An optimization approach of hybrid PV-wind renewable energy systems for power generation in Egypt

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Abstract

Different criteria of selecting the right sizing of different components of hybrid renewable energy power plant at the most preferable economical and logistical environmental considerations are discussed. A methodology to perform the optimal sizing of an autonomous hybrid PV-wind system is discussed considering the fact that the potential of the wind and solar energy is not equal in Egypt. Optimization study of a hybrid PV/wind system is based on the availability of sunshine all over the year with global solar radiation varying from 5 to 8 kWh/m^2/day and with wind speed varying from 5 to 13 m/s is needed which is available in Egypt in different locations. The storage unit containing an energy $B(t)$ of hybrid solar-wind energy at different locations in Egypt has a minimum value of 870 W/m^2 (at Cairo), maximum value of 2065 W/m^2 (at Hurghada), a mean value of 1250 W/m^2, and a standard deviation value of 348 W/m^2.

Keywords: hybrid energy, solar power, wind power, global solar radiation.

1 Introduction

Energy is one of the essential inputs for economic development and industrialization. Fossil fuels are the main resources which play a crucial role to supply world energy demand. However, fossil fuel reserves are limited and the usage of fossil fuel resources has a negative environmental impact. In Egypt, the low level of electricity generation from conventional fossil fuel has been the major constraint to accelerate the socio-economic development especially in rural communities. Although Egypt is among the top countries in the world receiving

WIT Transactions on Ecology and The Environment, Vol 210, © 2016 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP160451

the total solar radiation as shown in Fig. 1, there is still a significant need and shortage in energy in the country (World Energy Council [1]). Hence, there is a need to develop an indigenous technology to harness the renewable energies to generate electricity. Wind mills can be set up ranging scales of: on-shore grid connected to wind turbine systems, off-shore wind turbine systems and small hybrid energy decentralized systems. International facilities of power generation sources are based on the U.S. Energy Information Administration's national energy profiles as shown in Fig. 2 (Mosaic [2]).

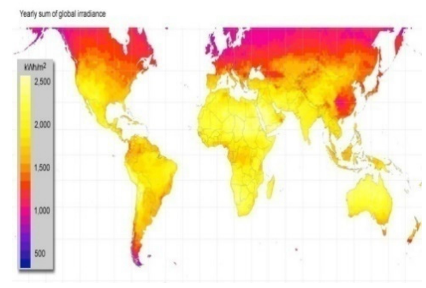


Figure 1: Yearly sum of global irradiance at the world kWh/m^2 [1].

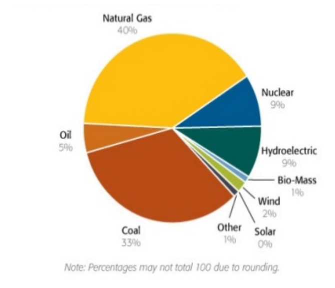


Figure 2: Mosaic indirect energy consumption of generation source, 2015. [http://www.mosaicco.com/2015sustainabilityreport/environment/]

2 Literature review

Hybrid power systems are rapidly growing area of research. Not only domestic, commercial and industrial loads are studied to be switched to these systems but this technology is also under research to be implemented effectively in automobiles (Liu *et al.* [3]). Renewable energy resources are solar power, wind power, tidal power, geothermal power, wave power and biomass. They are persistent, naturally renewing themselves and environment friendly. This is why they are called green energy resources. Unrenewable conventional energy resources such as oil, coal, gas etc. decrease slowly with time (Fesli *et al.* [4]).

The main feature of hybrid renewable energy systems is to combine two or more renewable power generation so they can address efficiency, reliability, emissions and economical limitations of single renewable energy source. The methodology aims finding the configuration, among a set of system components, which meets the desired system reliability requirements with the lowest value of costs.

