Solar and Wind Energy Potential in the Tabuk Region, Saudi Arabia

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Abstract

The global demand for renewable energy in the recent years is increasing in the context of increasing demand for power as well as the energy security in future. Most renewable energy comes either directly or indirectly from the sun. Sunlight, or solar energy, is a form of clean energy and can be used directly for generating electricity for a variety of commercial and industrial uses. It is the best form of energy from an environmental perspective. The sun's heat also drives the winds, whose energy, is captured with wind turbines and converted in electrical power. The annual growth of power consumption in KSA is estimated to be at 7.5 %. To meet this increasing demands, Saudi Arabia has already started extracting renewable energy from the sun, wind, nuclear and geothermal sources .In this study, we intend to review the possibilities of solar and wind energy sources applicable to Saudi Arabia, specific to the Tabuk region based on its topography and climatic conditions. Solar and wind data for 6 regions in the Tabuk province for a period of 12 months is used in this study. The solar and wind data used is recorded by the Solar and Wind Resource Monitoring Stations of the King Abdullah City for Atomic and Renewable Energy (KACARE) program and the Presidency of Meteorology and Environment, Saudi Arabi. The seasonal variations in the wind and solar parameters were studied. The wind energy potential for the 6 stations were also calculated. The analysis shows that out of the 6 stations, the coastal station of Haql has got the highest wind potential whereas the inland stations of Tabuk and Timaa has the highest solar power potential.

Keywords: Solar energy, wind potential, renewable energy, Saudi Arabia

Introduction

Energy in Saudi Arabia primarily involves petroleum production, consumption and export. Saudi Arabia is the world's largest holder of crude oil proved reserves and was the largest exporter of total petroleum liquids in 2013. In 2013, Saudi Arabia was the world's 2^{nd}largest petroleum liquids producer behind the United States and was the world's 2^{nd}largest crude oil producer behind Russia. Saudi Arabia's economy remains heavily dependent on petroleum.

Saudi Arabia is one of the few countries that burn crude oil for power generation. The domestic use of fossil fuels for generating electricity is increasing every year due to increasing demand for electricity. This demand is driven by the population growth and a rapidly increasing industrial sector. In 2013, Saudi Arabia has consumed 2.9 mb/d of oil, which was almost double the consumption in 2010 and 4.2 % more than the 2012 value. According to the Joint Organization Data Initiative (JODI), in July 2014, the country has burnt an average of 0.9 mb/d of crude oil, which is the highest ever recorded data in JODI for the month of July.

According to the BP statistical Review of World Energy 2014, Saudi Arabia generated 292.2 billion kWh of electricity in 2013, 7% more than that in 2012 and more than double in 2000. It also faces a sharp increase in the demand for power. Recent reports reveal that the power consumption in the country has shown an average increase of 8 % in the last decade. The number of subscribers has risen by an average of 5.2 %. Housing sector consumes 50 % of the total electricity produced. There has been an increase of 6.9 % in the electricity consumption by industries. This enhanced use of fossil fuel burning has resulted in an increase in the amount of carbon dioxide released into the atmosphere. In 2013, the amount of CO_2 released into the atmosphere by the combustion of fuels in Saudi Arabia was 458.8 million tons as against 429.8 million tons in 2012. It has recorded an overall increase of 203.7 % from its value in 1990.

Electricity use is increasing at about 7.5% annually, thereby raising the overall energy demand nationwide. Unless alternative energy and energy conservation methods are adopted, the overall demand for fossil fuel for power generation is expected to grow from 3.4 mb/d in 2010 to 8.3 mb/d in 2028. This diversion of oil to the power sector will potentially cut the export revenue significantly. The potential danger in the health of future generation due to increasing green house gases and other pollutants is another basic problem to be addressed in relation to the increased use of fossil fuel.

To overcome this crisis in future, Saudi Arabia plans to diversify its power generation sources and improve the overall efficiency. Saudi Arabia intends to capitalize on its solar power capacity to fulfill its energy requirement in future. The major requirements for various renewable resources, indicate that the most sustainable sources of renewable energy for Saudi Arabia are photovoltaic (PV) and concentrated solar power (CSP), geothermal, wind energy and waste-to-energy. With remarkably high solar radiation ofaround 2,550 kWh/m^2 per year, along with the availability of vast areas of empty desert that can host solar installations, Saudi Arabia turns out to be an ideal location for both CSP and PV power generation. The Kingdom has viable wind energy potential, with close to five hours of full-load wind per day on average. The Arabian Gulf and the Red Sea coastal areas are Saudi Arabia’s main regions with potential for wind energy development.

