Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering
15 (1) (2023) 0039~0049

*Research article*

# Estimation and mapping of the global component of solar radiation and wind power density over Chad

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(Manuscript Received --- 08 Jan. 2023; Revised --- 25 Feb. 2023; Accepted --- 08 Mar. 2023)

**Abstract**

Despite its very good potential of Chad in the field of wind and solar energy, very few studies have been conducted in the field of evaluation and estimation of these energies. Therefore, in order to develop the exploitation of these resources, for the first time, finding suitable places for the construction of wind and solar power plants has been done to help the decision-makers in the field of energy in Chad. The purpose of this work is to establish a solar map and the wind map of Chad using the geographic information system (GIS). ArcMap software was used to draw GIS maps, and determining the amount of radiation and wind speed in the neighboring points of the investigated stations was done using the Inverse Distance Weighted (IDW) method. Weibull distribution function was used to estimate wind power density and three analytical methods were used to estimate solar radiation. By comparing the different values of solar radiation, the lowest value was in N'Djamena (5.74 kWh/m$^2$/day) and the highest in Abeche (6.35 kWh/m$^2$/day). It turns out that the windiest site is Faya-Largeau located in the Saharan area with a value of 28.61 W/m$^2$. However, in the Sahelian zone, the wind density of Bokoro is the lowest at 3.16 W/m$^2$. Based on the results, the resource maps showing the wind power densities and solar irradiation over the entire regions of Chad were developed. Thus, the exploitation of solar energy seems favorable to meet the deficit in energy needs, and the use of technology namely wind turbines is desirable.

*Keywords:* Angstrom-Prescott method, Allen method, Sabbagh method, Saharan zone, Sahelian zone, Sudanese zone.

## 1- Introduction

The geographic information system (GIS) is a tool that has been used over the years to focus on ways of identifying the possible location of potential climatic or weather variables. Its use has helped to improve geographic variable analytics since the advent of technology in the 1980s [1]. Thus, various researchers have used GIS technology to determine the wind speeds and solar irradiance at a location to know the potential electricity production in Afghanistan, China, and Iran [2-4]. In India, it was used to map the solar power potential over Karnataka state [5], while Voivontas *et al*. [6] employed it to determine the spatial solar potential and its time fluctuations vis-à-vis the energy demand in Greece. Similarly, Gadsden *et al*. [7] demonstrated the application of the GIS for planning and forecasting solar power demand for domestic water heating in the city of Leicester, United Kingdom, while Johnson and Armanino [8] focused on the GIS solution for solar rooftop estimation in Marin, California. In addition, Simao *et al*. [9] employed the GIS technology for collaborative "web-based participatory wind energy planning" for Norfolk in East Anglia, England. Also, Voivontas *et al*. [10] carried out the assessment of wind energy potential using a GIS decision support system. It developed a GIS database of wind, topography, and location and employed the same for the mapping of the renewable energy resource potential and economic viability of adoption in the studied area. Thus, several research results exist that have demonstrated the suitability of GIS tools for renewable energy resource potential analysis, prediction, and spatial location identification. Choi et *al*. [11] mapped solar radiation based on GIS including potential assessment and site assessment. Thus, it is to elucidate the role of GIS as a problem-solving tool in relation to solar photovoltaic energy systems. Abdulaziz et *al*. [12] focused their study on the optimal identification of the site of a solar power plant using GIS and remote sensing for the Al-Qassim region. The result showed that the suitable areas are in the southwest and south of the region and account for about 17.53%. Nower et al. [13] based their study on solar basin mapping by GIS and analytical hierarchy process in Egypt. Based on the survey, it was concluded that AlWadi Al Jadid Governorate and some spatial areas shown in the mapping satisfy the renewable energy potential. For solar power systems in Mongolia, Uranchimeg et al. [14] did a GIS-based analysis. They obtained respectively poor (1.08%), weak (42.59%), good (3.27%), and average (53.06%) results. For the GIS-based multi-criteria decision-making method, Lijian et al. [15] used GIS for the selection of suitable sites and the evaluation of the potential of PV and CSP plants. Thus, the results obtained suggest that the middle area of Ningxia is recommended for the deployment of the solar power plant. Thus, several research results exist that have demonstrated the relevance of GIS tools for the analysis of the potential of renewable energy resources, the prediction, and the identification of the spatial location. In addition, based on the available research results, there has not yet been a comparative study focused on potential resource assessment, spatial differential location identification, and forecasting of renewable energy resources in Chad, particularly wind and solar resources. Research that identifies the local site or economically viable area across the entire Chadian nation is rare or non-existent. Therefore, this study focuses on that. It compares wind and solar resource potentials across the country using existing criteria and GIS technology [16]. Likewise, the study is based on the principle of economic parameters for the location of the most suitable solar and wind systems [17, 18].

