mauritanian basin and Liptako-Gourma/Upper Volta system [1]. Groundwater resources map shows that Sahelian zone in sub-Saharan Africa is characterized by abundance of groundwater. A study carried out in 13 zones in nine (9) Sahelian countries of Africa and published in the "nature" journal established that fresh water reserves stored in aquifers are much more important than imagined, especially in more arid regions[2]. According to this study results, groundwater resources also display certain resilience to climatic variations and a drop in rainfall does not necessarily translate into a decrease in groundwater reserves. Cuthbert et al. identified involved processes in groundwater renewal in aquifers by examining long-term trends in aquifers replenishment in sub-Saharan Africa and concluded that climate change may not have a negative impact on groundwater supply [2]. Healy also analyzed aquifers replenishment in sub-Saharan Africa and has shown that reduced precipitation does not necessarily deplete groundwater supplies [3]. Surface water scarcity in sahelian area means that groundwater stored in aquifers seem to be the only alternative for taming water in sahelian zone [4]. Groundwater reserves optimal exploitation in this part of African continent can increase livelihoods, reduce poverty, maintain vital ecosystems and reduce budget allocated to energy [5], [6], [7].

Several attempts have been made to make water available in Sahel region of Burkina Faso. High flow drillings such as "Christine Forage" whose aquifer provides flow greater than 100 m^3/h, operated by diesel generator pumping system, allowing several hundred animals and people to have access to water during dry periods [8]. However, technical breakdowns and fuel supplying difficulties led to this pumping system inoperability. Draining groundwater to great depths and at large flows requires a lot of energy, especially electrical energy. It is for this reason that most abundant endogenous renewable energies conversion into electricity is envisaged in this study. Renewable energies integration in electricity production is a part of energy sector policy of Burkina Faso, which plans to increase renewable energies share in the country's mix energy from 8% to 50% by 2025 and thus avoid approximately 220,100 tons of CO_2 emission per year [9], [10]. One of renewable energy forms technical and economic choice on isolated sites in Sahelian area is dependent on several parameters knowledge, such as electrical power required, investment cost and installation site access constraints [11]. This present study deals with groundwater pumping using electrical energy of hybrid system composed of photovoltaic solar and generators running on biogas, produced from animal droppings. Biogas production or anaerobic digestion is technical, ecological and social innovation, which recovers organic waste by producing renewable energy and fertilizer, while preserving environment by reducing polluting gases rejection [12], [13]. The advantage of this hybrid system is that it solves variable and unsecured power problem of photovoltaic solar, by biogas complementarity and increases water pumping time, compared to solar only use [14]. In addition, it minimizes generators usage time, also reducing maintenance costs.

The main objective of this work is to increase water resources access offer, in sufficient quantities, at lower cost, for people, breeding and date palm farming irrigation needs, in rural areas, using an autonomous hybrid electric system with renewable energies, to produce necessary electricity to pump groundwater in Sahel region of Burkina Faso.

2. STUDIED SITES

In Burkina Faso, Sahel region extends between 13th and 15th parallels of north latitude and covers an approximately 35,000 km² area. The Sahel region includes provinces of Oudalan, Seno, Soum and Yagha. Chief towns of these provinces are respectively Gorom-Gorom, Dori, Djibo, and Sebba (Fig. 1).

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Figure 1: Geographic location of studied sites (Source: Geographical Institute of Burkina Faso)

According to Burkina Faso population general census in 2006, the Sahel region had 903,084 people [15]. This population would reach 1,481,543 in 2020.

Table 1. Studied sites geographical coordinates and people number

Region	Province	Coordinats		Area (km²)	People number (-)	Density (people/km²)
		Latitude	Longitude			
Sahel	Oudalan	14°27'N	0°14'W	9 797	298344	30
	Seno	14°02'N	0°02'W	6 863	400557	58
	Soum	14°06'N	1°38'W	12 222	526898	43
	Yagha	13°26'N	0°32'E	6 468	241236	37

The region is characterized by a Sahelian style climate and alternating dry and 3 to 4 months rainy season. The annual rainfall is less than 600 mm and is characterized by variability in precipitation distribution, strong evapotranspiration of around 3 m/year and wide variations in daily and annual temperatures. Solar energy is the most abundant endogenous resource in Burkina Faso Sahelian zone. Breeding is the main socio-economic activity. It is a source of income for more than 80% of Burkina Faso people and contributes 10% to Gross Domestic Product [16]. However, water lack forces pastoralists and their livestock to migrate very often to agricultural areas in the south, in search of water and pasture [17], [18]. In Burkina Faso Sahel region, most of farming involves cattle, goats, sheep, donkeys, pigs, horses and poultry. Burkina Faso Ministry of Animal Resources statistics give livestock number on studied sites [19].