In the global perspective, Cristina and mark J (2005) has studied the global wind potential using 1.5 MW wind turbines at a hub height of 80m and projected a worldwide potential of 72000 GW. There have also been many studies focused on regional levels that indicate a vast potential of wind energy. The US based National Renewable Energy Laboratory (NREL) has carried out a number of studies and developed wind maps for many countries. In the International level, there are many agencies that are involved in developing wind maps for different parts of the world. The Energy Sector Management and Assistance Program (ESMAP) of the World Bank is one such organization involved in developing wind maps of different regions.

Similar studies are been reported on regional basis also. Ramazan K et.al (2004), Poje and Cividine (1998), Sansui and Abisoye(2011), Yahya et.al (2010) , Youm et.al (2005), G Louis(1986), Ramachandran et.al(1996), Sulaiman et.al(2002), Boudia et.al (2013) are some of the works done in this field.

Many studies related to the wind resource assessment for Saudi Arabia has also been published. Martin (1985) using wind data for 20 locations studied the wind potential in these stations and found that wind energy potential is small in the country, but not negligible. It was found to be higher in the coastal locations and the northern part of the country. Khogali et.al (1991) has studied the feasibility of wind and solar energy potential in the Makkah region ofSaudi Arabia. They found that moderate wind energy potential is available along the red sea coast between 16-26° latitudes, while in the inland regions, it decreases. They also found that solar energy offers better prospects in Makkah. Rehman and Halawani (1994) studied the statistical characteristics of winds in 10 locations in Saudi Arabia. Radhwan (1994) took data from 20 weather stations for 10 years and studied the wind patterns in remote areas in the country. His analysis also confirmed that the wind potential is more prominent in the northern and coastal regions. Shahid and Elhadidy (1994) using hourly mean wind speed and solar radiation data during 1987-1990 in Dahran reported that the wind speeds vary between 2.5 – 6.9 m/s and solar radiation between 3.46 – 7.43 kWh/m^2 . A complete description of the site specification, equipments and other technical details of the wind energy harnessing in Saudi Arabia is given by Alawaji (1996). Rahman et.al (1994) calculated the shape and scale parameters of Weibull distribution function for 10 locations in Saudi Arabia, using daily mean wind speed data from 1970-1990. They concluded that wind data in these locations can be well represented by Weibull Distribution function.

Rehman et.al (2003), estimated the wind power cost per kWh of electricity produced using 3 types of wind electric conversion systems at 20 locations. They found that compared to the inland stations , the coastal locations has the required wind speed for generating electricity during more than 50 % of the year. The minimum cost of electricity generated using 2500, 1300 and 600 kW machines were found to be 0.0234, 0.0295 and 0.0438 US$ per kWh respectively in Yanbu while the corresponding maximum values were 0.0706, 0.0829 and 0.121 US$ per kWh in Najran.

Rehman and Ahmad (2004) again investigated 5 coastal locations in Saudi Arabia for wind energy potential using hourly values of wind speed and direction for 14 years. They found that out of the 5 locations, Yanbu in the west coast is the best location for extracting wind potential, followed by Dehran in the east coast.

Rehman (2004) used hourly wind speed and direction for 14 years from 1970-1983 for studying the long term wind characteristics in terms of annual, seasonal and diurnal variations. His studies showed that the seasonal and diurnal pattern of wind speed matches with the electricity load pattern. He also showed that higher winds of ~5m/s or more are available during summer months and confirmed that Yanbu is a potential location for wind energy extraction in Saudi Arabia.

Another study by Naif (2005) taking data for 5 locations for Saudi Arabia between 1995-2002 has shown that Dhulum which is a high altitude station and Arar have the highest wind potential among the 5. Rehman (2005) describes the energy output of wind farms in terms of the total energy, renewable energy delivered and farm capacity factor in 5 locations. His study concluded that wind parks are economically feasible at Yanbu and Dhahran only. Elhadidy and Shahid (2007) studied the wind characteristics over Dhahran using hourly mean wind data from 1986-1997 and concluded that Dhahran experiences monthly average wind speeds of the order of 4.2-6.4 m/s. In view of this much of the available energy in wind can be harnessed. They also found that the hub height is an important parameter in energy generation. From 30-50 m height, the energy production increased by 12 %.

Similar studies have been done for solar energy assessment also. In 1977 King Abdullah City for

Science and Technology (KACST) has started a major research program for developing solar energy technology. Pazheri (2014) has given an update of the solar energy projects in KSA including the current status and future prospects. Al Masoud and Gandayh (2014) also explain the future of solar energy in Saudi Arabia.

Baras et.al (2012) described the opportunities and challenges of solar energy is Saudi Arabia including the over heating and cooling mechanisms as well as solar thermal processes and desalination opportunities. They focused on two of the many challenges faced by the solar energy field in Saudi Arabia. They found the effect of temperature in the energy reduction in Riyadh to be around 16.5 % and also that solar thermal energy approach is maximum economical in the desalination plants compared to fossil fuels.

