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Environmental Physics Study of Natural Renewable Energy Resources in Socotra, Yemen

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ABSTRACT

The best sources for energy production are renewable energy sources such as wind, solar, tidal energy, and other energy sources, which ensure the sustainability of power generation for life and even avoid the problems producing from fossil fuels combustion, which leads to air pollution, climate change, and many problems, but the main problem that facing Especially in developing countries, such as Yemen is the lack of a database and sufficient information to know the available capabilities for electricity production by natural resources that region possesses, especially the remote islands from the main power plant, which are powered by diesel and gas generators. In this paper, we will provide and list all-natural resources that possessed Socotra island, and its analysis to provide a clear vision that enables exploitation of these resources in the future on a clear scientific basis, as the study shows that mean wind speed is approximately 9.8 m/s, solar radiation reaches 180 kWh/m2, all these values confirm island has the total ability to generate electricity from these sources with high efficiency.

INTRODUCTION

Solar energy, wind, earth's interior heat, and tides are considered important renewable energy sources, which have drawn everyone's attention to the production of electric energy in all countries, due to their advantages, the best of which is avoiding pollution resulting from the use of fossil fuels to produce energy, which is known as a limited and non-renewable source (Mahyoub H, 2006). In addition to the large growth in global population, which the developing countries are primarily responsible for 99% of this rise, that in turn increases the energy demand and thus increases air pollution, especially in urban areas, as reported by World Health Organization. Therefore, the main solution to energy production is the use of renewable energy (Perea, 2019). The obstacles facing developing countries to use renewable energy sources are financial constraints and the lack of information and data needed to give a clear vision about these sources. Yemen is considered one of the most affected countries as a result of the chronic shortage in energy production and relies on its production on fossil fuels at a rate of 85% while it represents 15% of energy use Solar energy only and no other type of renewable energy source gets any attention (International 2007) (Yemen Electricity Statistics – Worldometer, n.d.).

Yemeni islands, including Socotra island, are considered one of the most important tourist attractions in the region due to their environmental, geographical, and biological diversity. It was recognized as a UNESCO World Heritage Site in 2008. Socotra is located in the Arabian Sea near the Horn of Africa and about 380 km south of the Arabian Peninsula, geographical coordinates 12.46°, 54°. It has an area of 3,600 Km^2 (Attorre et a. 2011) (Attorre and Van Damme 2020).

This paper will present the scientific and physical analysis of the renewable energy sources that this island possesses by studying geographical diversity, knowing and studying the statistical information of those sources to give a basic database and economic brief, that enables them to rely on in the future to produce electric energy to cover the region's needs.

The demand for electric power increased since the beginning of 1971 (33.22 kWh), energy consumption remained increased until it reached (136.56 kWh) in 1993 and then decreased at the beginning of the summer of 1994 due to the internal war in Yemen, then it rose again until it reached its highest levels in 2010 with 254.84, because the great population growth that Yemen is witnessing in addition to the increasing flow of people to housing in urban cities, then the level of consumption decreased due to continuous interruption in electricity service due to internal problems in Yemen, because of that, access to electric power has decreased significantly over past years due to the conditions it is going through. Yemen recently, where the percentage of access to electricity in urban cities decreased from 100% until reached 80% in 2018, this is the lowest percentage reached by Yemen since the beginning of electricity production in the region (World Bank Group - International Development, Poverty, & Sustainability, n.d.). All these matters urgently require a radical solution to these problems. A better solution will not be found than using the natural resources that each region owns, especially remote areas and islands that have large natural resources for energy production. All these resources will be studied. Which Socotra Island possesses, and in the form of an eco-physical study, to give a clear vision of the capabilities that that island possesses, which enables it to be exploited for the production of electricity in the future without the need for fossil energy sources.

The study site is the Socotra Archipelago. Considered the largest island of the Yemen islands with an area of 3650 Km^2, the island is located in the Arabian Sea. 380 km (238 miles) south of mainland Yemen and 250 km west of the Horn of Africa. It is located between two latitudes (12.18 - 12.24) North of the equator and longitudes (53.19-54.33) East of Greenwich. Socotra archipelago includes many small islands located on the western side, including Socotra, AbduAlkuri, Samhah, Arsah, Siyal Socotra (Serag, 2021).