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Table 2. Livestock numbers in the Sahel region

Region	Specise / Site	Asins	Cattle	Camelins	Goats	Equine	Sheep	Pigs	Poultry
Sahel	Oudalan	40470	318997	13135	499705	2234	334247	46	307762
	Seno	20293	1149894	1408	1259787	8503	610896	4355	581466
	Soum	24468	371799	2709	590083	1579	461577	85	775355
	Yagha	4537	263207	0	431750	185	147151	0	255464

Groundwater resources in this region are those of Liptako-Gourma/Upper Volta aquifer system. With approximately 159,500 km^2 area, Liptako-Gourma/Upper Volta aquifer covers a large part of northeastern Mali, northeastern and eastern Burkina Faso, and southern Niger [20].

3. MATERIAL AND METHOD

Pumping system sizing essentially concerns the daily water needs assessment, the peak power of renewable energies hybrid generator, drilling, the submersible pump choice meeting the service required under the reference conditions and finally technical and economic optimization using software [21].

Homer software presentation

Homer means: Hybrid Optimization of Multiple Energy Resources. It is software for hybrid energy systems (PV, wind, grid, storage and diesel) optimization [22]. It performs the optimization task by performing an hourly simulation of the energy flow between the load and the other components of the system over a period of one year. For each configuration of the hybrid system, the Homer software performs a time analysis of the installation. At each time step, the software observes the consumption and compares it with the photovoltaic production, which has priority. In the case of a lack of this energy, the Homer software must choose between use generator or Batteries. The main features of Homer software are: taking into account the hourly load profile as well as controllable loads, time simulation of a multi-source production system, production system economic optimization and sensitivity analysis. The operation of Homer is analyzed for hybrid systems comprising: photovoltaic installation, one or two generators, with or without an electrochemical storage unit. For parameters such as number of devices and powers, Homer software simulates the operation of the system for each of the parameterized values. Homer software presents a financial analysis on project life cycle, based on comparison results of produced kWh costs by different sources. Thus, for each architecture and configuration, it is possible to observe the following outputs: global cost of the updated kWh (LCOE: Levelized Cost of electricity), distribution of the items of expenditure, the detail corresponding to each source, daily charts over the life of the system, sensitivity analysis graphs, an economic analysis compared to a reference installation, sensitivity analysis presented in graphical form.

People water needs assessment

Daily water consumption per person, according to World Health Organization standard is 10 to 20 liters in sub-Saharan Africa [23], [24]. The people number on studied sites, at project horizon time, in year 2045 is given by the following equation [25].

$$P_d = P_0\left(1+\tau_c\right)^d \qquad (1)$$

where:
• P_n is the people number at the project time horizon (year 2045).
• P_0 is the current people number (2020).
• τ_c is the people growth rate in the locality
• d is the project duration (25 years).

Daily water needs are calculated using the following equation

$$D_{jm} = 1.1\left(\frac{C_s P_d}{1000}\right) \qquad (2)$$

where:
• D_{jm} is the daily needs.

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• C_S is the specific consumption (20 liters/day/individual).
• P_d is the people number at the project horizon time (year 2045).

The peak of daily need is given by the following equation

$$D_{jp} = D_{jm} C_{pj} C_{ps} \quad (3)$$

where:
• D_{jp} is the peak daily need.
• C_{pj} is the daily peak coefficient, generally between 1.05 and 1.15.
• C_{ps} is the seasonal peak coefficient, generally between 1.1 and 1.2.

Losses are estimated at 10% daily needs. A specific endowment is added according to the project orientations for the following needs in project year Y_0: 3 liters/day/student for schools, 5 liters per consultation for health facilities, 20 liters/day/hospital bed, 0.3 m^3/day/market, 0.1 m^3/day/mosque.

Livestock water needs assessment
Livestock water needs depends on the livestock size, the animal species, the forage quality and the climate [26].