A lot of research and development has been carried out in the area of renewable energy resources and hybrid systems. Off-grid alone hybrid systems have been designed and proposed for the places where either sun, wind or both are available. For the wind speed 4 m/s or more, a wind turbine serves efficiently, while in the case of limited wind power, solar power helps to run the system uninterruptedly. In other words, solar photovoltaic provides maximum energy during the day time, while a wind turbine provides maximum energy during the night. But the stand-alone hybrid system is not reliable. Therefore, on-grid hybrid system is highly recommended. In an on-grid hybrid system, the system is connected to the AC grid so that renewable energy helps the national grid in providing energy to the user (Ambia *et al.* [5]). However, in areas where a constant supply from the AC grid is not available, backup generator must be connected to the system, which would provide electricity when an AC supply from the main source is not available. So, the system that is most suitable for domestic use must have a hybrid power system consisting of: a wind power system, a solar power system, an AC main supply from grid and also a diesel/oil generator. Research and development has been made on the control and management of on-grid/off-grid hybrid power systems, but limited work has been done to make this technology handy to the domestic user (Prasad and Srinivasan [6]). Still further studies and research are needed to design, test and analyze the hybrid systems for domestic use. Solar radiation modeling and measurements for renewable energy applications with a currently installed capacity of about 145 MW corresponding to less than 1% of the electricity consumption wind power are still in their infancy in Egypt, but the goals for the future have been set higher: 850 MW in 2010 (3%) and 2750 MW in 2020 (6%) (Saleh Abdel-Kawy [7], Said and Mortensen [8], Goujan *et al.* [9]). A milestone in this development is the Wind Atlas for Egypt which was published recently by the New and Renewable Energy Authority (NREA) and the Egyptian Meteorological Authority (EMA) in Cairo in cooperation with Riso National Laboratory for Sustainable Energy in Denmark. The wind atlas allows wind resource assessment and setting anywhere in Egypt and provides bankable resource estimates in the most promising regions.

3 Geographic location

Egypt belongs to the global sun-belt. The country is in an advantageous position with solar energy (Shaltout *et al.* [10] and Rahoma [11]). In 1991 Solar Atlas for Egypt was issued indicating that the country enjoys 2900–3200 hours of sunshine annually with annual direct normal energy density between 1970 and 3200 kWh/m^2 and technical solar-thermal electricity generating potential of 73.6 PWh. An atlas of the wind speed for Egypt was also published, which gives that the minimum wind energy in Egypt is 4.4 km/h, while the maximum wind energy is 12.7 km/h (Mortensen *et al.* [13]). The article discusses perspectives of solar energy in Egypt and developmental trends till 2050 (Egypt's State Information System (SIS) [12]). Egypt as a developing fast growing country suffers a rapid annual population growth currently at a rate of 1.68%. According to Cairo Demographic Centre, Egypt's population is expected to reach 110 million by 2031 and 128 million by 2051. Such a fast population growth along with other environmental challenges is overstraining the limited energy resources of the country. Table 1 shows Egypt's projected population growth till 2027. On the other hand, improvement of human factor indicators including health care and general welfare necessitates correspond increase in per capita electric power consumption as indicated in Table 1, which describes Egypt's population and electric power indicators between 2007 and 2052, and Table 2, which shows that MoEE plans to increase the consumed energy during the time interval of 2007–2027 up to 76.6 GW. It is estimated that with the current level of technology, the 'on-shore' potential for utilization of wind energy for electricity generation is of the order of 65,000 MW (Mortensen *et al.* [14]). The 2009 statistics of the Ministry of Electricity and Energy (MoEE) targets to satisfy 11.26% of the electric energy generation from renewable energy sources (basically wind) by the year 2027.

Investigation of available wind power density at the height of 15 m indicates that Helwan has high wind power density ranging from 122 to 254 W/m^2 at this height. So, wind farms can be installed in this region to supply a reasonable amount of energy using a number of wind turbines (Guitas *et al.* [15]).

3.1 Data sources

The basic data were provided by the Meteorological Authority of Egypt in Cairo according to three available sources: solar radiation, radiation balance data of the world network and the monthly report published by Voeikov Main Geophysical Observatory in Leningrad, USSR for (1976–2010).