MATERIALS AND METHODS

Solar Energy

Solar energy is one of the largest sources of renewable energy on earth, and it is the main cause of most fossils and most other sources of renewable energies. Solar radiation arrives on the ground affected by several parameters as a result of the reflection and spread that it encounters in the dust in the atmosphere in addition to clouds. Solar radiation that reaches the earth is classified into two types, First is Direct Normal Irradiance, which is vertical radiation reaching from the sun to earth directly. This type of rays is directly affected by any visor located between our location on earth and the sun. For example, if there are clouds between the earth and sun, then the direct solar radiation, in this case, will probably be zero, Second type is Diffuse Horizontal Irradiance, this type of rays also comes from the sun, but it differs from its predecessor in that it reaches earth not directly from the sun. But it would be reflected from other sources. Where the sun's rays can reach some buildings or other sites on the earth, and then be reflected on the clouds or any other object before they reach our location on the earth (Department of Mechanical Engineering, Aligarh Muslim University, Aligarh 2020, India et al. 2012) (Adeniji et al., 2019). Global Horizontal Irradiance can be obtained by summing the previous two types of direct and diffuse radiation according to the equation $GHI = DNI \times Cos(\theta) + DHI$ Where represents θ the angle between perpendicular to the arrival point of solar radiation and sun position at moment.

Socotra Island has an annual direct normal irradiation equal 1852 kWh/m², and Diffuse horizontal irradiation equal to 877 kWh/m², while Global horizontal irradiation reaches 2226 kWh/m², and these values are sufficient to produce electrical energy with a power of 1.8 GWh/year when using solar panels with Power of 1000 kW. Figure 1 shows the hourly values of Direct normal irradiation for every month in 2019.

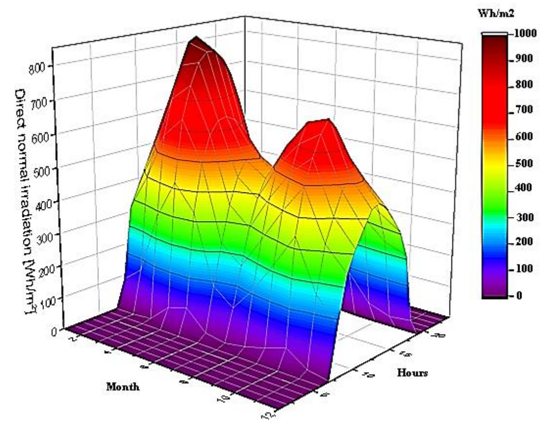

Figure 1. hourly values of Direct normal irradiation for every month in 2019.

To estimate the monthly average of global solar radiation, several methods are used based on information and data available from the meteorology, they are based either on the duration of daily monthly solar radiation (Angstrom-Prescott Model) or depending on the change in temperature (Hargreaves Model) as shown in the following equations(Khan and Ahmad 2012) (Nage, n.d.) (Maraj et al., 2014).

$$\text{(Angstrom)} \quad H/H_o = a + b \cdot \frac{S}{S_0} \quad (1)$$

$$\text{(Hargreaves)} \quad H/H_0 = a(T\,max - Tmin) \quad (2)$$

Where H is monthly average daily global radiation (MJ/m2day), Ho monthly extraterrestrial solar radiation (MJ/m2day), S monthly average daily hours of bright sunshine, so monthly average day length, a and b regression coefficients they depend on latitude, climate, season, etc.

The monthly extraterrestrial solar radiation can be calculated with the following equation:

$$H_0 = \frac{24\times3600\text{Isc}}{\pi}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times [\cos\phi\cos\delta\sin\omega_5 + \frac{2\pi\omega_5}{360}\sin\phi\sin\delta] \quad (3)$$

Where ω_5=cos-1(-tanφtanδ), $\delta = 23.45\sin\left(360\frac{284+n}{365}\right)$, Isc is solar constant (1367W/m2), ϕ site latitude, n days number of years starting from first January.

Solar energy economy

It is necessary to study the cost of solar energy to give a simplified view of the economics of this system and to encourage the use of these sources to generate energy on Island, as the price of installing a kilowatt of solar panels reached 2100 $/kW for a 10 kW system, the average price per watt for solar panels ranges from $ 2.40 to $ 3.22 (2021), as it decreased by 20% over the past years, Table (1) (Diab et al., 2016).