Table 3. Daily water requirement for each species of livestock

Speciee	Asins	Cattle	Camelins	Goats	Equine	Sheep	Pigs	Poultry
Water need/day (liter)	10	40	2.5	7	40	7	10	0.32

Palm irrigation water needs assessment
Date palms, in addition to their usefulness for food, are used to form a vault with their branches, in order to grow plants that would sweat more if they were in direct sunlight, such as orange, lemon, vegetables and cereals. Using palm will help fight desert spread. Indeed, the date palm, because of its size is the most suitable for stopping sand dunes. For date palm irrigation, the water needs is calculated for ten hectares area of date palms on each site, at start project [27]. This is equivalent to 1,230 date palms spaced 10 m apart. The Penman model, based on evapotranspiration knowledge is adopted in the palmer water needs estimation. The localized "drip" irrigation technique is chosen to preserve water resource, thus allowing the pumping power plant optimal sizing [28], [29]. An empirical relationship exists between water quantities required for irrigated cultivation in gravity mode and those to bring in case of localized irrigation, expressed by the following equation [30].

$$Q_l = Q_g \left(k_0 + 0.90p\right) \quad (4)$$

where:
• Q_l is the water volume for localized irrigation.
• Q_g is the water volume for gravity irrigation.
• p is the soil fraction covered by plant foliage.
• k_0 is the oasis effect coefficient.

Submersible pump modeling
To determine a drilling submersible pump power, it is necessary to know the total manometric height and the desired flow. The pump curve allows choosing the right pump. The submersible pump annual energy consumption cost is calculated by the following equation.

$$E = cnP_1 \quad (5)$$

where:
• E is the submersible pump annual energy consumption cost.
• c is the energy specific price ($/kWh).

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• n is the operating hours by year number (hours).
• P_1 is the submersible pump power (kW).

with:

$$P_1 = \frac{QH_{tm}\rho}{367\,\eta_{pum}\,\eta_{eng}} \quad (6)$$

where:
• Q is the pump flow (m³/h).
• H_{tm} is the total manometric height (m).
• ρ is the water density (kg/m³).
• η_{pum} is the pump efficiency.
• η_{eng} is the engine efficiency.
• *367* is a conversion factor.

The electrical power supplied to a pump for a flow Q is given by the following equation [31].

$$P_2 = P_1\eta_{eng} \quad (7)$$

where:
•P_1 is the submersible pump power.
•P_2 is the pump supplied power.
•η_{eng} is the engine efficiency.

Biogas production from livestock effluents modeling

The aim is to assess biogas production potential and solar radiation potential at each site. Biogas production makes it possible to recover organic waste by producing renewable energy [32], [33]. Five (05) types of animal droppings are considered in this study [34]. This is waste from pigs, cattle, goats, sheep and poultry. The digester sizing is done on basis of livestock numbers present on the site. Depending on the animal species, animal's number required to produce the organic material quantity to produce one (1) m³ of biogas per day is known (Table 4) [35].

Table 4. Animals number for 1 m³ of biogas production per day

Species	Cattles	Pigs	Sheeps	Goats	Poultry
Number	1	3	11	11	93

With livestock number on each site, slurry quantity per day is calculated with the relationship below [36].

$$Q_{slur} = 30\left(n_{ca} + \frac{1}{3}n_{pi} + \frac{1}{11}n_{sh} + \frac{1}{11}n_{ga} + \frac{1}{93}n_{po}\right) \quad (8)$$

where:
• Q_{slur} is the slurry available per day quantity.
• n_{Ca} is the cattle number.
• n_{pi} is the pigs number.
• n_{sh} is the sheep number.
• n_{go} is the goats number.
• n_{po} is the 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 [37].

$$V_{Biogas} = n_{ca} + 3n_{pi} + 11n_{sh} + 11n_{go} + 93n_{po} \quad (9)$$

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where:
• V_{Biogas} is the biogas available volume per day.
• n_{Ca} is the cattle number.
• n_{pi} is the pigs number.
• n_{sh} is the sheep number.
• n_{go} is the goats number.
• n_{po} is the poultry number.

Biogas can be valorized in electricity by generators, where it is used as gaseous fuel [38]. The biogas plant power is calculated based on methane content in biogas and calorific value of this biogas [39]. 100% methane content in biogas has 12.67 kWh/m^3 calorific value. The digester electrical power is given by the following relationship.

$$P_{Dig} = \frac{tP_{CI\,100}V_{Biogas}}{24} \qquad (10)$$

where:
• P_{Dig} is the digester power.
• t is the methane content in biogas.
• P_{CI100} is the 100% methane content calorific value in biogas.
• V_{Biogas} is the biogas volume per day.
• 24 is a day hours number.

