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Sizing optimization of hybrid electric system composed of wind turbine and biogas generator for groundwater drainage in semi-arid zones: Case study of sahelian zone in Burkina Faso

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Abstract This paper focuses on techno-economic optimization of hybrid electric system for production of electricity necessary for pumping groundwater to satisfy daily needs of population and for watering livestock. Three sites were chosen for the study, namely Dori, Ouagadougou and Ouahigouya, all located in the semi-arid zone of Burkina Faso, in West Africa. Water needs assessment made it possible to size elements of hybrid electric system at each site. Techno-economic optimization is done by Homer software. The simulation results gave competitive kWh costs of 0.1926$ for Dori's site, 0.1917$ for Ouagadougou's site and 0.0611$ for Ouahigouya's site. These highly competitive kWh costs can promote water supply to population and livestock activities development in semi-arid zone of Burkina Faso. The hybrid electric system takes into account environmental consequences by calculating carbon dioxide equivalent before and after biogas upgrading into electricity in generators. Carbon dioxide quantity avoided is three hundred and seven thousand and fifty four (307054) tons per year.

Keywords Hybrid system, Electricity, Pumping, Optimization

1. Introduction

The water lack for population basic needs in semi-arid zone is an obstacle to their socio-economic development. As the rains are scarce in this area, surface water hardly exists. This forces herders and their livestock to migrate very often to agricultural areas in the south, in water and pasture search, especially during the hottest months of year [24]. This farm animals movement to host areas creates conflicts between farmers and herders. However, groundwater resources map in this area of Burkina Faso shows that studied sites are characterized by abundance of groundwater, with reservoir roof ranging from 10 to 100 meters deep [34]. Study carried out by several researchers has established that the reserves of fresh water stored in aquifers are much greater in arid regions and display resilience face to climatic variations and decrease in rainfall does not necessarily translate into decrease in groundwater reserves [10]. It is therefore possible to resolve the problem in this area, which is water control, in sustainable manner. But, pumping groundwater to great depths requires a lot of electrical energy. The electricity network does not exist or is located very far from this area, the conversion of endogenous renewable energies into electricity is considered for pumping in this study. Renewable energy potential assessment in semi-arid zone shows that it is favorable to establishment of energy systems based on solar, wind and biomass [7]. The semi-arid zone of Burkina Faso being breeding area with large herd, it has very high potential for biogas production from animal effluents. Biogas production or anaerobic digestion is innovative solution which makes it possible to recover breeding waste by producing renewable energy and fertilizers, while preserving environment [30], [36]. The use of hybrid electric system consisting of wind power and biogas generator to produce electricity needed to pump groundwater will solve guaranteed power problem and increase pumping time at same time reducing pumping system maintenance cost.

This work main objective is technical and economic optimization of hybrid electric system composed of wind turbines and biogas generator to provide the electricity necessary, at lower cost, for pumping groundwater in order to satisfy populations water needs and livestock watering.

2. Studied sites characterization

The present study concerns Dori, Ouagdougou and Ouahigouya sites located in Sahelian zone of Burkina Faso, in West Africa. This Sahelian zone is located between 13th and 15th parallel of northern latitude and covers approximately 35000 km² area [13].

Figure 1: Studied sites location

The studied sites correspond to given geographic coordinates.

Table 1: Geographical coordinates of the studied sites

Country	Sites	Longitude	Latitude	Altitude
Burkina Faso	Dori	0°03 West	14°03 North	282 m
	Ouagadougou	1°32 West	12°21 North	299 m
	Ouahigouya	2°25 West	13°35 North	339 m

Ouagadougou is capital and the largest city of Burkina Faso. Ouagadougou is located approximately in center of Burkina Faso, at full intertropical zone. Ouagadougou city covers 2805 km^2 area, with 2453000 inhabitants [15]. The city is subject to tropical savannah climate, comprising two seasons: dry season and rainy season. The dry season runs from mid-October to mid-May. The rainy season runs from end of May to end of September. The average temperature in Ouagadougou is 28.6 °C. Precipitation averages is 569 mm per year.