3.2 Methodology

In this paper, we consider the energy flow in the off-grid hybrid solar–wind power generating system; one part of this combined electromotive force generator consists of PV modules of total area, while the second consists of a wind turbine spanning a certain area. Flow chart of hybrid solar-wind resource is depicted in Fig. 3. The storage unit, depicted in Fig. 4, collects electric energy from the wind turbine rotor and from the PV cells. In this particular study, we are not concerned with the way this energy is stored.

4 Solar energy

It is clear from Fig. 5 that the preferable locations for solar energy farms are along the north coast, while those for wind energy farms are along the Red Sea coast and in the West of Oweinat area. Nowadays, utilization of solar energy includes the use of photovoltaic cells, solar water heating and solar thermal power. The main innovation of an integrated solar combined cycle power plant is the integration of steam generated by solar energy into a combined cycle power plant, which will require a larger steam turbine to generate electrical energy from the additional solar-generated steam (Central Agency for Public Mobilization and Statistics [16]). Fig. 3 shows the flow chart of hybrid solar-wind resource map of Egypt determined by mesoscale modeling (Wind Atlas for Egypt, 2006), Fig. 4 shows a design of hybrid solar-wind resource, Fig. 5 shows the displays the atlas of the wind speed for Egypt [13, 14] and Fig. 6 shows the study of variation of different components of solar radiation with time (Rahoma [11]).

Table 1: Egypt's population and electric power indicators (2007–2027) (EEHC Report 2008 [17]).

Year	2007	2012	2017	2022	2027
Population (million)	78.3	85.2	92.1	98.8	105.1
Per capita installed power (MW/c)	0.28	0.34	0.41	0.48	0.55
Total (GW)	21.9	29.0	37.8	47.1	57.7
Installed power annual growth rate (%)	4.4	5.8	5.4	4.5	4.0
Year	2032	2037	2042	2047	2052
Population (million)	111.1	116.5	121.2	125.3	128.5
Per capita installed power (MW/c)	0.63	0.72	0.82	0.92	1.02
Total (GW)	70.0	84.0	100	115	132
Installed power annual growth rate (%)	4.0	3.7	3.5	2.8	2.7

Table 2: MoEE generation plans 2007–2027 [18]).

	2007	2007-12	2012-17	2017-22	2022-27	Total	Total%
Thermal	18.9	6.55	11.9	10.4	13	60.8	79.35
Hydro	2.7	0.06	0.3	-	-	2.8	3.75
Wind	0.22	1.6	2.9	2.5	0.5	7.8	10.18
Solar-thermal	-	0.14	-	-	-	0.14	0.183
Nuclear	-	-	1	2	2	5	6.55
Total	21.9	8.35	15.9	14.9	15.5	76.6	100

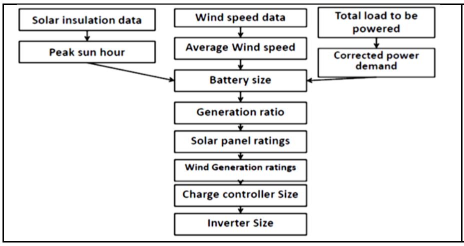


Figure 3: Flow chart of hybrid solar-wind resource.

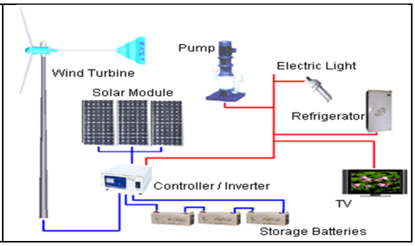


Figure 4: Design of hybrid solar-wind resource.

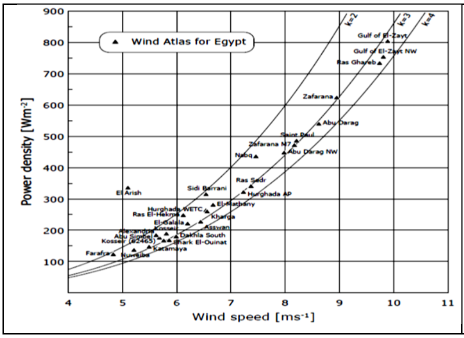


Figure 5: Atlas of the wind speed for Egypt [14].