Solar energy modeling
The global solar radiation is the sum of direct radiation and diffuse radiation. The solar direct radiation on a horizontal plane is given by the following equation.

$$S = 1370\exp\left[-\frac{T_L}{0.9+9.4\sin(h)}\right]\sin(h) \quad (11)$$

where:
• S is the solar direct radiation.
• T_L is the link disorder factor.
• h is the sun height.
• 1370 is a conversion factor.

The solar diffuse radiation D is calculated by the equation below.

$$D = 54.8\sqrt{\sin(h)}\left(T_L - 0.5 - \sqrt{\sin(h)}\right) \qquad (12)$$

where:
• D is the solar diffuse radiation.
• T_L is the link disorder factor.
• h is the sun height.

Biogas generators modeling
Several parameters are used to describe biogas engines performance, among which the specific consumption and the total or effective efficiency. The specific consumption (CS) is equal to the biogas consumed quantity during one hour to produce 1 kW of electrical power [40]. For biogas generators, it is expressed in m^3/kWh and given by the following equation [41]:

$$CS = a'P^2(t) + b'P(t) + c' \qquad (13)$$

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where:
• a', b' and c' are the generator constant characteristics.
• *P(t)* is the power generated at a given time by the generator.

The generator global efficiency expresses the biogas chemical energy conversion efficiency into electrical energy. Efficiency is directly linked to specific consumption by the following equation [41].

$$\eta_{GBio} = \frac{3600}{P_{CI}\, C_S} \tag{14}$$

where:
• P_{CI} (MJ/kg) is the biogas lower calorific value.
• C_S (g/kWh) is the generator specific consumption.

Photovoltaic generator modeling
The photovoltaic generator performance depends on the radiation, the temperature and the load to be supplied. The photovoltaic generator maximum output power is given by the following equation [42].

$$P_{mp} = \eta_{PV} A_{PV} G_S \tag{15}$$

where:
• P_{mp} is the generator maximum output power.
• A_{PV} is the photovoltaic generator area;
• G_S is the solar radiation.
• η_{PV} is the photovoltaic modules efficiency.

The photovoltaic modules efficiency is given by the following equation.

$$\eta_{PV} = \eta_{ref}\left[1 - \alpha\left(\frac{G_S}{18} + T_a - 20\right)\right] \tag{16}$$

where:
• η_{PV} is the photovoltaic modules efficiency.
• η_{ref} is the photovoltaic module reference efficiency.
• G_S is is the solar radiation.
• α is the temperature coefficient ($\alpha = 0.0042$).
• T_a is the ambient temperature.

Inverter modeling
An inverter input power is that produced by the photovoltaic generator. The inverter output power can be expressed from the inverter input power and the inverter efficiency according to the following equations.

$$P_{out} = \eta_{inv} P_{in} \tag{17}$$

with:

$$\eta_{inv} = \frac{p}{p + p_0 + kp^2} \tag{18}$$

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$$p = \frac{P_{out}}{P_n} \quad (19)$$

where:
•P_{out} is the inverter output power.
•P_{in} is the input power.
•η_{inv} is the inverter efficiency.
•p_0 and k are coefficients from manufacturer data.
•p is the reduced power.

Carbon dioxide emitted quantity
The photovoltaic field, in its operation does not produce greenhouse gases. In this study, the equivalent carbon dioxide (CO_2) is calculated by considering the biogas consumed and the gases emitted after combustion in generators, taking into account their global warming potential. CO_2 equivalent quantity is calculated using the following equation [43].

$$m_{CO_2\_equivalent\_i} = m_{CO_2\_i} + 3m_{CO\_i} + 25\, m_{CH_4} + 298\, m_{NO_x\_i} \quad (20)$$

where:
• $m_{CO_2\_i}$ is the mass of carbon dioxide.
• m_{CO_i} is the mass of carbon monoxide.
• m_{CH_4} is the mass of methane;
• $m_{NO_x\_i}$ is the mass of nitrogen oxide.

Technical and economic analysis
The pumped water cubic meter (m^3) cost calculation takes into account the investment, maintenance, operation, renewal updated costs, and the residual value of pumping system elements [44]. The water cubic meter (m^3) actual cost is given by the following formula.

$$C_{real} = \frac{\sum C_n + C_I - V_R}{D \cdot d} \quad (21)$$

where:
•C_{real} is the water cubic meter (m^3) actual cost.
• ΣC_n is the sum of pumping system operation, renewal, and maintenance up dated costs, during the project life.
• C_I is the initial investment cost.
• V_R is the pumping system residual value.
• *D is* the annual water needs (m^3/year).
• *d* is the project lifetime.