The population of Chad in 2009, for information purposes, was estimated at 11,039,873 inhabitants, unlike the current population of approximately 15,177,557 inhabitants. Making electricity available in Chad is an important socio-economic issue because the population still encounters difficulties in obtaining it. This sufficiently shows in the CEMAC sub-region, Chad is one of the most poorly supplied countries. Production is estimated at over 480 GWh in 2016. The share of independent production is 54%. Despite the proven potential of renewable energies, the production of electrical energy is mainly dominated by thermal power plants. In total, the cumulative nominal power is 146 MW, and the total available power of 111 MW at the end of 2016. The means of production of the existing fleet are insufficient to meet demand (according to the average scenario of the ICEA study - diagnostic SNE in 2017 the peak demand is 105 MW in 2018, 124 MW in 2019 and 142 MW in 2020). Thus, 8% of the Chadian population has access to electricity, with a significant gap between areas, including 1% rural and 20% urban (2022). The rate of access to electricity is 11% in urban areas and 2% in rural areas (2020) and comes only from thermal power plants. In sub-Saharan Africa, it is 6.4% against an average of 48% (2022). While load shedding is frequent because the network does not provide sufficient and adequate electricity, the greatest consumption is in N'Djamena (80%). There is not yet a national electricity grid that interconnects the whole country. Wood represents 90% of primary energy consumption. Chad can count on renewable energies to ensure its energy production and independence. The objective of this work is to establish the solar and wind map of Chad. Thus, we will present the methodology, results, and discussion and we will end with the conclusion.

## 2- Methodology

In this section, we will present the different methods for estimating global solar radiation, modeling using the Weibull distribution of wind speed before estimating the wind power density. We will then proceed to establishment of the solar and wind map of Chad.

### 2-1- Modeling global solar radiation

On a horizontal plane, extraterrestrial radiation is evaluated according to the following equation [19-22]:

$$H_0 = \frac{24}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360D_n}{365}\right)\right] * \left[\cos\varphi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\varphi\sin\delta\right] \quad (1)$$

$\omega_s$ are given by [23, 24]:

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \quad (2)$$

$$\delta = 23.45\sin\left[\frac{360(284+D_n)}{365}\right] \quad (3)$$

where $I_{sc}$: solar constant(W/m$^2$); $\omega_s$ sunset hour angle (°C); δ solar declination (°) and φ latitude (°).

### 2-2- Modeling by the Angstrom-Prescott method of global solar radiation

In this method [25-27], the most practical correlation to evaluate is given by the equation [28-30]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) \quad (4)$$

Thus, the duration of sunshine is given by [23-24]:

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan\varphi\tan\delta) \quad (5)$$

where $S_0$ monthly average day length (h); a and b are regression coefficients, S monthly mean of daily sunshine hours (h).

### 2-3- Modeling of global solar radiation using the Allen method

In this method [31, 32], maximum and minimum daily air temperature data are used to estimate radiation. The estimated radiation also depends on extraterrestrial radiation and an empirical coefficient and is obtained from the following equation:

$$\frac{H}{H_0} = K_r(T_M - T_m)^{0.5} \quad (6)$$

We express $K_r$ by:

$$K_r = K_{ra}\left(\frac{P}{P_0}\right)^{0.5} \quad (7)$$

where according to Lunde [32], $K_{ra} = 0.17$, and the pressures $\frac{P}{P_0}$ is defined as:

$$\frac{P}{P_0} = \exp(-0.0001184h) \quad (8)$$

where h is altitude, varies from site to site; $T_M$ maximum temperature and $T_m$ minimum temperature.