Data and Method of Analysis

Data: This study aims to explore the availability of wind energy resources in the Tabuk region based on the data available from different regions. Six locations in Tabuk province are chosen for this purpose. They are Tabuk, Timaa, Haql, AlWajh, Duba and Umluj. The details of all the stations are given in Table 1.

Table 1: Details of Stations used

No	Station	Latitude	Longitude	Altitude (m)
1	Tabuk	28.38	36.48	786
2	Duba	27.34	35.72	45
3	AlWajh	26.25	36.44	26
4	UmLuj	25.00	37.27	10
5	Timaa	27.61	38.52	862
6	Haql	29.28	34.93	36

The data for this study is the monthly average wind speeds in the 6 locations for a 12 month period from Oct 2013 – September 2014 . For Tabuk, Duba, Umluj and Al Wajh, meteorological data is available at 10m height. For Timaa and Haql, since meteorological wind data at 10m is not available, data at 3 m height recorded by the solar and wind resource monitoring stations of the KACARE program are used. The data is then normalized to 10m height using $1/7^{th}$ wind power law.

Methods Adopted

(i) Vertical Winds

The winds near the earth's surface vary with height and this variation is an important factor in the establishment of wind turbines at a certain location. This makes it important to have an equation that predicts the velocity of wind at a particular height, in terms of the measured wind velocity at another height based on the atmospheric conditions. The wind power law gives this relationship between wind speeds at one height to those at other heights.

$v_2 / v_1 = [h_2 / h_1]^{\alpha}$ ------------------ (1)

where v_2 is the velocity at the height h_2 and v_1 is the velocity at the measurement height v_1. The exponent α is an empirical value derived from atmospheric conditions. Empirical studies have found that an α value of 1/7~ 0.143 best fits most of the sites. This method therefore is generally known as the 'one-seventh' power law. This value of 0.143 is used in this study to normalize the wind speeds at different heights.

(ii) Wind Power Density

Power in wind is due to the kinetic energy of a moving mass of air. The amount of energy that the wind carries increases as the velocity of the wind increases and hence the power also increases. The power that can be harvested from the wind depends on the swept area, i.e., the area through which the rotor blade passes, and the wind speed.

Power $P = 0.5 \rho v^3 A$ --------------------(2)

Where P is the power in Watts, ρ is the density of air in kg/m^3, v is the wind velocity in m/s and A is the area in m^2.

The Wind Power Density (WPD) is given as

$WPD = P/A = 0.5 \rho v^3 W/m^2$ ------------------------------ (3)

However, when only the monthly mean values are available, eqn (3) needs to be modified as

$WPD = 0.5 \rho v^3 \times EPF$ ------------------------------- (4)

Where EPF is the Energy Pattern Factor and is given as

$EPF = 1/ (n v_a^3) \times \Sigma v_i^3$ -------------------------------- (5)

where n is the no of data points, v_i is the velocity in each month and v_a is the average annual velocity. The air density is calculated as a function of the site elevation using the equation

$\rho = \rho_0 - (1.194 \times 10^{-4}) Z$ ------------------------------ (6)

Here ρ_0 is the mean density at sea level and is = 1.226 kg/m^3 and Z is the site elevation in meters.

(iii) Turbulence Intensity

Turbulence Intensity is an important parameter in the characterization of wind power production. Turbulence can be thought of as fluctuations in air flow. A steady flow of air would have low turbulence and an unsteady flow of air would have higher turbulence.

It is normally obtained by normalizing the standard deviation of the wind speed σ by the mean wind speed v_a over time.

$TI = \sigma / v_a$ -------------------------------- (7)

Solar Data used in this study is the monthly average values of GHI, DNI and DHI recorded by the solar and wind monitoring stations in the respective locations.

Results

Wind Data

(a) Average wind speeds : The average annual wind speeds at 10m height for all stations is shown in Figure 1. The highest annual average wind speed of 7.5 m/s was observed at Haql, while the lowest was recorded in Timaa as 2.85 m/s. Significant winds of 5.04 m/s and 4.39 m/s were observed in AlWajh and Duba respectively.

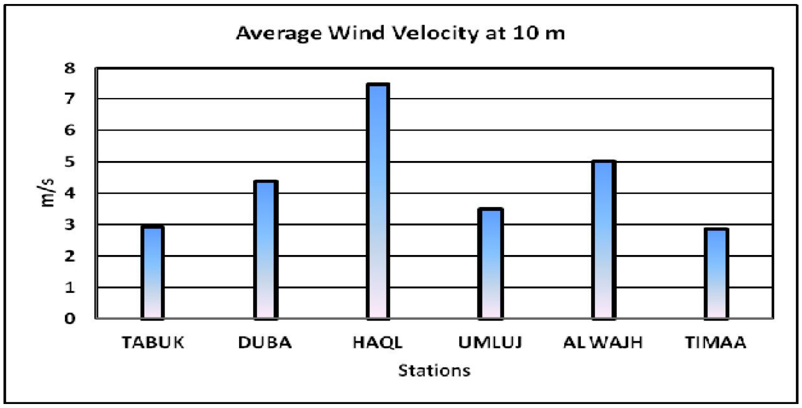


Figure 1: Average Wind at 10m Height for all the Stations

(b) Seasonal Behavior of winds: The seasonal variation of the mean wind speeds at 10m height at all the stations is shown in Figure 2**.** Except for stations Haql and AlWajh, not much variation is seen. Timaa recorded the minimum average wind while Haql recorded the highest