This study is carried out for 25 years project duration. The Homer software will be configured with the simulation parameters for each pumping system element (Table 5 to 10).

Table 5. Digester simulation parameters

Elements	Parameters	Value	Unit
Peak power	x_1	50.68	[kW]
Lifetime	n_{Dig}	25	[year]

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Acquisition coefficient 1	a_1	80601	[$/kW]
Acquisition coefficient 2	b_1	-0.479	[$/kW]
Maintenance coefficient	m_{PBio}	2	[%]
Operating coefficient	E_{PBio}	2	[%]

Table 6. Biogas generator simulation parameters

Elements	Parameter	Value	Unit
Peak power	x_2	32	[kW]
Lifetime	n_{GBio}	10	[year]
Acquisition coefficient 1	a_2	4747.9	[$/kW]
Acquisition coefficient 2	b_2	0.2925	[$/kW]
Maintenance coefficient	m_{GBio}	2	[%]
Maintenance coefficient 1	a_0	22.204	[-]
Maintenance coefficient 2	b_0	0.0049	[-]
Biogas consumption coefficient 1	a_6	3.8	[kg/h]
Biogas consumption coefficient 2	b_6	0.96	[kg/h]
Biogas cost coefficient	C_0	0.17	[$/m^3]
Maximum load	D_{max}	30.77	[kW]
Fixed load rate	β	80	[%]

Table 7. Photovoltaic generator simulation parameters

Elements	Parameters	Value	Unit
Peak power	x_3	8	[kW]
Lifetime	n_{PV}	25	[year]
Acquisition coefficient 1	a_3	5654	[$/kW]
Acquisition coefficient 2	b_3	0.03	[$/kW]
Maintenance coefficient	m_{PV}	2	[%]

Table 8. Inverter simulation parameters

Elements	Parameters	Value	Unit
Nominal power	x_4	10	[kW]
Life time	n_{OND}	20	[year]
Acquisition coefficient 1	a_4	1398	[$/kW]
Acquisition coefficient 2	b_4	0.27	[-]
Efficiency	η_{OND}	0.95	[%]

Table 9. Pumping system simulation parameters

Elements	Parameters	Value	Unit
Drilling lifetime	n_{For}	25	[year]
Drilling flow	Q_h	120	[m^3/h]
Pump nominal power	P_n	25	[kW]
Pump lifetime	n_{pom}	10	[year]
Total manometric height	H_{tm}	120	[m]
Acquisition coefficient 1	a_6	6465	[$/m^{3}h^{-1}]
Acquisition coefficient 2	b_6	0.49	[-]
Maintenance coefficient	η_{Dr}	2	[%]

Table 10. Discount rate

Elements	Parameters	Value	Unit
Inflation rate	i	3	[%]
Discount rate	a	8	[%]

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4. RESULTS AND DISCUSSIONS

The chosen sites for this study are those of Oudalan, Seno, Soum and Yagha located in the Sahel region of Burkina Faso. It is about increasing the access to water resources supply in Burkina Faso Sahelian region by exploiting aquifers groundwater and by using endogenous renewable resources, in particular photovoltaic solar and biogas as gaseous fuel in generator. The study is carried out for 25 years project duration.

Water needs and pumping analysis

The water needs profile for people, livestock and for irrigation at Oudalan, Seno, Soum and Yagha sites, in the Sahel region is determined and represented (Figures 2 to 5).