Ouahigouya city is in Northwest of Burkina Faso, capital of Yatenga province of North region in Burkina Faso. Ouahigouya city covers 491 km^2 area and has 124580 inhabitants [15]. Ouahigouya has dry and hot steppe climate, with 28.7 °C annual average temperature and rainfall of 599 mm per year.

Dori is town in the northeast of Burkina Faso, capital of Séno province, in the Sahel region. Dori city covers approximately 2532 km^2 area, with 46521 inhabitants [15]. The climate is Sahelian, hot and dry from March to June, rainy from July to October, cold and dry from November to February, characterized by drought long periods. The rainfall is irregular and lasts only about 3 months. Rainfall is around 567 mm per year [20].

Studied sites groundwater resources are those of Liptako-Gourma/Upper Volta aquifer system [2]. With approximately 159500 km^2 area, this aquifer covers large part of northeastern Mali, northeastern and eastern Burkina Faso, and southern Niger [3]. Breeding is the main socio-economic activity of Dori and Ouahigouya sites. Livestock is income source for more than 80% of Burkina Faso population and contributes 10% to Gross Domestic Product [22]. At three study sites, mainly animal husbandry concerns cattle, goats, sheep, donkeys, pigs, horses and poultry. Statistics from the Burkina Faso Ministry of Animal Resources give livestock number at study sites [22].

Table 2: Livestock numbers at study sites

Cheptel	**Sites**		
	Dori	**Ouagadougou**	**Ouahigouya**
Donkeys s	32133	47481	20293
Cattle	1149894	125347	170020
Camels	1408	0	109
Goats	1259787	244120	426141
Horses	8503	1404	2845
Sheep	610896	161607	345759
pigs	4355	149588	8837
Poultry	581466	1102689	768433

3. Material and method

Optimizing sizing of hybrid electric system using renewable energy sources involves evaluating daily water requirement, estimating the site's renewable energy potential as well as technical and economic analysis of hybrid electric system.

3.1. Water demand assessment

The assessment water quantity to be pumped per day concerns daily water needs for population and those for livestock watering. Daily water consumption per person, according to the World Health Organization standard is 10 to 20 liters in sub-Saharan Africa [23]. The project duration is 25 years, the project horizon is 2046. Population at project time horizon is given by the following equation [18]:

$$P_d = P_0 (1+\tau_c)^d \tag{1}$$

P_d is population at project time horizon (2046), P_0 current population (2021), τ_c locality population growth rate, d project duration (25 years).

The average daily water requirements (m^3/d) is given by:

$$D_{jm} = 1{,}1\left(\frac{C_s \cdot P_d}{1000}\right) \tag{2}$$

D_{jm} is average daily demand, C_S specific consumption (20 liters/day/individual), P_d individuals number at project time horizon (2046).

The daily peak demand (m^3/d) is given by:

$$D_{jp} = D_{jm} \cdot C_{pj} \cdot C_{ps} \tag{3}$$

D_{jp} is daily peak demand, C_{pj} daily peak coefficient generally between 1.05 and 1.15, C_{ps} seasonal peak coefficient generally between 1.1 and 1.2. Losses are estimated at 10% of average daily needs.

Specific allocation can be added according to project orientations for following needs at project start year: 3 liters/day/student, 5 liters per consultation for health structures, 20 liters/day/hospital bed, 0.3 m^3/day/market, 0.1 m^3/day/mosque.

Herd water demand depends on herd size, animal species, forage quality and climate [32]. Water needs are 40 liters/day for a Cattle or a horse, 51 liters/day for a sheep or a goat, 20 liters/day for a donkey and 20 liters/day for a camel (8 days reserve).

3.2. Daily electrical energy required for pumping

The daily electrical energy to be supplied for lifting a quantity of water is given by the following equation:

$$E_d = \frac{\rho \times Q_{water} \times g \times H_{tm}}{3600 \times \eta_G} = \frac{2{,}725 \times Q_{water} \times H_{tm}}{\eta_G} \tag{4}$$

E_d is daily energy required to lift water, ρ water density, g gravity acceleration, Q_{water} maximum water requirement, H_{tm} total manometric height, η_G overall efficiency, 2.725 conversion factor.

3.3. Evaluation of biogas production from livestock waste

Five types of animal droppings are considered in this study [33]. These are waste from pigs, cattle, goats, sheep and poultry. Digester sizing is made based on livestock number present at a site. Depending on animal species, heads number required for 1 m^3 of biogas production per day is given [16].