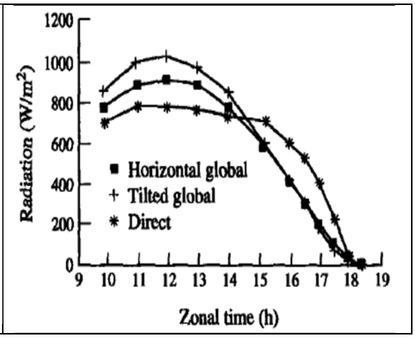


Figure 6: The variation of different components of solar radiation with time (Shaltout *et al.* [10], Rahoma [11]).

The global formula to estimate the electricity generated in output of a photovoltaic system is:

$$E = A \times r \times H \times PR \tag{1}$$

where E is the output generated energy (kWh), A is the total solar panel area (m²), r is the solar panel yield given by the ratio: electrical power (in kW) of one solar panel divided by its area (www.photovoltaic-software.com) 17.68% (SPR-220-BLK-U, Rating=220, Tier=1), H is the annual average solar radiation on tilted panels (shading is not included) and PR is the Performance ratio, which is the coefficient of losses (ranges between 0.5 and 0.9 and the default value = 0.75).

5 Wind energy

When air mass flows through an area (of radius r = 3.5 m, A = 38.5 m^2), wind power also depends on the air density that given by Ghitas *et al.* [15] and Blasone *et al.* [20].

$$\rho = 1.2929\ \frac{P_r - V_P}{760}\frac{273}{T} \tag{2}$$

where ρ is the density of air, which is around 1.22 kg/m³, P_r is atmospheric pressure (mm of Hg), V_P is vapor pressure (mm of Hg) and T is temperature (Kelvin). The vapor pressure term is a small correction (around 1%) and can be neglected. High temperatures and low pressures reduce the density of air, which will reduce the power per area (kWh). Then,

$$P_r = \frac{1}{2}\rho A V^3 C_p \tag{3}$$

where V is the speed of the air moving at time t and C_p is Power Coefficient. Taking account of wind fluctuations and the energy from an air flow over a time period, P_r is made up of the sum of wind speeds of small time intervals. Often, the hourly average wind speeds are measured providing 24 time buckets per day. While the air density is more or less constant, the two parameters to watch out for are the windswept area A and the wind speed V. Another way to capture the same energy, the blades of the wind turbine in the low wind speed location would have to be almost 3 times longer (Green Rhino Energy [19]). So, we can see from the data that velocity is the most important factor of wind energy equation. Higher velocity gives higher power.

5.1 Energy balance equation

A schematic representation of the power generating system of the storage unit and of the consumer is $C(t)\ \Delta t$. The total energy (solar and wind) $\Delta EP = P(t)\Delta t$, generated in a small time interval Δt, goes into the storage unit containing an energy $B(t)$ at time t, from which the consumer can derive, with no delay, a quantity of energy $\Delta EC = C(t)\Delta t$. The difference ΔEP and ΔEC, assumed as being known, can be either positive or negative depending on the particular time t we choose. We can, therefore, set by energy conservation law:

$$B(t + \Delta t) = B(t) + P(t)\,\Delta t - C(t)\,\Delta t. \tag{4}$$

For infinitesimal values of Δt, Equation (4) can be reduced to the following equation:

$$\frac{dB(t)}{dt} = P(t) - C(t) \tag{5}$$

In principle, we could choose B_{max} to be as large as we wish. However, by choosing a very large value of the energy storage capacity, the power $S(t)$

generated by the PV cells of area $A_{PV} = 31.6$ m^2 and of the power $W(t)$ generated by a wind turbine of area $A_{TB} = 38.5$ m^2 during a whole year can be mathematically represented by the energy balance equation which is $S(t)+W(t)–C(t)$, for $C(t) =$ 3.0 kW. Since $B(t)$ can only take values between 0 and B_{max}, energy stored in a battery is of 500 kWh maximum capacity. By now, setting $B_0 = B_{max}$, by taking $\Delta E_0 = B_{max}/3$ and assuming a constant rate $C_0 = 3.0$ kW, the solutions reported for $B_{max} = 3.0 \times 24$ kWh and for $B_{max} = 4.0 \times 24$ kWh. After defining the dimensions of the surface occupied by the PV cells and of the area swept by the wind turbines suitably, it is crucial to determine the storage capacity of the battery (Blasone *et al.* [20]).

