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Analysis of the Complementarity Between Solar and Wind Energy in the Perspective of Installing a Hybrid System: Case Study in the Sahel of Burkina Faso

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Abstract: In this study, interest is focused on the complementarity of solar and wind energy, in order to assess the profitability of a hybrid renewable energy system that can be installed at three sites located in Burkina Faso, in West Africa. An analysis of the relationship intensity that may exist between the temporal and energy variations of solar and wind sources has been carried out. The assessment of the complementarity between solar and wind energy at the studied sites is carried out using the Pearson correlation coefficient, the ratio between the annual value of wind and solar energy and coupling coefficient at the three sites. The results obtained show that the values of the Pearson coefficient are positive and almost equal to zero on the three sites. There is no correlation along the time between the quantities of the two energy sources. In addition, the positive and very close to zero values of the ratio and coupling coefficient at the three sites show that a low wind potential characterizes the studied sites. The sites studied do not present an interesting complementarity between solar and wind energies. For the studied sites Solar/wind energy hybridization is not part of a great economic interest. The study carried out shows that it is not interesting to operate a photovoltaic/wind system on these sites.

Keywords: Solar Energy, Wind Energy, Pearson Coefficient, Energy Complementarity, Hybrid System

1. Introduction

The conversion of renewable energy to electricity appears to be the miraculous solution to the problems caused by the overexploitation of fossil fuel reserves. Inexhaustible on human scale, the conversion of renewable energies into electricity produces less impact on the environment than fossil fuels. Environmental concerns and the announced exhaustion of fossil fuels position renewable energy technologies as a good candidate compared to conventional energy sources [1]. Among the renewable energies most in demand are the photovoltaic and wind [2]. However, the intermittent nature of their availability is often an obstacle to their massive use, particularly on isolated sites. In order to solve this problem, the concept of hybrid system was introduced. The hybrid system for electricity production, in its most general view is one that combines and exploits several available sources and easily mobilized [3]. It consists of the combination of two or more complementary technologies in order to increase the supply of electricity through better availability. The electricity production from hybrid system using renewable energy sources is of great interest for developing countries [4]. Hybrid systems are an excellent solution for the electrification of rural areas where the extension of the network is difficult and unprofitable and also for the production and injection of excess electrical power into the electrical network [5]. Hybrid systems can be economical solutions for power generation systems by reducing investment costs [6]. Electricity production by a hybrid combining solar and wind energy is an interesting solution for isolated sites with significant wind and solar potential. It allows the continuous supply of electricity to the load and to reinforce the autonomy of the system in energy, which leads to an efficient and profitable hybrid system [7, 8]. The coupling of photovoltaic-wind system can be very interesting in terms of ecological and economic development, when wind and sunshine are available on a given site [9]. Periods of the year with low insolation correspond to those with better wind potential [10]. It is therefore obvious that a complementarity between solar and wind energy is desirable, especially since the coupling of these two energy sources is the most reliable and least expensive solution for autonomous hybrid systems of electrification [11]. A variation of solar and wind energy in opposite directions is desirable so that the absence of one of the two sources of energy is filled by the abundance of the other. This condition is particularly important when no energy storage system is integrated into the hybrid system. In addition, the analysis of the energy complementarity between the energy sources is important for such a hybrid system. As greater is this complementarity, more the sources complement each other and the higher is the electricity production of the hybrid system. From this perspective, This paper presents a study of the complementarity of solar and wind energy for a hybrid renewable energy system at the sites of Dori, Ouagadougou and Ouahigouya, located in Burkina Faso, West Africa. The objective of this study is to analyze the intensity of the relationship that may exist between solar and wind energy, in order to optimize the design of hybrid photovoltaic/wind systems. The objective of this study is to analyze the intensity of the relationship that may exist between solar and wind energy on three sites, with a view to seeing the possibility of installing photovoltaic/wind hybrid systems.

2. Characterization of the Studied Sites

The study concerns the sites of Dori, Ouagadougou and Ouahigouya located in the Northwest of Burkina Faso in the Sahelian zone. The Figure 1 shows the location of the studied sites [12].

The Table 1 gives the geographical coordinates of the sites studied.