Table 1. Cost of PV system at 2021

Description	Cost	Unite
Capital Cost	2100	$/kW
Operation and Maintenance	10	$/Year
Life Time	20	Years
Converter	300	$/kW

It can to calculate of (Levelized cost of energy) by Equation (4)

$$\text{LCOE} = \frac{\text{Total Cost At Lifetime}}{\text{Total Energy Production At Lifetime}} \quad (4)$$

Wind Energy

Wind energy is one of the fastest and most growing energy sources in the world, with an annual growth rate of 30% (Leung and Yang 2012), it is characterized by generating electric power without emitting pollution gases to the environment, such as those produced by fossil fuels, in addition to the possibility of using it in remote areas which far from Main electrical stations. In order to know how to best exploit wind energy, an analytical study of wind characteristics must be presented, the most important of these is wind speed distribution, to assess wind energy potential, wind performance, and conversion system for this energy (Mahyoub H, 2006) (Kumar and Gaddada, 2015).

Many models are used to calculate wind speed distribution, and among the best models that can be applied are Weibull and Rayleigh distribution models, where Weibull distribution is characterized by the use of two prominent parameters, one of which is called shape parameter (k) and other is scale parameter (c), which is most appropriate with the study of monthly probability density distributions at different heights. The variation in wind speed is characterized by two functions: probability density function, which indicates the probability of winds at a certain speed, and cumulative distribution function, which indicates the probability of wind speed equal to or less than mean wind speed or within a certain wind speed range. The Weibull distribution is given by the following equations (Gökçek, Bayülken, and Bekdemir, 2007) (Ohunakin and Akinnawonu, 2012):

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \times e\ p\left[-\left(\frac{v}{c}\right)^{k}\right]. \quad (5)$$

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right]. \quad (6)$$

$$k = \left(\frac{\sigma}{v_m}\right)^{-(1.086)}. \quad (7)$$

$$c = \left(\frac{v_m}{\Gamma(1+\frac{1}{k})}\right). \quad (8)$$

Where vm is the mean wind speed, v is wind speed, σ standard deviation given by equation:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2}. \quad (9)$$

The gamma function is expressed by the equation (7) if y = (1+1/k):

$$\Gamma(y) = \int_0^\infty exp(-x)x^{y-1}\,dx\,. \quad (10)$$

As for the Rayleigh distribution, it can be calculated by knowing wind speed v and the mean wind speed vm by equations:

$$f_r(v) = \frac{\pi v}{2v_m^2} exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right]. \quad (11)$$

$$F_R(v) = 1 - exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right]. \quad (12)$$

All the information gathered from meteorology in Yemen for Socotra Island showed that mean wind speed until 2014 is equal to 9.17 m/s, and wind speed is distributed throughout the year as in Figure (3), where wind speed is low on April 3. 7, October 3. 6 m/s, and average values are taken in January, February, March, November, and December with values between 5.1 to 7.46 m/s. As for the largest values of wind speed, they are in June, July, August, and September, as their values are between 11.34 to 18.38 m/s, this information becomes clear to us that wind speed in the region is sufficient to generate electricity with high capacity.

In the case of studying the wind speed distribution, annual Weibull parameters take values 2.8, 9.6 m/s, and 3.16 m/s for each of k, σ, and c, respectively, the values of these parameters differ according to height, Tables (2) are shown every value of all parameters with different heights.

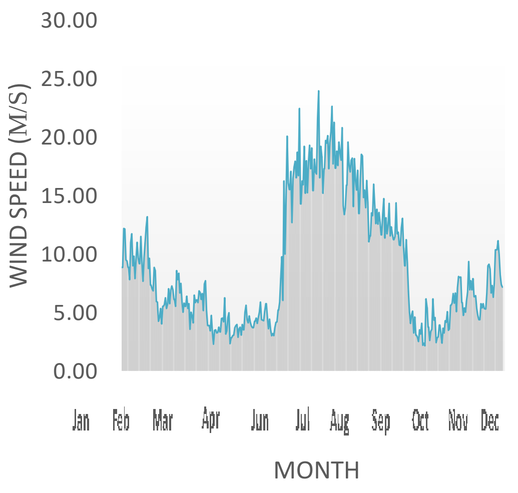

Figure 2. Wind speed in Socotra for one year.

The following Figure (3) shows the division of winds average value for all sites on Socotra island, and through it becomes clear that the largest value of wind speed is in Ras Rusayl, Dyabalhan, Raida, Mahfarhin, Qalansiyah, Sharprop, and Kaysuh, in addition to the island of Abd al-Kuri attached to Socotra Island.