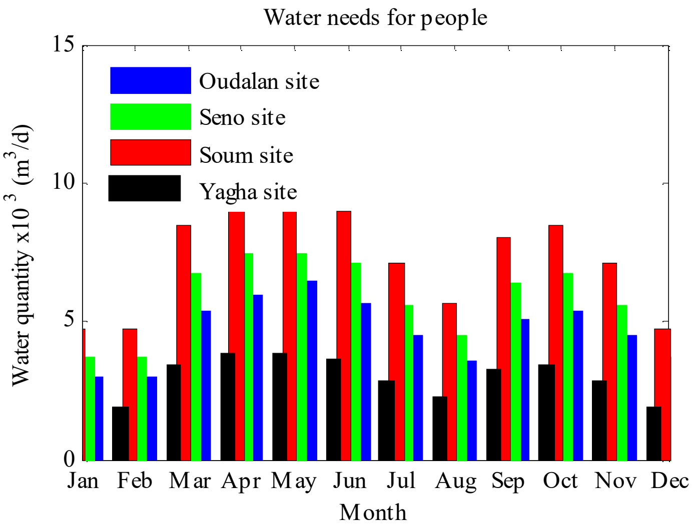

Figure 2: People water needs profile at studied sites

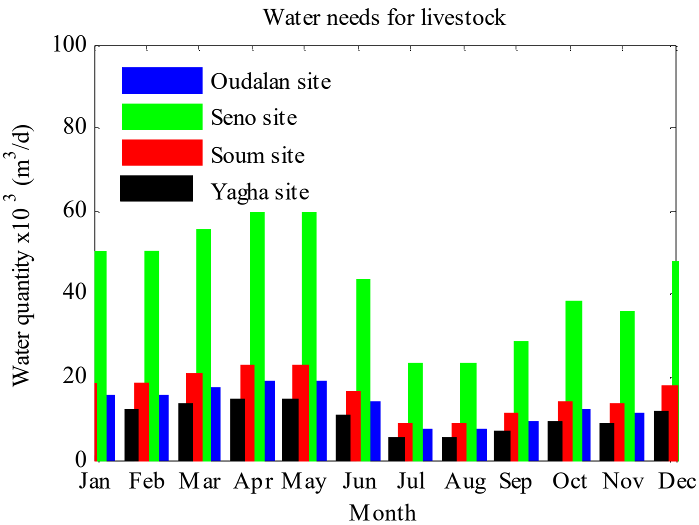

Figure 3: Livestock water needs profile at studied sites

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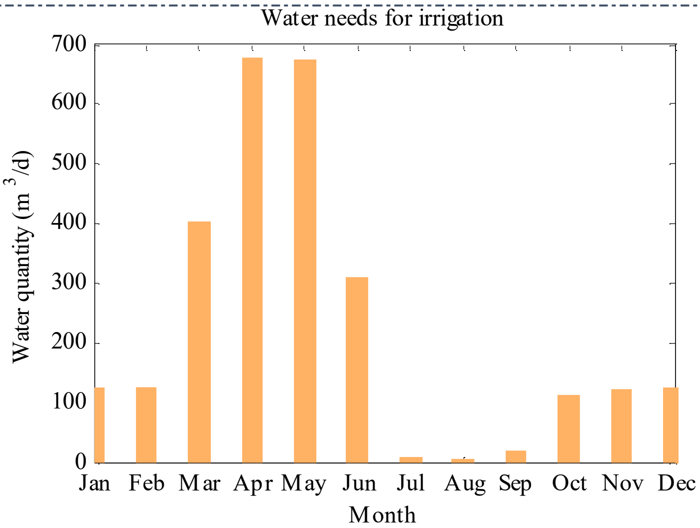

Figure 4: Water needs profile for palm irrigation at studied site

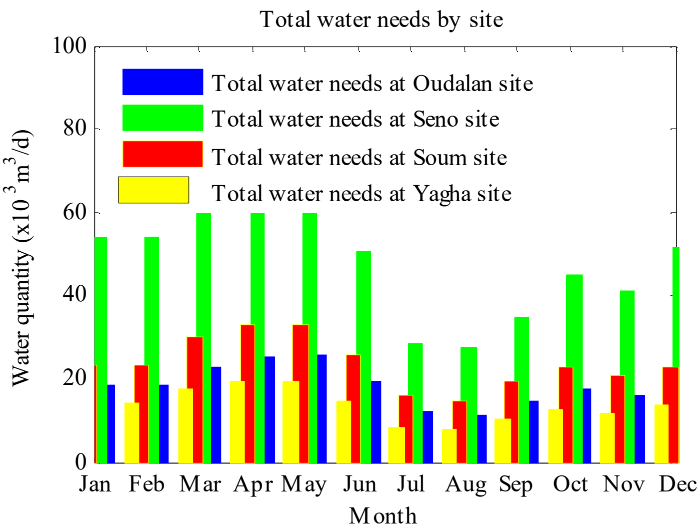

Figure 5: Monthly total water needs profile at studied sites

At Oudalan, Seno, Soum and Yagha sites, water needs for livestock is the greatest. This is explained by the fact that in the Sahel region the main activity is breeding and livestock number is very large. The Soum site has the highest people water needs. However, water needs for irrigation of 10 ha palm trees on each site are very low compared to livestock and people water needs. The bulk of the total water needs at each site is for watering livestock. At all four sites, water needs is very high in the year hottest months, from March to May. The maximum water needs is in May at the four sites. This maximum water needs values at Oudalan, Seno, Soum and Yagha sites are respectively: 25,866 m^3/d, 68,021 m^3/d, 32,899 m^3/d and 19,238 m^3/d. The biogas production potential is calculated in the four sites of the Sahel region.