Table 1. *Geographical coordinates of the studied site.*

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

The climate of these sites is of the Sahelian type, characterized by long periods of drought and irregular rainfall. The rainy season lasts only about 4 months in the year and the average annual rainfall is between 300 and 600 millimeters. Solar energy is the most abundant endogenous resource in Burkina Faso. Numerous studies allowed to analyze and quantify the solar resource available to this country.

Figure 1. *Location of the studied sites on Burkina Faso map.*

3. Methodology

For the study of the complementarity between solar and wind energy sources, three sites were chosen across Burkina Faso. In order to analyze the temporal and energetics complementarities between the solar and wind energy sources on these sites, it was necessary to collect data on the global daily radiation on horizontal surface and the wind speed at height of 10 meters level above ground.

The wind speed and solar radiation data for the sites studied were provided by the General Direction of Meteorology of Burkina Faso [13]. Daily values of wind speed were not available; three-hourly values from 10 years of collection, measured at height of 10 meters, are used in this study.

For solar data, daily values of a typical annual profile obtained from 10 years data were used in our calculations [14]. These wind and sunshine data made it possible to calculate and analyze temporal and energetics correlation coefficients between solar and wind energy sources. Solar radiation is expressed per unit area on the ground. The energy recovered from the wind is expressed per unit area swept through the air by the blades of a wind turbine. If these two energies cannot be placed on the same plane, an analysis of the complementarities that exist between them is possible.

3.1. Solar Energy Calculation

The solar deposit can be defined as the amount of solar radiation received by a surface for a certain period of time.

The direct insolation on a plane perpendicular to the solar radiation can be estimated using the following equation:

$$I = 1370\exp\left[-\frac{T_L}{0{,}9 + 9{,}4\sin(h)}\right] \tag{1}$$

I is the direct insolation on a plane perpendicular to the solar radiation, T_L is the Linke haze factor and h is the height of the sun.

The direct illumination on a horizontal plane is given by:

$$S = I \sin(h) \tag{2}$$

S is the direct illumination on a horizontal plane, I is the direct sunshine on a plane perpendicular to the solar radiation, h is the height of the sun in the sky.

Diffuse illumination is calculated by:.

$$D = 54{,}8\sqrt{\sinh}\left(T_L - 0{,}5 - \sqrt{\sinh}\right) \tag{3}$$

D is the diffuse illumination, h is the height of the sun in the sky.

The global illumination on a horizontal plane, is the sum of the diffuse and direct illumination, it is given by:

$$G=S+D \tag{4}$$

G is the global illumination on a horizontal plane, D is the diffuse illumination, S is the direct illumination on a horizontal plane.

The solar energy received on a horizontal surface is calculated by:

$$E_{sol}=G\times I_{ins} \tag{5}$$

E_{sol} is the solar energy received on a horizontal surface, G is the global radiation, I_{ns} is the insolation.

3.2. Wind Energy Calculation

The wind speed measurements in this study are taken at airports and the ground roughness is of the open country type, i.e. r_0 = 0.07 m [15]. The wind power density expresses the wind power available per unit area swept by the blades of the wind turbine. It is given by the following equation [15]:

$$P_{win,avg} = \frac{1}{2}\rho V_{avg}^3 \tag{6}$$

$P_{win,avg}$ is the wind power density, ρ is the air density, V_{avg} is the average wind speed.

The average wind energy density is the energy available per unit area, swept by the blades for a duration Δt and can be calculated according to the following relationship [16]:

$$E_{win,avg} = P_{win,avg}\times\Delta t \tag{7}$$

$E_{win,avg}$ is average wind energy density, $P_{win,avg}$ is the wind power density.

3.3. Complementarity and Temporal Simultaneity Between Solar and Wind Energy

In order to analyze the complementarity and temporal simultaneity between solar and wind energy, it is necessary to quantify the complementarity between wind energy and solar energy for the three sites. It is then necessary to calculate the correlation coefficient between the average daily wind and solar energies of each month [17]. The Pearson coefficient was calculated to quantify the temporal simultaneity of solar and wind sources. It is given by following relationship:

$$C_p = \frac{\sum_{i=1}^{12}\left(E_{win,i} - \overline{E}_{win,i}\right)\left(E_{sol,i} - \overline{E}_{sol,i}\right)}{\sqrt{\sum_{i=1}^{12}\left(E_{win,i} - \overline{E}_{win,i}\right)^2\left(E_{sol,i} - \overline{E}_{sol,i}\right)^2}} \tag{8}$$