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

Species	Cattle	Pigs	Goats	Sheep	Poultry
Number	1	3	11	11	93

With livestock number on site, slurry quantity per day is calculated according to the following equation [14]:

$$Q_{slur} = 30\left(n_{ca} + \frac{1}{3}n_{pi} + \frac{1}{11}n_{sh} + \frac{1}{11}n_{ga} + \frac{1}{93}n_{po}\right) \quad (5)$$

Q_{slur} is the quantity of slurry available 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.

If we have livestock number at a given site, biogas volume per day (m^3/d) to produce can be estimated [31].

$$V_{Biogas} = n_{ca} + 3n_{pi} + 11n_{sh} + 11n_{go} + 93n_{po} \quad (6)$$

V_{Biogas} is biogas volume available 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 upgraded into electricity by generators, where it is used as gaseous fuel [9]. The digester power is calculated according to methane content in biogas and this biogas calorific value according to following equation [19], [6]:

$$P_{Dig} = \frac{t \times PCI_{100} \times V_{Biogas}}{24} \quad (7)$$

P_{Dig} is digester power, t methane content in biogas, PCI_{100} calorific value of 100% methane content in biogas, V_{Biogas} biogas volume per day.

3.4. Biogas generator modeling

Several parameters are used to describe biogas engines performance, including specific consumption and overall efficiency. The specific consumption is equal to biogas quantity consumed during one hour to produce 1 kW electric power [29]. For biogas generator, it is expressed in g/kWh or Nm^3/kWh [35].

$$CS = a' P^2(t) + b' P(t) + c' \quad (8)$$

CS is specific consumption, a', b' and c' genrator characteristic constants, $P(t)$ power generated at a given time by generator.

The overall efficiency of generator expresses efficiency of converting biogas chemical energy into electrical energy. It is directly linked to specific consumption [35].

$$\eta_{GBio} = \frac{3600}{PCI \cdot CS} \quad (9)$$

PCI is biogas lower calorific value, CS the generator specific consumption.

3.5. Wind potential assessment

To assess the wind potential at a site, it is necessary to express wind speed frequency distribution [21]. Weibull distribution is the most used and recommended in the literature to express wind speed frequency distribution [28]. In Weibull distribution, which is a special case of Pearson distribution, variations in wind speed are characterized by two functions: probability density function and cumulative distribution function [17]. Probability density function indicates the probability for which wind gave speed v.

$$f(v)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{10}$$

f(v) is probability density function, *c* Weibull scale factor, *k* Weibull form factor, *v* wind speed.
The Weibull cumulative distribution function gives fraction of time for which wind speed is less than or equal to *v*.

$$F(v)=\int_0^v f(v)dv=1-\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{11}$$

F(v) is Weibull cumulative distribution, *c* Weibull scale factor, *k* Weibull form factor, *v* wind speed.

3.6. Mean wind speed

The mean wind speed according to Weibull distribution is calculated.

$$\overline{V}=\int_0^{+\infty} v f(v)dv \tag{12}$$

f(v) is probability density function, *v* wind speed.

3.7. Available power density in wind

The available power density in wind per unit area swept by wind turbine blades is given by following expression [25]:

$$P_{dispo}=\frac{1}{2}\rho\int_0^{+\infty} v^3 f(v)dv \tag{13}$$

P_{av} is power density available in wind per unit area, ρ air density, *v* wind speed, *f(v)* probability density function.

3.8. Power density recoverable from wind

Based on Betz's limit, maximum recoverable power density from wind at a site becomes 16⁄27 of available power [25].

$$P_{Recup}=\frac{16}{27}P_{dispo} \tag{14}$$

The power supplied by wind turbine is given by following equation [25]:

$$P_u=\begin{cases}0 & v\le V_{start}\\ a+bv^k & V_{start}\langle v\langle V_{rat}\\ P_n & V_{rat}\le v\langle V_{stop}\\ 0 & v\ge V_{stop}\end{cases} \tag{15}$$

with: $a=\frac{P_n V_{start}^k}{V_{start}^k-V_{rat}^k}$ et $b=\frac{P_n}{V_{rat}^k-V_{stat}^k}$ (16)