### 2-4- Modeling by the Sabbagh method of global solar radiation

In this method [33], H is evaluated according to the following equation:

$$H = 1.530K * \exp\varphi\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right) \quad (9)$$

where k is given by:

$$K = 100\left(n\, T_{max} + \psi_{ij}\cos(\varphi)\right) \quad (10)$$

$$n = \frac{1}{(1+0.1\varphi)} \quad (11)$$

### 2-5- Wind speed performance modelling

The Weibull and Rayleigh distributions are the most used for statistical analysis of wind speed. Thus, for the description of the statistical properties of the wind, the Weibull distribution with two parameters is the most utilized because it gives better results in relation to the experimental data [34-38]. To characterize the variation in wind speed, the cumulative Weibull distribution and the probability density give appreciable results. We obtain the Weibull probability density function using the equation [39-41]:

$$f(v) = \left(\frac{\beta}{\alpha}\right) . \left(\frac{v}{\alpha}\right)^{\beta-1} . \exp\left(-\left(\frac{v}{\alpha}\right)^{\beta}\right) \quad (12)$$

The cumulative function of the Weibull distribution was expressed by [42]:

$$F(v) = 1 - \exp\left(-\left(\frac{v}{\alpha}\right)^{\beta}\right) \quad (13)$$

To analyze the performance of the Weibull statistical distribution and the accuracy, there are several methods. Some of these methods include the energy form factor method, method of moments, graphical method, power density method, and maximum likelihood method. This study employed the power density method given by [43-46]. The form factor can be estimated by [46, 47]. The standard deviation and the average wind speed are given by the equation [48].

### 2-6- Wind power density estimation

Using equation 14, we can estimate the power density of the wind [50, 51]:

$$WPD = P(V) = \frac{P(V)}{A} = \frac{1}{2}\rho\alpha^3\Gamma\left(1 + \frac{3}{\beta}\right) \quad (14)$$

## 3- Results and discussions

### 3-1- Solar map of Chad

Figure 1 shows the distribution of the average annual solar irradiation over Chad. The maximum value is 6.354 $kWh/m^2$ and the minimum value is 5.742 $kWh/m^2$ which shows that the north experiences better solar radiation than the south. Also, based on analysis and the observation of climatic variation over the country, it can be concluded that the seasons (climate) and their atmospheric (cloudiness, dust) or cosmic (inclination of the incident solar rays) modifications considerably influence the solar potential during the year. Hence, locations northward enjoy an average of more solar exposure than the southern regions.

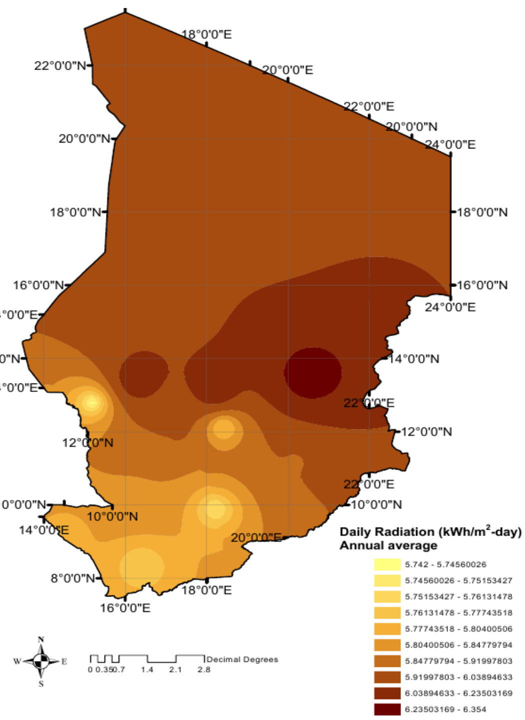


Fig. 1 Chad's annual average daily radiation from the solar map.

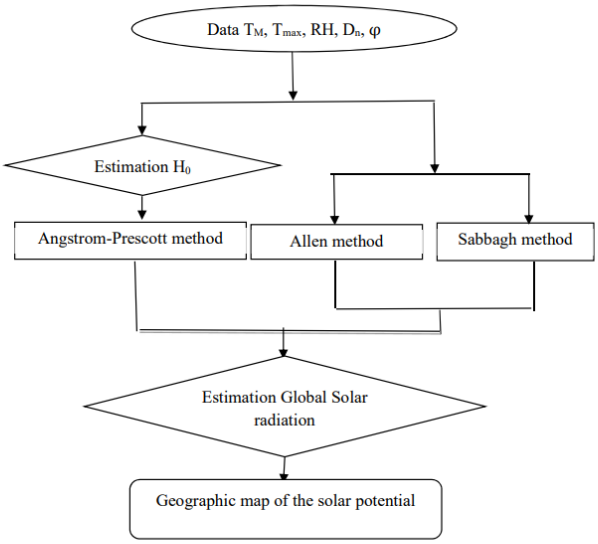


Fig. 2 Flow chart – methodology

## 3-2- Wind Map

### 3-2-1- Wind Card

The wind map summarizes all the possible information on the wind power density in Chad. This map will give you an idea of the windiest area.