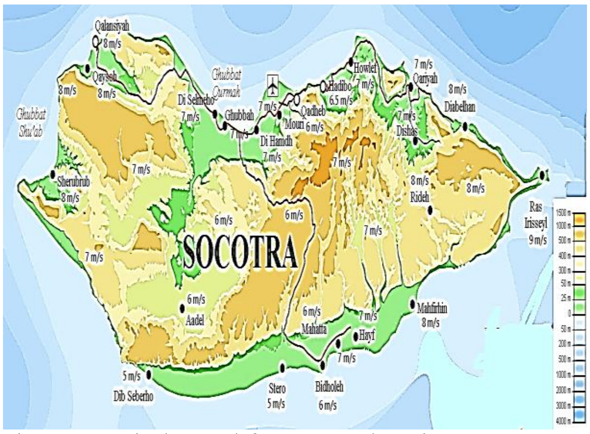

Figure 3. Wind speed for every place in Socotra.

Wind energy economy

The cost of wind turbines varies according to several factors, industry type, efficiency, the energy produced, turbine power, tower height, and turbine type (onshore or offshore). Turbine cost can be summarized according to turbine power and tower height, as shown in Table (2), these prices may change according to new developments in turbine manufacturing.

Table 2. Wind turbines cost with nominal turbine power and tower height.

Nominal turbine power (MW)	Tower Height (m)		
	<100	100- 120	>120
<2	1218	1341	-
2 – 3.5	1128.5	1285	1497.5

To find a Levelized cost of energy (LCOE) from a wind turbine, several factors must be studied such as the investment cost (turbine cost, cost of civil engineering, Wiring cost), the cost of exploitation (maintenance and operation of turbines, management, and turn, rent or purchase of land, insurance taxes ... etc), a lifetime of turbine, interest rate, inflation rate. Then can apply the equations (12,13) (Ohunakin and Akinnawonu 2012).

$$PVC = C_{inv} + C_{omr} \times \left(\frac{1+i}{r-i}\right) \times \left[1 - \left(\frac{1+i}{1+r}\right)^t\right] - C_s \times \left(\frac{1+i}{1+r}\right)^t \quad (12)$$

Where (r) interest rate = 2 %, (I) inflation rate = 1.5 %, (t) lifetime of wind turbine

For calculating kWh cost we should applicate this equation:

$$(\text{kWh cost}) = PVC/PE \quad (13)$$

Where PE= energy production in a rated lifetime.

RESULTS AND DISCUSSION

Solar Energy

When using the previous equations and taking all the measured values of Socotra, which were collected from the Meteorological Authority, in addition to analyzing these data, obtained Table 3. Also, by studying the correlation between (S/S0) and (H/H0), the linear relationship shown in Fig. 5 is formed, where total value (a) equal 0.333, and (b) equal 0.392.

Table 3. Solar radiation parameters.

Month	S (hour)	S_0 (hour)	S/S_0	Tmax (^{0})	Tmin (^{0})	a	b	H MJ/m^2 day	H_0 MJ/m^2day	H/H_0
Jan	9.1	11	0.83	28	23	0.39	0.32	5.9	8.95	0.66
Feb	9.1	12	0.76	28	23	0.37	0.37	6.6	10.14	0.65
Mar	9.8	12	0.82	29	23	0.39	0.33	7.11	10.8	0.66
Apr	10.2	12	0.85	32	25	0.4	0.31	7.47	11.31	0.66
May	10.9	13	0.84	34	27	0.4	0.32	7.16	10.85	0.66
Jun	7	13	0.54	33.5	27	0.3	0.52	6.18	10.65	0.58
Jul	4	13	0.31	33	27	0.22	0.68	5.84	13.45	0.43
Aug	3.5	12	0.29	32	26	0.22	0.7	6.34	15.05	0.42
Sep	6.2	12	0.52	32	25	0.29	0.54	6.73	11.81	0.57
Oct	10	12	0.83	30	22	0.39	0.32	6.54	9.92	0.66
Nov	10	11	0.91	29	22	0.42	0.27	5.88	8.9	0.66
Dec	9.3	11	0.85	28	22	0.4	0.31	5.5	8.33	0.66