V_{start} is starting speed, V_{rat} rated speed, V_{stop} machine stop speed, P_n nominal power.
Electrical output power average (P_{el}) is given by following expressions [12].

$$P_{el}=\int_0^{\infty} P_u f(v,k,c)dv \tag{17}$$

$$P_{el}=\int_{V_{start}}^{V_n}\left(a+bv^k\right)f(v,k,c)dv+\int_{V_n}^{V_{stop}} f(v,k,c)dv \tag{18}$$

3.9. Usable wind power

The average useful power is linked to machine output electrical power by ratio expressing transformation efficiency. Considering wind generator efficiency, average actually usable wind power is given by following equation [1]:

$$P_u = \eta P_{el} \tag{19}$$

P_u is average useful power of wind turbine, P_{el} average electrical output power

3.10. Quantity of carbon dioxide equivalent emitted

The wind farm, in its operation does not produce greenhouse gases. In this study, the amount of carbon dioxide (CO_2) equivalent is calculated by considering biogas consumed and gases emitted after combustion in generators, taking into account their global warming potential. CO_2 equivalent quantity is calculated using following equation [26]:

$$m_{CO_2\_équivalent\_i} = m_{CO_2\_i} + 3m_{CO\_i} + 25m_{CH_4} + 298m_{NO_x\_i} \tag{20}$$

$m_{CO_2\_équivalent\_i}$ is CO_2 equivalent quantity, $m_{CO_2\_i}$ carbon dioxide mass, m_{CO_i} carbon monoxide mass, m_{CH_4} methane mass, $m_{NO_x\_i}$ nitrogen oxide mass.

3.11. Technical-economic analysis

Technical and economic analysis includes capital cost, as well as costs present value of operation, maintenance and replacement of components over the expected project life. Discounting procedure takes into account the moment when an expenditure is made. Depending on whether the expenditure is current or non-current, the expenditure discount factor is expressed according to following equations, respectively:

$$PW(i,a,d) = \frac{\left(\frac{1+i}{1+a}\right)\left[\left(\frac{1+i}{1+a}\right)^d - 1\right]}{\left(\frac{1+i}{1+a}\right) - 1} \tag{21}$$

$$PW(i,\bar{a},d) = \frac{\left(\frac{1+i}{1+\bar{a}}\right)\left[\left(\frac{1+i}{1+\bar{a}}\right)^d - 1\right]}{\left(\frac{1+i}{1+\bar{a}}\right) - 1} \tag{22}$$

PW(i,a,d) is current expenditure discount factor, *PW(i,* $\bar{a}$ *,d)* non-current expenditure discount factor, *a* discount rate, $\bar{a}$ discount rate for non-current expenditure, *i* inflation rate, *d* project lifetime.

The discount rate for non-current expenditure is given by following relation:

$$\bar{a} = \frac{(1+a)^{nj}}{(1+i)^{nj-1}} - 1 \tag{23}$$

$\bar{a}$ is discount rate for non-current expenditure, n_j component *j* lifetime, *a* discount rate.

For residual values calculation, knowledge of component remaining service life is necessary. For a component *j*, the remaining service life is given by the following relation:

$$nr_j = n_j - \left[d - n_j FIX\left(\frac{d}{n_j}\right)\right] \quad (24)$$

nr_j is component j remaining lifetime, n_j component j lifetime, *FIX* Matlab function that rounds number down to next whole number, d project lifetime.

The discount facto of residual values during project lifetime is given by the following equation:

$$S(a,d) = \frac{1}{(1+a)^d} \quad (25)$$

$S(a,d)$ is discount factor, a discount rate, d project lifetime.

The discount factor for acquisition cost of component j is given by following equation:

$$A(a,n_j) = \frac{a(1+a)^{nj}}{(1+a)^{nj} - 1} \quad (26)$$

$A(a,n_j)$ *is* discount factor for acquisition cost, a discount rate, n_j is component j lifetime.

The updated maintenance cost of equipment is calculated using following equation:

$$C_{M-ac} = C_{M\_ini} * PW(i,a,d) \quad (27)$$

C_{M-ac} is updated maintenance cost, C_{M-ini} maintenance initial cost, $PW(i,a,d)$ is current expenditure discount factor.