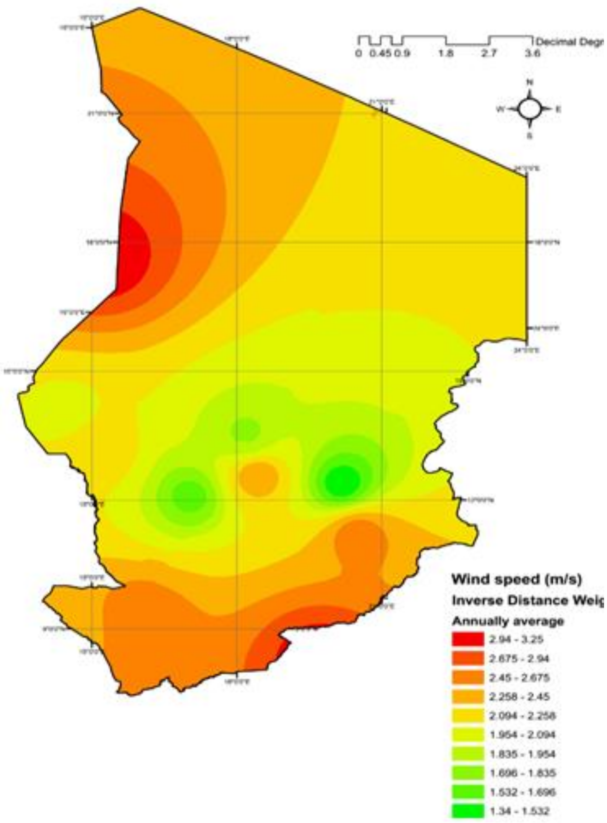


Fig. 3 The annual wind speed map which showing the wind energy resource distribution across the geopolitical landscape of Chad.

The map was developed using mathematical models first, which is the statistical distribution of Weibull. The results obtained were finally introduced into the geographic information system software for obtaining the map.

The wind map of Chad estimated at 10 m from the ground is shown in Figure 3. It shows that the core northern parts and far south experiences better wind profiles than the central and western regions. The results of the wind speed analysis demonstrate that the range of wind speeds from the south to the north is between 1.34 m/s to 3.25 m/s. Worth noting is the fact that, within the Sudanian zone of Chad, the speed is greater than 2 m/s, while the windiest parts are found in the Saharan area of Chad. Moreover, the annual wind speed map shows that there are two areas of the country that demonstrate favourable wind speed for small wind turbine applications at elevated heights. These areas include the North West (NW) and South East (SE) geopolitical zones. The probable cause of the intensity of the speed in the NW can be adduced to the presence of the sandy desert (erg of Manga) between Niger and Chad and the acceleration of the wind due to the tunnel effect created by the presence of the Tibesti massif and from the Ennedi massif. Also, between these two lies the Mourdi depression which plays the tunnel effect. To the SE is the Salamat plain, clear of all obstacles of high relief. Hence, the sites in the area will likely be devoid of mechanical turbulence effects associated with topographical features. A central strip going approximately from Bokoro to Abeche constitutes a beach of low potentiality with a favourable island around Mongo (Mont Guera).