6 Results

The average annual solar radiation in Al-Arish and Marsa Matrouh amounts about 5.18 and 5.48 kW/m^2/day respectively, while the average annual temperature in Al-Arish and Marsa Matrouh amounts to about 19.9 and 19.4 degrees Celsius respectively. As well as paired with the highest average annual temperature, largest average annual solar radiation in the stations emerging in Aswan amounts to the amount of solar radiation in Aswan and Khargha about 6.29 and 6.37 kW/m^2/day, respectively, while the average annual temperature in Aswan and Khargha are about 26 and 24.7 degrees Celsius respectively (as shown in Table 3). The statistics of the large-scale meteorological situation was used for 34 years to estimate the long-term wind conditions in Egypt in the grid points of the mesoscale model. The distance between these grid points is 7.5 km for the two domains that cover all of Egypt corresponding to more than 50,000 grid points in the domains. Based on these estimates of the wind climate, we can draw a wind resource map of Egypt. The minimum wind speed at different locations in Egypt is 4.4 km/h, the maximum is 12.7 km/h, the mean value is 7.7 km/h and the standard deviation is 2.7 km/h. But the accuracy in the resource estimates for any specific site is limited because it does not take all the small-scale features of the terrain into account and the map is plotted based on simple interpolation between the grid point values. Comparisons for six different domains in the Wind Atlas for Egypt indicates that the mean absolute error (the difference between the two estimates divided by their mean value) is typically around 10% for the two large-scale domains which cover all of Egypt. Figs 7 and 8 show the annual mean of global solar radiation (kWh/m^2/day) and wind speed (km/h) at different locations over Egypt. Figs 9 and 10 show the output photovoltaic power from global solar radiation kWh/m^2/day and electrical power from wind energy (W/m^2) at different locations over Egypt. Fig. 11 shows that the storage unit, containing an energy $B(t)$ at hybrid (solar and wind energy) W/m^2 at different locations over Egypt, has a minimum of 870 W/m^2 maximum of 2065 W/m^2, mean of 1250 W/m^2, and standard deviation of 348 W/m^2. Fig. 12 shows the hybrid energy of solar and wind for different regions over Egypt.

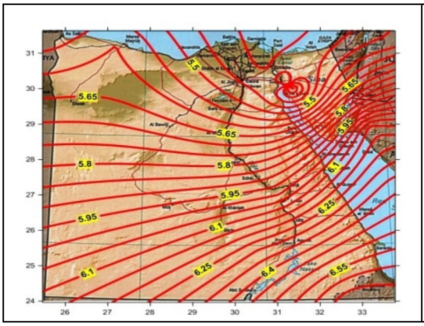


Figure 7: Annual mean of global solar radiation (kWh $/m^2/day$) at different locations over Egypt.

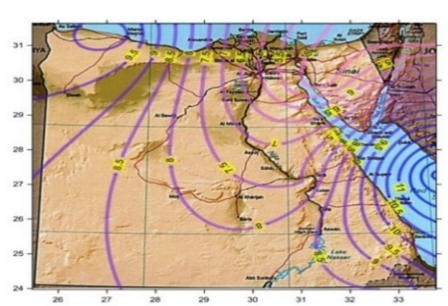


Figure 8: Annual mean of wind speed (km/h) at different locations over Egypt.

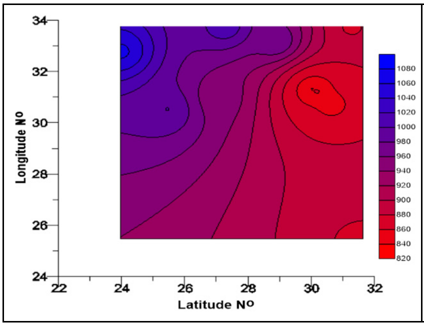


Figure 9: Output photovoltaic power from global solar radiation $Wh/m^2/day$ at different locations over Egypt.