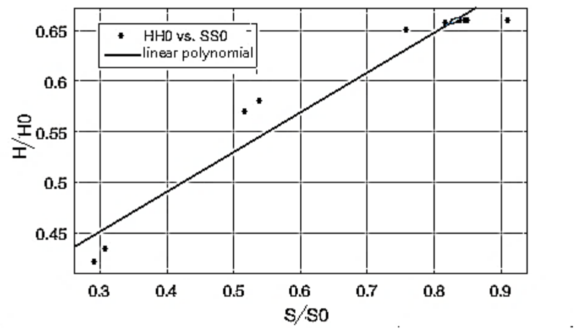

Figure 4. The linear correlation between (S/S0) and (H/H0),

The use of PV is a successful project by all standards, as it can produce large energy as the production reaches energy approaching 2 GWh per year. Figure (5) shows the energy output of a fixed solar energy system at an angle of 180 degrees for every month in a year, and Table (4) shows the detailed costs of electricity generated from this system.

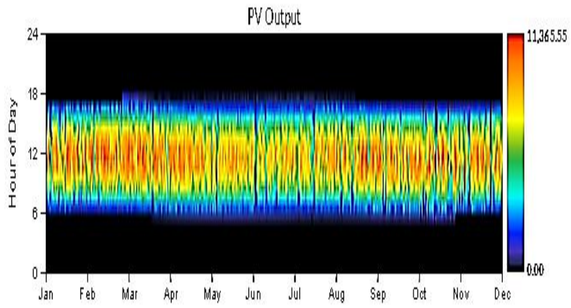

Figure 5. Energy Output in PV system.

Table 4. Detail of PV system operation and cost

Quantity	Value	Unite
Rated capacity	1015	kW
Capacity factor	21	%
Total Production	1.9	GWh/year
Hours of operation	4436	Hours
Levelized cost	0.102	$/kWh

Wind Energy

By applying Weibull's equations (5) and (6), and Rayleigh's equations (11) and (12), which can find the probability density and the cumulative density of wind speed distribution from zero to 33 m/s (minimum and maximum of wind speed observed in the region), It can to obtain Figures (6) which are given a graphical representation of both probability and cumulative curve.

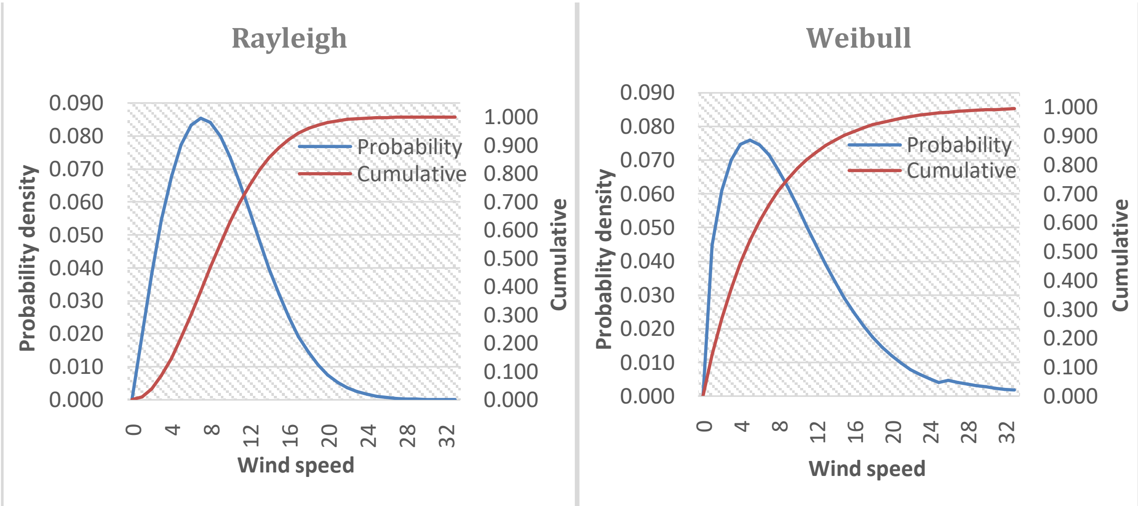

Figure 6. Weibull and Rayleigh distribution.

When taking three different models for turbines at different heights, namely (Suzlon 1000 kW), (Nordex 1500 kW) and (Gamesa 2000kW) at heights of 65,80,100 m and applying the equations (12,13) and taking the values from Table (2), in addition to wind speed distribution values for Socotra Island and the Weibull parameters, Tables (6) is deduced, which Shows LCOE by $/kWh. It should be noted that the unit energy cost depends on the annual energy production from the turbine, which in turn depends on wind speed distribution in the region and Weibull parameters Table (7).