Table 11. Biogas production in the four sites

	Oudalan	Seno	Soum	Yagha
Volume (m^3/d)	38114473	75816810	84048329	30389270
Weight (tons/d)	44213	87947	97496	35252
Energy (MWh/d)	231800	461090	511150	184820
Power (MW)	9658	19212	21298	7700

The four studied sites have very high biogas production potential. However, the Soum site has the highest biogas production potential. The animals number at this site explains this, which is higher than at other sites. Due to their geographic location, the studied sites have a huge solar deposit. The curve of best radiation at the four studied sites is that of March. This curve is used in this study to better understand the hybrid electric system dynamics. The solar radiation profile at the four sites is determined for this month.

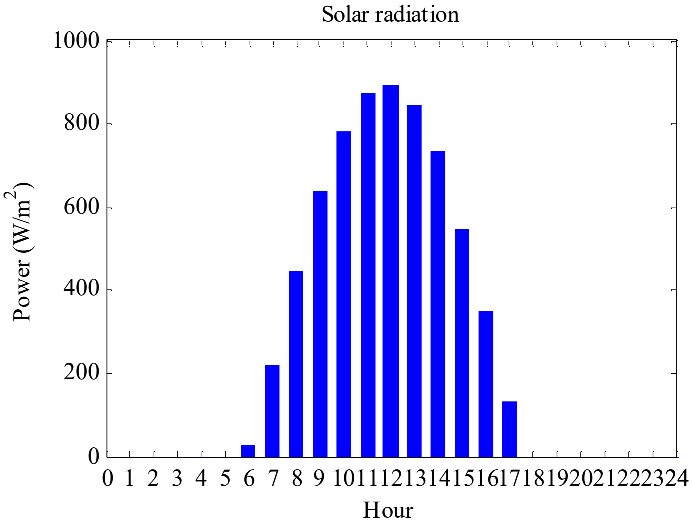

Figure 6. Solar radiation profile at each site

The daily solar radiation average is 5.5 kWh/m^2/d. The isolation time is 3,000 to 3,500 hours per year, with average producible estimated at 1,620 kWh.

Technical and economic analysis

The simulation is done with the Homer software. Homer software is a time series model that performs an hourly energy balance over year course for each system configuration entered by the user. In Homer, linear cost functions are adopted and components dimensions to be taken into account must be planned beforehand in order to carry out the optimization.

Optimal sizes of hybrid electrical systems generating elements and biogas-consumed quantity by generator are obtained by simulation in Homer software.

Table 12. Hybrid power plant elements optimal sizes

Site	Digester power (kW)	Generator power (kW)	PV field power (kW)	Inverter power (kW)	Biogas (tons/year)
Oudalan	1115	704	176	220	968739
Seno	2889	1824	456	570	2509915
Soum	1368	864	216	270	1188907
Yagha	811	512	128	160	704537

The highest digester power is found at Seno site, with 2888 kW power, while the smallest is at Yagha site, which registers 810 kW power. The same is true for hybrid system generating elements at all sites. Seno site records the greatest power of hybrid electric system. The pumping system number and their optimal sizes at each pumping site are calculated.

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Table 13. Pumping system number, water drilling and pump optimal sizes on each site

Site	Pumping system number (-)	Pump power (kW)	Pumping flow (m^3/h)
Oudalan	22	660	2640
Seno	57	1710	6840
Soum	27	810	3240
Yagha	16	480	1920

The maximum water needs on each site can be satisfied with water drilling equipped with three-phase electric pumps of 30 kW electric power, operating 10 hours a day, with 120 m^3/h hourly flow, at 120 m maximum total manometric height. The pumping system number is respectively 22, 57, 27 and 16 at Oudalan, Seno, Soum and Yagha sites. The pumping system optimal costs and pumped water m^3 cost at each site are recorded.

At Seno site, pumping systems number is more than double of pumping systems number at Oudalan and Soum sites and more than three times of pumping systems number at Yagha site. This difference is due to fact that the water requirement for the livestock at Seno site is three times higher than at three other sites (see figure 3). This induces a water demand of same order of total water demand at this site (see figure 5). It will take three to four times more electrical energy than at other sites to supply pumping systems at Seno site.