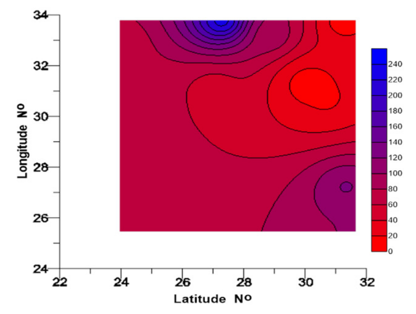


Figure 10: Output electrical power from wind energy W at different location over Egypt.

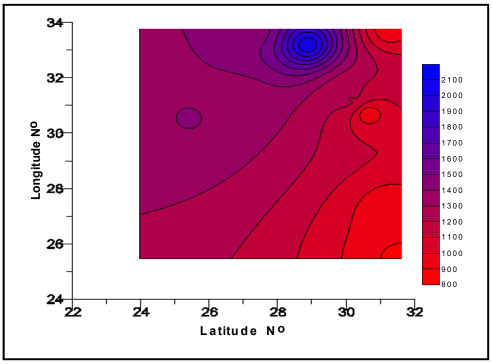
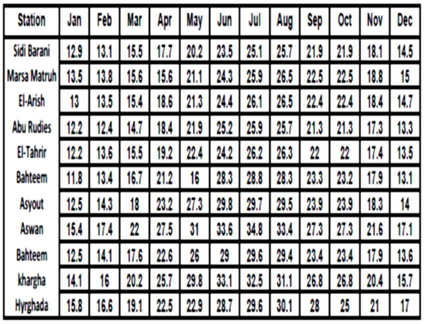


Figure 11: Storage unit containing an energy *B(t)* at a hybrid (solar and wind) energy (W/m^2) at different locations over Egypt.

Table 3: Monthly mean temperature (°C) in Egypt some stations [17].



Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sidi Barani	12.9	13.1	15.5	17.7	20.2	23.5	25.1	25.7	21.9	21.9	18.1	14.5
Marsa Matruh	13.5	13.8	15.6	15.6	21.1	24.3	25.9	26.5	22.5	22.5	18.8	15
El-Arish	13	13.5	15.4	18.6	21.3	24.4	26.1	26.5	22.4	22.4	18.4	14.7
Abu Rudies	12.2	12.4	14.7	18.4	21.9	25.2	25.9	25.7	21.3	21.3	17.3	13.3
El-Tahrir	12.2	13.6	15.5	19.2	22.4	24.2	26.2	26.3	22	22	17.4	13.5
Bahteem	11.8	13.4	16.7	21.2	16	28.3	28.8	28.3	23.3	23.2	17.9	13.1
Asyout	12.5	14.3	18	23.2	27.3	29.8	29.7	29.5	23.9	23.9	18.3	14
Aswan	15.4	17.4	22	27.5	31	33.6	34.8	33.4	27.3	27.3	21.6	17.1
Bahteem	12.5	14.1	17.6	22.6	26	29	29.6	29.4	23.4	23.4	17.9	13.6
khargha	14.1	16	20.2	25.7	29.8	33.1	32.5	31.1	26.8	26.8	20.4	15.7
Hyrghada	15.8	16.6	19.1	22.5	22.9	28.7	29.6	30.1	28	25	21	17

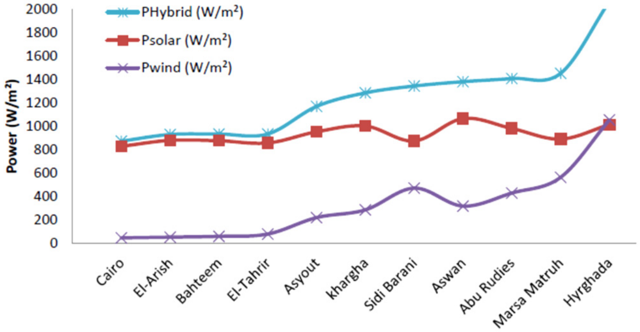


Figure 12: The hybrid energy of solar and wind for different regions over Egypt.