The updated operating cost of equipment is calculated according to following equation:

$$C_{Op\_ac} = C_{Op\_ini} * PW(i,a,d) \quad (28)$$

C_{Op_ac} is updated operating cost, C_{Op_ini} operating initial cost, $PW(i,a,d)$ is current expenditure discount factor.

The updated replacement cost of equipment is calculated using following equation:

$$C_{R\_ac} = PW(i,\bar{a}_2,d)C_I \quad (29)$$

C_{R_ac} is updated replacement cost, $PW(i, \bar{a}, d)$ non-current expenditure discount factor, C_I investment cost.

The residual value V_{R_up} of equipment is calculated according to following equation:

$$V_{R\_ac} = S(a,d)\frac{nr}{n}C_I \quad (30)$$

V_{R_ac} is residual value, $S(a,d)$ discount factor, n operating time, n remaining lifetime, C_I investment cost.

Calculation of cost per kilowatt-hour (kWh) produced by hybrid electric system takes into account discounted costs of investment, maintenance, operation, renewal, and residual value of hybrid electric system elements [8]. The real cost per kilowatt hour (kWh) is given by the following equation:

$$C_{reel} = \frac{\sum C_n + C_I - V_R}{D \cdot d} \quad (31)$$

C_{reel} is real cost per kilowatt hour, ΣC_n hybrid system operation, renewal and maintenance discounted costs sum during project lifetime, C_I initial investment cost, V_R residual value of hybrid electric system, D annual electrical energy demand, d is project lifetime.

Homer software will be configured with the simulation parameters of each element of the hybrid electric system (see tables 4-7).

Table 4: Digester simulation parameters

Elements	Parameter	Value
Peak power (kW)	x_1	50.68
Life time (Years)	n_{Dig}	25
Acquisition coefficient 1 ($/kW)	a_1	80601
Acquisition coefficient 2 ($/kW)	b_1	-0.479
Maintenance coefficient (%)	m_{PBio}	2
Operating coefficient (%)	E_{PBio}	2

Table 5: Biogas generator simulation parameters

Elements	Parameter	Value
Peak power (kW)	x_2	32
Life time (Years)	n_{GBio}	10
Acquisition coefficient 1 ($/kW)	a_2	4747.9
Acquisition coefficient 2 ($/kW)	b_2	0.2925
Maintenance coefficient (%)	m_{GBio}	2
Maintenance coefficient 1 (-)	a_0	22.204
Maintenance coefficient 2 (-)	b_0	0.0049
biogas consumption coefficient 1(kg/h)	a_6	3.8
biogas consumption coefficient 2 (kg/h)	b_6	0.96
biogas cost coefficient ($/m^3)	C_0	0.17
Maximum load (kW)	D_{max}	30.77
Load rate (%)	β	80

Table 6: Wind farm simulation parameters

Element	Parameter	Value
Peak power (kW)	x_5	45000
wind turbine lifetime (An)	n_{TE}	20
Acquisition coefficient 1 ($/kW)	a_5	17465
Acquisition coefficient 2 (-)	b_5	0.973
Maintenance coefficient (%)	m_{TE}	2
Operation coefficient (%)	E_{TE}	2

Table 7: Discount rate

Element	Parameter	Value
Inflation rate (%)	i	3
Discount rate (%)	a	8

4. Results and discussions

The chosen sites for present study are those of Dori, Ouagadougou and Ouahigouya located respectively in North-East, Center and North-West of Burkina Faso, in West Africa. The work objective is to increase the supply of access to water resources by harnessing groundwater using biogas and wind as renewable energy sources. The study is being carried out for 25 years project duration.

4.1. Water demand profile

The water requirements for populations and livestock at each site are determined. The water demand profile at three study sites is shown (Figures 2 to 4).