Table 14. Optimal pumping system cost and water m^3 cost

Site	Initial capital ($)	System cost ($)	Operating cost ($)	Maintenance cost ($)	Water m^3 cost ($)
Oudalan	788422	1487656	342904	370973	0.152
Seno	786573	1801980	661518	368861	0.184
Soum	785870	1480214	340907	368547	0.151
Yagha	788422	1487656	342904	370973	0.152

Simulation results gave water cost at four studied sites: 0.152 \$/m^3 at Oudalan site, 0.184 \$/m^3 at Seno site, 0.151 \$/m^3 at Soum site and 0.152 \$/m^3 at Yagha site. The finding is that the cost per m^3 of pumped water is roughly the same at Oudalan, Soum and Yagha sites. On the other hand, one m^3cost of water is higher at Seno site where it is worth \$ 0.184. A difference of approximately \$ 0.032 is observed between one m^3 cost of pumped water at Seno site and at other sites. This is explained by system cost and operating cost which are higher at Seno site, compared to these same costs at other three sites. Indeed, according to Table 14 results, the system cost is \$ 1,801,980 at Seno site against approximately \$ 1,488,000 on other three sites. That is a difference of about \$ 406,000. In addition, a difference of over \$ 310,000 exists between operation cost at Seno site and at other sites. These observed various differences in system cost and in operating cost led to a higher cost per m^3 of pumped water at Seno site. The kWh cost of electricity produced from renewable energies increases with hybrid electric system power. The electricity kWh cost is necessarily higher at Seno site, and consequently, a cost per m^3 of pumped water more expensive than at other sites.

Carbon dioxide emissions analysis
The biogas combustion in generators engines produces carbon dioxide, carbon monoxide, nitrogen oxide, unburned biogas that are greenhouse gases and polluting particles, which quantities are obtained by simulation in Homer software. Rejected greenhouse gases and polluting particles equivalent carbon dioxide (CO_2) quantities are calculated by considering the effect of each gas on global warming. The consumed biogas, gases emitted by generators and equivalent CO_2 avoided quantities on each site are calculated.

Table 15. Biogas consumed and gases emitted quantity

Site	biogas consumed CO_2 equivalent (tons)	Gases released CO_2 equivalent (tons)	CO2 equivalent avoided (tons)
Oudalan	24218480	10398	24208082
Seno	62747880	26940	62720939
Soum	29722680	12761	29709919

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Yagha	17613440	7562	17605878
Total	134302480	57663	134244818

All sites total CO_2 equivalent of biogas consumed by generators is one hundred thirty four million three hundred two thousand four hundred eighty (134,302,480) tons per year. This CO_2 quantity could have been emitted into atmosphere, if it had not been converted into electricity. CO2 equivalent quantity avoided is one hundred thirty four million two hundred forty-four thousand eight hundred and eighteen (134,244,818) tons per year.

5. CONCLUSION

This study main objective is to increase access to water resources offer, at lower cost, for daily needs on four sites in sahelian zone. The study consisted of assessing water needs for people, livestock and for irrigation. Then, optimizing a pumping system including stand-alone hybrid electrical system, using endogenous renewable energies, to produce the necessary electricity to pump groundwater to satisfy water needs at four sites. The simulation is carried out with data from four sites in the Sahel region of Burkina Faso. Simulation results gave 0.152 $/m^3 at Oudalan site, 0.184 $/m^3 at Seno site, 0.151 $/m^3 at Soum site and 0.152 $/m^3 at Yagha site.

Groundwater pumping system sizing optimization allowed to get very low cost per m^3 of water on four sites, compared to water cost charged by the national water supply company, which is on average of 1.65 $/m^3 for water needs quantities on studied sites. These highly competitive water cost can favor people water supply, livestock and irrigation activities development. The availability of water in quantity and at a lower cost will boost sustainable socio-economic development in Sahel region.

The biogas use in addition to solar as energy source for hybrid electrical system has made it possible to significantly reduce polluting and avoid one hundred thirty four million two hundred forty-four thousand eight hundred and eighteen (134,244,818) tons of CO_2 per year.

The expected socio-economic impact of this project is job creation in farming domain, in particular, installation and maintenance technician profession in electric pumping system, food self-sufficiency and local wealth creation through dates, grains and vegetables production.

The parameters similarity in the Liptako-Gourma area requires that this study results be applicable to this area, which covers a large part of Northeast of Mali, Northeast and East of Burkina Faso, and South of Niger as well as to whole Africa Sahelian zone.

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