With:

$$\overline{E}_{sol,i} = \frac{1}{n}\sum_{1}^{n} E_{sol,i} \tag{9}$$

$$\overline{E}_{win,i} = \frac{1}{n}\sum_{1}^{n} E_{win,i} \tag{10}$$

Cp is the Pearson coefficient, $E_{sol,i}$ and $E_{win,i}$ are the values of daily densities of solar and wind energies in month i, $\overline{E}_{sol,i}$ and $\overline{E}_{win,i}$ are the average densities values of solar and wind energies in day *i*.

Possible values for the Pearson's coefficient can be between -1 and 1. A good complementarity between the two forms of solar and wind energy corresponds to the negative Pearson's correlation coefficient, the closest to «-1». While a value of the Pearson coefficient close to «+1», confirms that the potentials of the two forms of energy vary in the same direction. When the value of the Pearson coefficient is close to 0, the intensity of the linear relationship is weaker.

For a hybrid PV/wind system without storage, which directly supplies the load demand, the Pearson coefficient must be negative and close to the value -1 for it to have good complementarity between renewable energies.

3.4. Energy Complementarity Between Solar and Wind Power

To analyze the relationship between the energy contained in the wind and that of incident solar radiation on a horizontal surface for a full year, another factor is calculated with:

$$R_e = \frac{E_{win,avg,year}}{E_{sol,avg,year}} \tag{11}$$

$E_{win,avg,year}$ is the annual average density value of wind energy, $E_{sol,avg,year}$ is the annual average density value of solar energy.

In order to couple the analyzes of time and energy complementarities between solar and wind, a new coefficient R*p* which takes into account the values of the temporal complementarity coefficients C_P and the energetics complementarity R_e is calculated with:

$$R_p = C_p\times R_e \tag{12}$$

For a hybrid photovoltaic/wind system, more the value of R_p, is negative, more the site is suitable for the use of a hybrid system without storage. For positive value of R_p, hybrid system with storage will be adopted.

4. Results and Discussions

The objective of this study is to analyze the intensity of the relationship that may exist between solar and wind energy, in order to optimize the design of hybrid PV-wind systems.

4.1. Solar Radiation Calculation

Depending on the geographical location of the three sites studied, the characteristics of solar radiation are almost identical. The Table 2 presents the characteristics of the solar radiation calculated from the meteorological data of the sites.

Table 2. *Characteristics of solar radiation at the studied sites.*

Month	Solar radiation (W/m^2)	Sunstroke (hour)	Irradiation (kWh/m^2.m)	Link's disorder (-)
January	5199.97	9.62	50.04	0.59
February	6030.11	9.81	59.18	0.63
March	6474.75	9.70	62.78	0.62
April	6589.93	9.09	59.90	0.60
May	6590.03	9.47	62.41	0.60
June	6249.93	9.22	57.65	0.56
July	5970.26	8.36	49.90	0.52
August	5629.84	6.30	35.47	0.51
September	5780.00	8.27	47.78	0.53
October	5810.29	9.37	54. 7	0.58
November	5359.73	9.66	51.76	0.57
December	5024.19	9.25	46.50	0.57
Annual	5892.42	9.01	53.15	0.57

The insulation average value is around 9 hours per day. The monthly sunshine average is 53 kWh per square meter. The insulation time is 3,000 to 3,500 hours per year, with an estimated average yield of 1,620 kWh per kWp installed. The Link's disorder monthly average is 0.57.

The Figure 2 shows the variation in the monthly average value of the solar radiation power density at studied sites.

The highest solar radiation value is in the period from March to May, with a value reaching 6 kW per square meters and per day for the three studied sites (Figure 2).