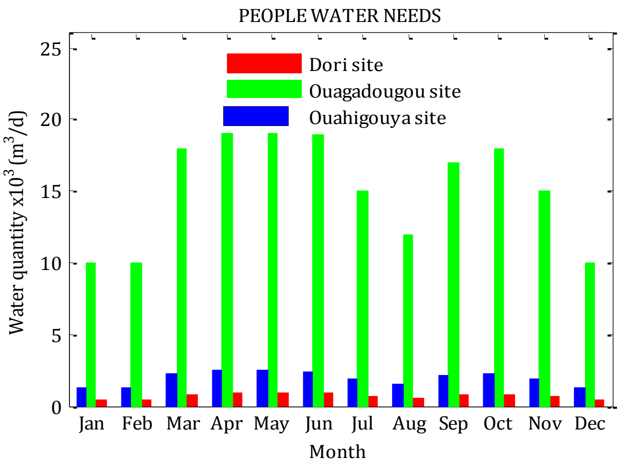

Figure 2: Water needs for population at each site

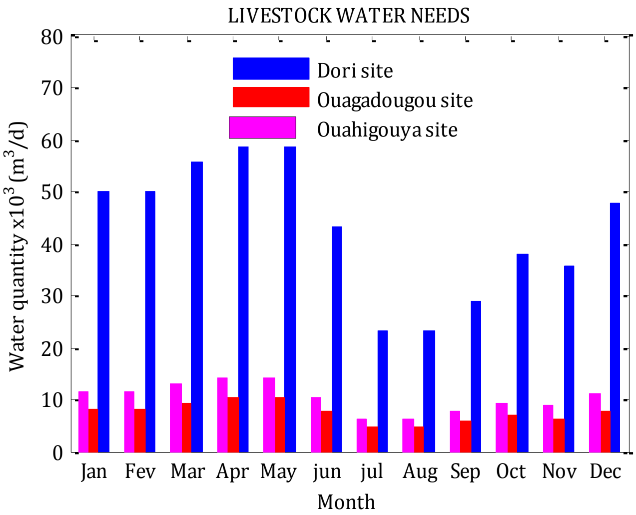

Figure 3: Water needs for livestock at each site

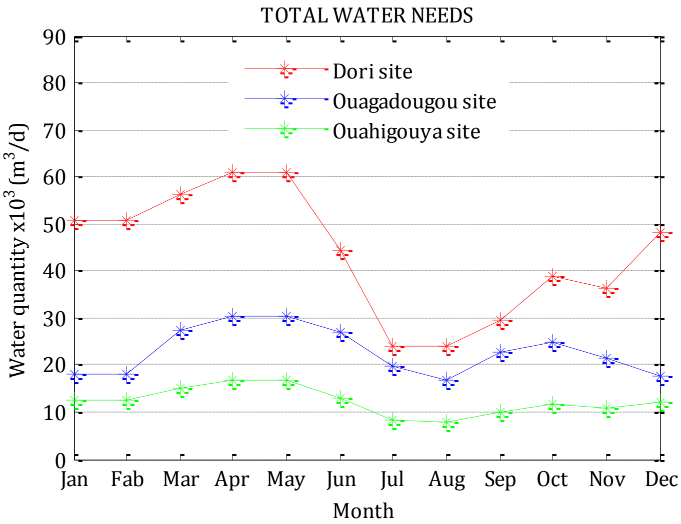

Figure 4: Total water needs at each site

For Dori, Ouagadougou and Ouahigouya sites, water need for watering livestock is greater for population water needs. This is explained by the fact that herd is very large and breeding activity requires much more water than daily needs of populations. The Dori site records the highest demand for livestock needs because livestock number is greater there. However, water demand for population at each site is very low compared to demand for livestock. Most of total water demand at each site is for livestock watering, because each individual has several farm animals. At all three sites, water demand is very high in the hottest months, from Marcs to May. The maximum total water demand is in May at the three sites. This maximum demand values are respectively 60,797.15 m^3/d for Dori site, 30,233.68 m^3/d for Ouagadougou site and 16,560.1 m^3/d for Ouahigouya site.

4.2. Evaluation of the amount of biogas

The potential of biogas production is calculated at the three study sites. The digester characteristics and quantity of biogas produced at each site are calculated.

Table 8: Digester characteristics and biogas quantity produced at each site

Characteristics	Site		
	Dori	**Ouagadougou**	**Ouahigouya**
Slurry Quantity (tons/day)	135710	92618	71155
Biogas volume (m^3/day)	1035400	258240	253990
Biogas quantity (tons/day)	1201	299560	294630
Digester power (kW)	262360	65438	64362

In view of large numbers of each species in the herd, the three studied sites have very high potential for biogas production. However, it is at Dori site that the highest biogas quantity production is observed, with value of 1035400 m^3/day. This is due to animals total number at this site, which is higher than at other sites.