7 Discussion

Global solar radiation and wind speed are the most important sources of renewable energy available in Egypt. The availability of sun shine all over the year with global solar radiation varies from 5 to 8 kWh/m^2/day, which represents more than seven times its value in Europe (1 kwh/m^2/day) and (1.7 kwh/m^2/day in Greece). To get reasonable wind energy sources, wind speeds of 5 to13 m/s are needed, which is available in Egypt in different locations such as Zafarana, Al-Arish, Marsa Matrouh and Khargha.

According to Figs 11 and 12, the hybrid energy of solar and wind energies for different regions over Egypt (Cairo, El-Arish, Bahteem, and El-Tahrir) represents the lowest value ranging between 800 and 900 W/m^2. Regions of Assiut, Khargha, Sidi Barani, Aswan, Abu Rudies and Marsa Matrouh represent the average value ranging between 1000 and 1300 W/m^2, while Hyrghada has the value of 2065 W/m^2 which represents the highest value of hybrid energy because of the high energy generated from the wind. Generally, Zafarana, Al-Arish, Matrouh and Khargha have the highest wind energy values. Zafarana wind farm has a very effective and positive environmental impact to obtain an amount of energy of 600 MW/year.

Winter is the lowest season of the year in which the amount of solar energy in Egypt is generated. Three lines pass through the land of Egypt representing the main features of the amounts of energy:

1. The first line includes the northern coast and the Nile Delta, in which the lowest solar energy ranges in Egypt during the four seasons, scoring its lowest amount of solar energy in Sidi Barani and in Al-Arish.
2. The second line runs from west to east through Mallawy.
3. The third line runs from west to north east of the city of Luxor.

In spring, solar energy rises clearly because of the increase of the solar energy and two main lines pass over Egypt:

1. The first line includes northern and middle Egypt up to Assiut.
2. The second line passes north of Luxor up to the north of Ras Banas.

In summer, the amount of solar energy rises above the line and runs from the northwest to the southeast starting from Siwa to the southern end of the Gulf of Suez. In autumn, the amount of solar energy and only a line representing an amount of energy passing Assiut is plotted.

The monthly average of the amount of solar energy reaching Egypt varies from one month to another and also from the south to the north during one month. But it is characterized by an increase in the amount of energy from north to south during the months according to the season. Hurghada is considered one the best websites that give higher value (2065 W/m^2) because it has the highest value of wind power and solar energy.

Also, it is clear from Fig. 12 that more advantaged areas of percentage for a hybrid system of solar and wind energy for different regions in Egypt are Hurghada, Marsa Matrouh, Abu Rudies, Aswan, Sidi Barani, Khargha, Assiut, Al-Tahrir, Bahteem, Al-Arish and Cairo respectively with a lineal percentage of 1, 0.7, 0.68, 0.66, 0.64, 0.62, 0.56, 0.453, 0.451, 0.449 and 0.421 respectively.

8 Conclusion

Global solar radiation and wind speed are the most important sources of renewable energy available in Egypt. The availability of sunshine all over the year with global solar radiation varies from 5 to 8 kwh/m^2/day. Accordingly, 5 to 13 m/s wind speed is needed, which is available in Egypt in different locations such as: Zafarana, Al-Arish, Marsa Matrouh and Khargha. Zafarana wind farm has a very effective and positive environmental impact to obtain an amount of energy of 600 MW/year. According to the national strategy, wind and solar power are to be used to cover ~20% of total demand in the country by 2027. Hence, a carefully balanced mix is to be adopted taking in consideration the regional integration with more reliance on the introduction of concentrated solar technologies.

The storage unit, containing an energy *B(t)* at hybrid solar/wind energy at different locations over Egypt, has a minimum value of 870 W/m^2, maximum value of 2065 W/m^2, mean value of 1250 W/m^2, and standard deviation value of 348 W/m^2.

Hurghada is considered one the best websites that give higher value because it has the highest value of wind power and solar energy.

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