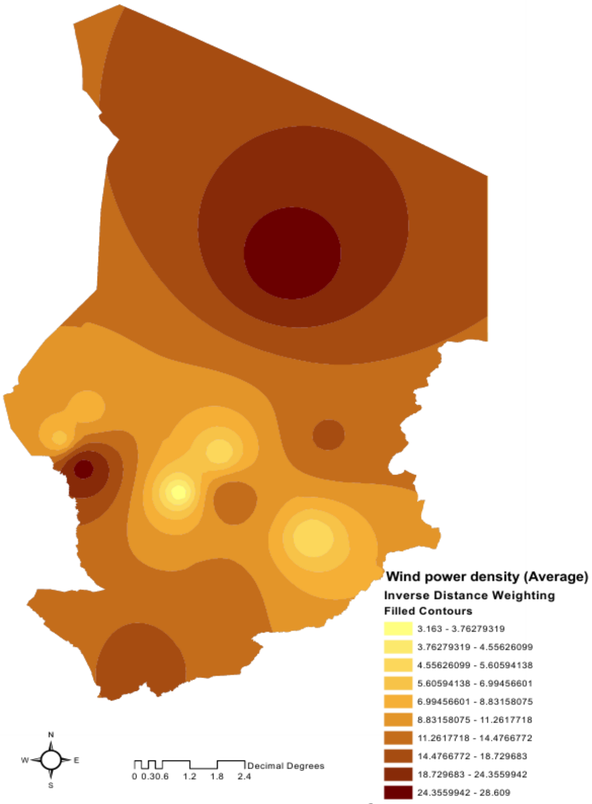


Fig. 4 Wind power density (W/m$^2$) map of Chad.

**3-2-2- Estimation of wind power density**

Analysis of wind power density versus wind speeds across the country resulted in the wind power density map of Chad as shown in Figure 4.

Figure 4 demonstrates that the potential for wind power harvest is higher in the entire northern region with small scatters around the southern parts. A range of variation in the density of wind power is seen in Figure 3 and depicts a fluctuation between 3.16 to 28.61 W/m$^2$. In other words, the Saharan area remains the most energetic place in Chad for renewable electricity generation. Hence, going by the annual wind power density map, the North is clearly favoured for installations of small wind energy farms with potential high yield at Borkou (Faya). The N'Djamena region and the far south of the country also have a high wind power potential. A sling band from Mao to Am-Timan (center-west to the southeast) has very little potential.

Overall, it is the northern region that has the greatest potential, all year round and precisely the Faya-Largeau area. The least favoured region, all year round, is the centre of the country (Lake Fitri and Ati). Overall, it can be noted that the climate (the seasons), the altitude, and the relief intervene through their actions on the spatial and temporal distribution of wind power density potential in Chad.

**3-3- Comparison of solar and wind potential in Chad**

Table 1 compares two sources of energy solar and wind. We observe that for the twelve sites considered, the highest solar energy is recorded in Abeche (2317.75 kWh/m$^2$/year) and the lowest in N'Djamena (2095.10 kWh/m$^2$/year). As for wind energy, the windiest site is Faya-Largeau (249.87 kWh/m$^2$/year) and the least windy is Bokoro (27.95 kWh/m$^2$/year). Thus, for the sites considered, solar energy is the most favorable for judicious exploitation in the three climatic zones of Chad. Moreover, operating a hybrid wind/solar power system will be much more advantageous than wind-alone or solar-alone power generation.

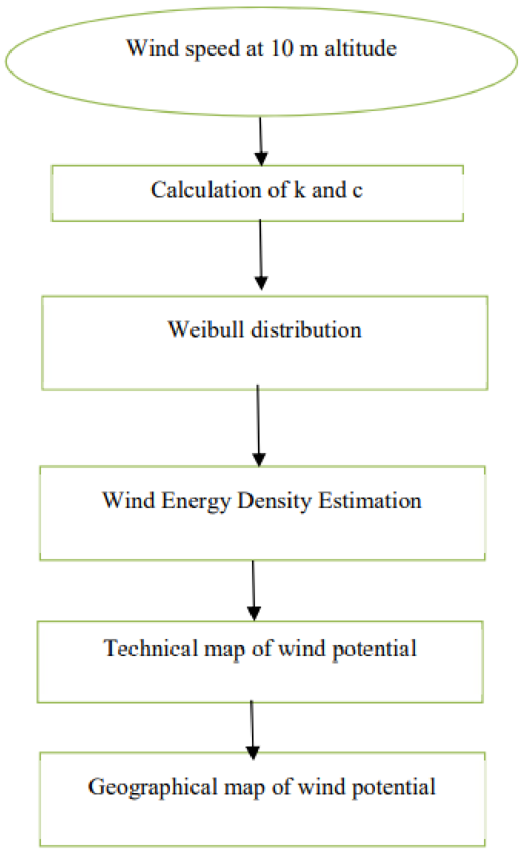


Fig. 5 Flow chart – methodology

**3-4- Comparison of the two energy sources by climatic zonal arrangement**

Table 2 compares the two sources of energy based on the demonstrable potential per the climatic zones. As the only site in the Saharan zone in the center north of Faya-Largeau, shows that solar is the best option for renewable electricity. However, wind power can also be adopted on small scale for water pumping, farm management, and small community power supply. As for the Sahelian zone, for the sites considered, in terms of solar energy, there is a significant increase in solar irradiation for the city of Abeche compared to N'Djamena.