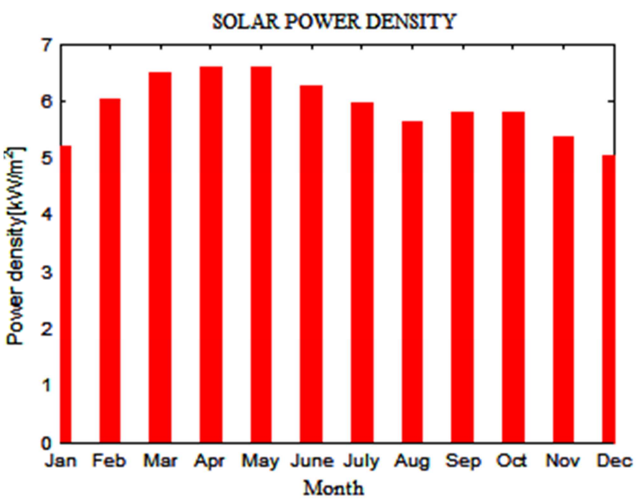

Figure 2. *Power density of solar radiation.*

4.2. Evaluation of the Wind Potential at the Three Sites

Monthly average of wind speeds at 10 meters altitude at the three sites were calculated. The Figure 3 shows the average monthly wind speeds at 10 meters altitude at the three sites.

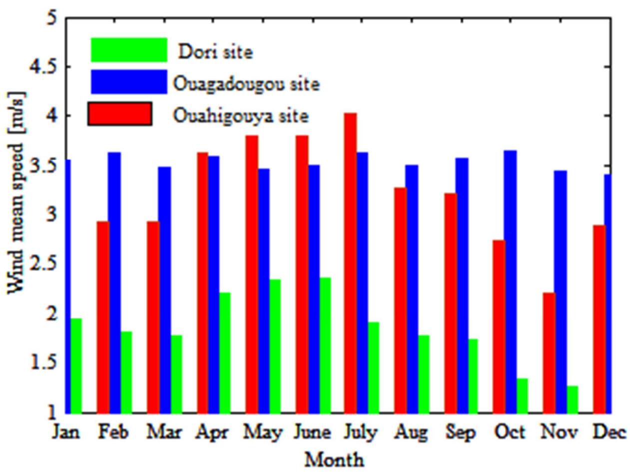

Figure 3. *Monthly average of wind speed at the three sites.*

The wind speed has a maximum value of 4.63 m/s at Ouahigouya in June, while the minimum wind speed of 1.26 m/s is recorded in November at Dori. The minimum annual average wind speed is observed at Dori, with a value of 1.85 m/s, while the maximum annual average wind speed is recorded at Ouagadougou with value of 3.53 m/s. From the monthly averages and the distribution of the wind speed, it can be seen that the monthly averages of the wind speed are less than 4 m/s at 10 meters from the ground, except for the months of June and July at Ouahigouya site. The studied sites are therefore not windy enough. The Figure 4 gives the values of the recoverable power of wind at the three sites.

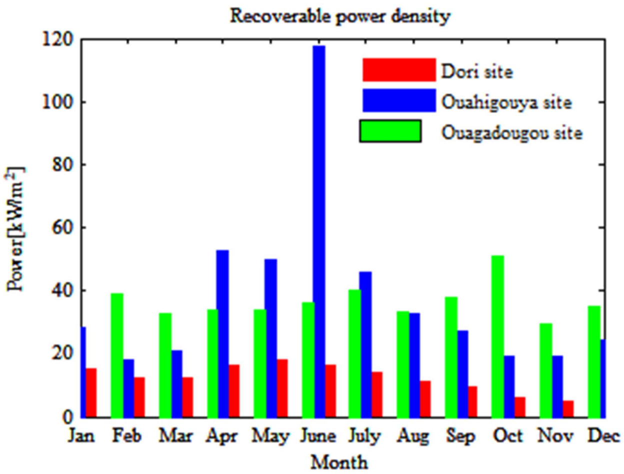

Figure 4. *Recoverable wind power at the three sites.*

The maximum value of the monthly average of recoverable power density of 115.86 W/m^2 is recorded at Ouahigouya in June at 10 meters altitude. While, the minimum value of 4.90 W/m^2 is recorded at Dori in November. The maximum value of the annual average recoverable power density of wind energy, at 10 m altitude of 42.10 W/m^2 is recorded at Ouahigouya, while the minimum value of 12.77 W/m^2 is recorded at Dori. The annual average of recoverable power density estimated at Ouagadougou is 36.40 W/m^2. The power density values at Ouagadougou and Ouahigouya are significantly better than those at Dori.