4.3 Wind energy evaluation

The wind data used in this study are provided by National Direction of Meteorology of Burkina Faso [11]. These are results of three hourly observations of wind force and direction, from weather station at the three sites from 0 hour to 24 hours and 10 meters above the ground. Recordings are made daily, 3 hours apart, for 29224 measurements collected at each site over 10 years. The histograms of the measured wind speed distribution at Dori, Ouahigouya and Ouagadougou sites are shown.

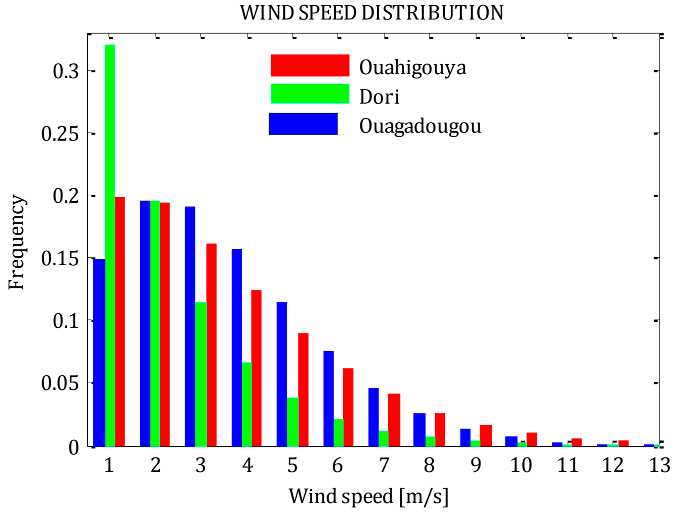

Figure 5: Wind speed distribution histogram at studied sites.

The observation in figure 5 is that wind speeds of less than 1 m/s (calm winds) are frequent at three sites. The frequency of calm winds is 0.35 for Dori site, 0.20 for Ouahigouya site and 0.15 for Ouagadougou site. The Weibull distribution shows that wind potential at three studied sites is low. However, Ouagadougou site has the best wind distribution among the three sites. Figure 6 represents recoverable power density at three studied sites at 10 meters height.

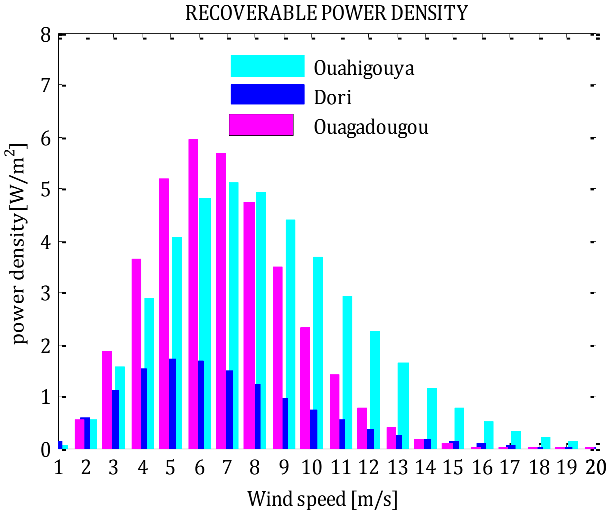

Figure 6: Recoverable power density from wind at three sites

The highest recoverable power density from wind is 6 W/m^2, recorded at Ouagadougou site. It occurs for a wind speed of 6 m/s. For Ouahigouya site, the greatest power density, about 5 W/m^2 is recorded at wind speed of 7 m/s. As for Dori's site, the highest power density is less than 2 W/m^2, recorded at wind speed of 5 m/s. These power densities at studied sites are consistent with their measured distributions of wind speeds at each site.

4.4 Technical economic analysis

The simulation is made with Homer software. Homer software is a time series model that performs an hourly energy balance along a year for each system configuration entered by user. In Homer, linear cost functions are adopted and dimensions of components to be considered must be planned in advance in order to achieve the optimization.