**Table 1:** Results of solar and wind analyzes for different sites and areas of Chad

| areas | Sites | Solar energy (kWh/m$^2$/year) | Wind power (kWh/m$^2$/year) |
|---|---|---|---|
| Saharan zone | Faya-Larg. | 2193.65 (4) | 249.87 (1) |
| Sahelian zone | Abeche | 2317.75 (1) | 131.16 (4) |
| | N'Djamena | 2095. 1 (12) | 233.49 (2) |
| | Moussoro | 2237.45 (3) | |
| | Ati | 2244.75 (2) | 40.25 (10) |
| | Mao | | 69.24 (8) |
| | Mongo | 2103. 13 (9) | 121.79 (5) |
| | Bokoro | 2164.45 (5) | 27.59 (12) |
| | Am-Timan | 2160.8 (6) | 38.15 (11) |
| | Bol | | 52.76 (9) |
| Sudanese zone | Bongor | 2131.6 (7) | |
| | Moundou | 2102.4 (10) | 148.85 (3) |
| | Pala | 2113.35 (8) | 97.82 (7) |
| | Sarh | 2098.75 (11) | 110.80 (6) |

**Table 2:** Ranking the power resources on zonal basis

| areas | Sites | Solar energy (kWh/m$^2$/ year) | Wind power (kWh/m$^2$/year) |
|---|---|---|---|
| Saharan zone | Faya-Largeau | 2193.65 (1) | 249.87 (1) |
| Sahelian zone | Abeche | 2317.75 (1) | 131.16 (2) |
| | N'Djamena | 2095. 1 (7) | 233.49 (1) |
| | Moussoro | 2237.45 (3) | |
| | Ati | 2244.75 (2) | 40.25 (6) |
| | Mao | | 69.24 (4) |
| | Mongo | 2103. 13 (6) | 121.79 (3) |
| | Bokoro | 2164.45 (4) | 27.59 (8) |
| | Am-Timan | 2160.8 (5) | 38.15 (7) |
| | Bol | | 52.76 (5) |
| Sudanese zone | Bongor | 2131.6 (1) | |
| | Moundou | 2102.4 (3) | 148.85 (1) |
| | Pala | 2113.35 (2) | 97.82 (3) |
| | Sarh | 2098.75 (4) | 110.80 (2) |

More so, the results for the entire zone demonstrate better potential for solar power harvest than wind. As for wind power, N'Djamena is the site with the highest wind energy potential while Bokoro is the poorest. However, in hybrid formation, Abeche shows the most promising site in the Sahelian zone. Similarly, results for the Sudanian zone show that solar power is most feasible in terms of the magnitude of energy production with Bongor with the highest potential. However, the results of wind power analysis show that Moundou has the best potential for small wind turbine applications in the entire Sudanian zone.

## 4- Conclusion

Currently, Chad has an energy problem to meet the needs of its population because not everyone benefits from it. To achieve the expected results, the Sabbagh, Allen, and Angstrom-Prescott models were used to estimate the global radiation for the sites. Resource maps showing wind energy densities and solar irradiance over all regions of Chad were developed and GIS software is used in the design process. Due to the data currently available, measurements made at weather stations or airports were only made for twelve towns in Chad. The work will extend to other sites in Chad to exploit solar and wind potential and propose energy systems adapted to the local environment when site data becomes available. The main results are:

- Angstrom-Prescott model is adaptable for Am-Timan, Pala, Bongor, and Mongo.
- Allen model is favorable for the city of Moundou, Sarh, and Bokoro.
- Sabbagh model is suitable for N'Djamena, Faya-Largeau, Ati, Abeche, and Moussoro.
- The lowest solar radiation value is in N'Djamena (5.74 kWh/m$^2$) and the highest in Abéché (6.35 kWh/m$^2$).
- The average power density varies from 3.16 W/m$^2$ in Bokoro and 28.61 W/m$^2$ in Faya-Largeau.
- The wind potential varies annually between 27.59 kWh/m$^2$ and 249.87 kWh/m$^2$.

## Acknowledgement

The authors would like to thank all the organizations that provided data for this work.

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