4.3. Complementarity Between Solar and Wind Energy

The Table 3 shows the power densities of solar and wind energy at the three sites studied.

Table 3. *Power densities of solar and wind energy at the three sites.*

Month	Dori site		Ouagadougou site		Ouahigouya site	
	Solar power density (W/m^2)	Wind power density (W/m^2)	Solar power density (W/m^2)	Wind power density (W/m^2)	Solar power density (W/m^2)	Wind power density (W/m^2)
January	5199.97	14.71	5199.97	35.70	5199.97	27.63
February	6030.11	12.18	6030.11	38.23	6030.11	17.68
March	6474.75	11.71	6474.75	31.96	6474.75	20.59
April	6589.93	16.07	6589.93	33.21	6589.93	51.88
May	6590.03	17.42	6590.03	33.06	6590.03	48.72
June	6249.93	16.16	6249.93	35.40	6249.93	115.86
July	5970.26	13.63	5970.26	39.38	5970.26	44.97
August	5629.84	10.60	5629.84	32.73	5629.84	32.31
September	5780.00	9.39	5780.00	37.11	5780.00	26.44
October	5810.29	5.71	5810.29	48.69	5810.29	18.58
November	5359.73	4.90	5359.73	28.97	5359.73	18.94
December	5024.19	9.74	5024.19	34.57	5024.19	23.67
Annual	5892.42	11.85	5892.42	35.75	5892.42	37.27

The power density of solar energy is greater than wind energy at all three sites. In addition, these sites are characterized by low wind potential. The analytical quantification of the complementarity between solar and wind energy at the studied sites is carried out using the Pearson correlation coefficient C_p, the ratio coefficient R_e and the product of coefficients R_p. The Table 4 gives the result of the calculations.

Table 4. *Values of parameters Cp, Re and Rp.*

Site	C_P	R_e	R_P
Dori	0.0721	0.4972	0.0358
Ouagadougou	0.0324	0.1648	0.0053
Ouahigouya	0.0676	0.1581	0.0107

The calculated values of these parameters (Table 4) shows that the power densities of solar energy are much greater than those of wind energy at the three sites.

The low calculated value, 0.4972, 0.1648 and 0.1581 of the ratio R_e, respectively for the sites of Dori, Ouagadougou and Ouahigouya shows that a low wind potential characterizes the studied sites.

For a photovoltaic/wind hybrid system without storage, which supplies a load directly, the Pearson coefficient must be negative and close to the value « -1 ». The positive value of the calculated Pearson correlation coefficients (C_P), 0.0721, 0.0324 and 0.0676, respectively for the sites of Dori, Ouagadougou and Ouahigouya shows that the densities of solar and wind energy vary in the Same direction. This means that there is not a good complementarity between these two forms of energy at the studied sites. The Pearson coefficient value is almost equal to zero. In this case, there is no correlation in time between the quantities of the two energy sources.

The R_p values of 0.0358, 0.0053 and 0.0107 respectively for the sites of Dori, Ouagadougou and Ouahigouya are positive and very close to zero on three sites. This indicates that the installation of hybrid photovoltaic/wind system, without storage at these studied sites is not appropriate.

5. Conclusion

This work consisted in analyzing the time and energy complementarities between the solar energy and the wind energy at three sites located in Burkina Faso, using daily data collected. The complementarity and temporal simultaneity between solar energy and wind energy were analyzed using the Pearson coefficient C_P and energy complementarity with the coefficients R_e and R_P.

In view of the obtained values from the Pearson coefficients and the two other coefficients, there is neither complementarity nor temporal simultaneity, nor energy complementarity between solar energy and wind energy on these sites. The sites studied are not suitable for installing a hybrid system without storage. For the studied sites, solar/wind hybridization is not of great economic interest, as the energies density of the two energy sources vary in the same direction. In addition, there is the low wind potential that characterizes the sites studied since the maximum monthly average wind speed does not exceed 4 m/s. This is almost equal to or less than the starting speed of the majority of industrial wind turbines.

The study carried out suggests the exploitation of a single form of energy at a time, at these sites. The choice between the installation of one of both solar or wind energy sources requires a technical and economic study in order to select the most profitable solution.

For the studied sites, all located in the Sahelian zone in Burkina Faso, it is not recommended to install a hybrid photovoltaic/wind system without storage.

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