The maximum water demands at each site can be satisfied with boreholes equipped with electric pumps of 30 kW electric power, operating 10 hours per day, with of 120 m^3/h flow rate at maximum total manometric head of 120 m. The number of boreholes equipped with electric pumps with 120 m^3/h flow rate is 51 for Dori site, 25 for Ouagadougou site and and 14 for Ouahigouya site. The simulation with Homer software gives optimal sizes of hybrid electric system generators and consumed biogas quantity by generators at each site.

Table 9: Optimal sizes of hybrid electric system elements

Site	Digester power (kW)	Biogas generator power (kW)	Wind turbine power (kW)	Consumed biogas quantity (t/an)
Dori	3825	1913	306	15701.14
Ouagadougou	1875	938	150	7698.73
Ouahigouya	300	150	28	1231.14

The highest digester power is at Dori site, with 3825 kW power, while the smallest is at Ouahigouya site, which records 300 kW power. The same applies to hybrid electric system elements at all sites. It is Dori site that record the greatest power of hybrid electric system, because biogas generators power is the greatest. The optimal costs of the hybrid power system and the cost per kWh of electricity produced at each site are recorded.

Table 10: Optimal costs of hybrid electric system and electricity per kWh cost at each site

Site	Initial capital ($)	Operation cost ($)	Maintenance cost ($)	Renewal cost ($)	Residual value ($)	kWh cost ($)
Dori	2615400	1039100	2046700	3276	227910	0.1926
Ouagadougou	1295600	509550	1455300	3214	114250	0.1917
Ouahigouya	228380	81887	232910	3072	22241	0.0611

The simulation results gave $0.1926 per kWh at Dori site, $0.1917 per kWh at Ouagadougou site and $0.0611 per kWh at Ouahigouya site. The highest kWh cost is observed at Dori site, while Ouahigouya site has the lowest cost per kWh. Which gives difference of $0.1315. This difference in the cost per kWh between Dori site and that of Ouahigouya site is explained by the higher investment, operation and maintenance costs at Dori site than at Ouahigouya site. High costs are themselves inherent in the higher powers of digester, biogas generator and wind farm at Dori site.

4.5 Calculation of carbon dioxide equivalent

The amount of carbon dioxide (CO_2) equivalent is calculated by considering effect of each gas on global warming. The quantities of biogas consumed, gases emitted by biogas generators and equivalent CO_2 quantity avoided at each site are calculated.

Table 11: Biogas consumed and gases emitted quantity by biogas generators

Site	CO_2 equivalent of biogas consumed (tons/year)	CO_2 equivalent emitted (tons/year)	CO_2 equivalent avoided (tons/year)
Dori	196576	843	195733
Ouagadougou	96387	413	95973
Ouahigouya	15413	66	15348
Total	**308376**	**1322**	**307054**

The CO_2 equivalent of total biogas consumed for biogas generators operation at studied sites is three hundred eight thousand three hundred seventy six (308376) tons per year. This CO_2 quantity could have been emitted into the atmosphere, if it had not been converted into electricity. The CO_2 equivalent quantity avoided is three hundred seven thousand fifty four (307054) tons per year.

5. Conclusion

The objective of this study is to increase access to electricity supply for pumping groundwater in semi-arid zones. The study consisted of evaluating water needs for population and livestock, then optimizing sizing of autonomous hybrid electric system composed of wind turbines and biogas generators, to produce necessary electricity for pumping groundwater. The simulation was carried out with data from three sites in semi-arid zone of Burkina Faso. The simulation results gave $0.1926 per kWh at Dori site, $0.1917 per kWh at Ouagadougou site and $0.0611 per kWh at Ouahigouya site. Optimizing hybrid electric system sizing resulted in very low kWh electricity costs at all three sites.

Upgrading animal waste into biogas, used as gaseous fuel, has significantly reduced cost of electricity needed to pump groundwater. Biogas used in addition to wind as energy for the hybrid electric system has made it possible to significantly reduce polluting and greenhouse gas emissions. The expected socio-economic impact of this project is jobs creation in farming fields in particular, but also in profession of hybrid electric system installation and maintenance technicians.

The similarity of Sahelian zone parameters requires that results of this study be applicable to whole of Burkina Faso, as well as to whole West Africa arid zone.

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