Table 5. Weibull variation with different height

Variation	**Mean wind speed v_m**				**Standard deviation σ**				**Shape parameter k**				**Scale parameter c**			
Height (m)	10	65	80	100	10	65	80	100	10	65	80	100	10	65	80	100
Jan.	7.5	9.7	10.0	10.3	2.2	3.0	3.0	3.1	3.7	3.6	3.8	3.7	8.3	10.8	11.1	11.4
Feb.	6.1	8.0	8.2	8.4	2.5	3.4	3.4	3.6	2.6	2.5	2.6	2.5	6.9	9.0	9.2	9.5
Mar.	5.1	6.6	7.0	7.4	2.6	3.4	3.5	3.3	2.1	2.1	2.1	2.3	5.8	7.5	7.9	7.9
Apr.	3.7	4.6	4.8	5.1	2.2	2.8	3.0	3.1	1.8	1.8	1.6	1.7	4.2	5.4	5.1	5.7
May.	4.4	5.7	5.8	6.0	2.5	3.2	3.3	3.4	1.9	1.9	1.9	1.9	4.9	6.4	6.6	6.8
Jun.	14.6	19.0	19.6	20.2	6.3	8.0	8.2	8.4	2.5	2.6	2.5	2.6	16.5	21.4	17.3	22.7
July.	18.4	23.9	24.6	25.4	4.6	6.0	6.1	6.3	4.5	4.5	5.9	4.5	20.2	26.8	26.5	27.8
Aug.	15.6	20.3	20.9	21.5	4.0	5.2	5.0	5.6	4.4	4.3	4.3	4.3	17.1	22.3	21.3	23.7
Sep.	11.3	14.7	15.2	15.7	3.4	4.4	4.5	4.8	3.7	3.7	3.7	3.6	12.6	16.3	16.8	17.4
Oct.	3.6	4.7	4.8	5.0	2.6	3.1	3.2	3.4	1.6	1.6	1.6	1.5	4.1	5.2	5.4	5.5
Nov.	5.9	7.7	7.9	8.2	2.5	3.3	3.4	3.5	2.5	2.5	2.4	7.5	6.7	8.7	8.9	9.2
Dec.	7.1	9.2	9.5	9.8	2.5	3.3	3.3	3.4	3.1	3.0	3.2	3.2	8.0	10.3	10.7	11.0

Table 6. Change in the power of a turbine for one year in different height.

Height	**Variables**	**(Suzlon)**	**(Nordex)**	**(Gamesa)**
65	Energy	4701.7	6307.72	8332.34
	Cp	68%	61%	60%
80	Energy	4819.6	6506.35	8596.17
	Cp	70%	63%	62%
100	Energy	4966.3	6637.45	8765.86
	Cp	72%	64%	64%

Table 7. (LCOE) for three different turbines with three heights

Turbines type	**65**	**80**	**100**	**Unit**
Suzlon1000 kW	0.079	0.076	0.081	$/kWh
Nordex1500kW	0.089	0.083	0.088	$/kWh
Gamesa 2000kW	0.096	0.092	0.089	$/kWh

CONCLUSION

All information and studying to Socotra Island become clear that it contains natural sources of energy, namely (solar and wind) energy, which are renewable and clean sources, through which energy can be produced permanently and environmentally friendly. By statistical study and physical application of all information obtained, the following appears:

1. Socotra Island has direct natural irradiance of 1852 kWh/m2 and diffuse horizontal irradiance equal to 877 kWh/m^2, while the global horizontal irradiance reaches 2226 kWh/m2 and the monthly average of daily global irradiance is 6.43 MJ/m2day and a month from Extraterrestrial solar irradiance 10.84 MJ/m2day.
2. Socotra Island has a mean wind speed = 9.17 m/s, with parameters = (2.8, 9.6 m/s, and 3.16 m/s) for (k, σ, and c) respectively, and a maximum value of wind distributing probability for Weibull at speeds 4 and 5 m/s, the maximum probability for Rayleigh at 7 m/s.
3. When studying the economic use of wind turbines and solar panels for Socotra, we find that the amount of cost is low and ranges from 0.076 and 0.097 $/kW for wind turbines and 0.102 $/kW when using solar panels, which is a low cost and suitable to cover the region's need of electricity.

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