average wind speed. Compared to other stations, strong seasonal variation of wind is seen at Al Wajh.

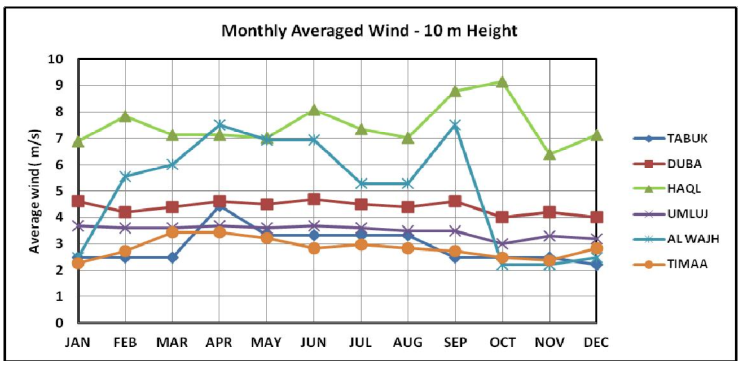


Figure 2: Seasonal Variation of Monthly Mean Winds at 10 m for all the Stations

The winter months of Oct – Jan shows the minimum winds while the seasonal transition months of April (Winter to Summer) and again September (Summer-Winter) show maximum wind speeds of around 7.5 m/s.

The seasonal patterns observed for the different stations are summarized below.

Tabuk - Maximum wind speed of 4.4 m/s was observed in April and minimum of 2.2m/s in December. Not much seasonal variation was observed.

Duba- Maximum wind speed of 4.61 m/s was observed during April and minimum 4 m/s in December. Not much seasonal variations were observed.

Haql – Does not show much seasonal variation. Maximum winds were 9.15 m/s and was observed in October while the minimum of 7.01 m/s was observed during the months of May and August.

Umluj – Winds remained almost steady during the 12 months. Maximum winds were during the month of April and minimum during October.

Al Wajh – This is the only station where the seasonal variations were prominently seen. Maximum winds were observed during summer months and minimum during winter season.

Timaa – Winds in Timaa does not show any prominent variations during the period of study.

However, the wind velocity is found to increase during March-April months.

(c) Wind Power Density: Figure3 shows the wind power density calculated using eqn (4) at 10m above the ground. It is seen that out of the 6 stations, only 3 stations are showing a wind power potential above 50 W/m^2 at 10m. They are Duba, Haql and Al Wajh. This is possible only if the wind speed exceeds 4.5m/s. Al Wajh shows a wind potential of 114.6 W/m^2 with an average wind velocity of 5.04m/s and Haql offers the maximum wind power density of 265.72 W/m^2 with an average wind velocity of 7.49 m/s.

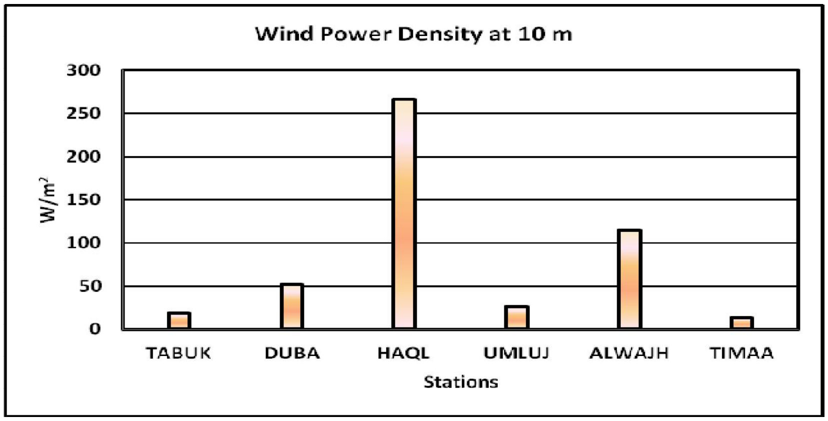


Figure 3: Wind Power Density at 10 m Height for all the Stations

(d) Turbulence Intensity: Figure4 shows the turbulent intensity calculated at 10m height for all the stations. It is seen that annual turbulence intensity has the minimum value in Duba and maximum in Al Wajh.

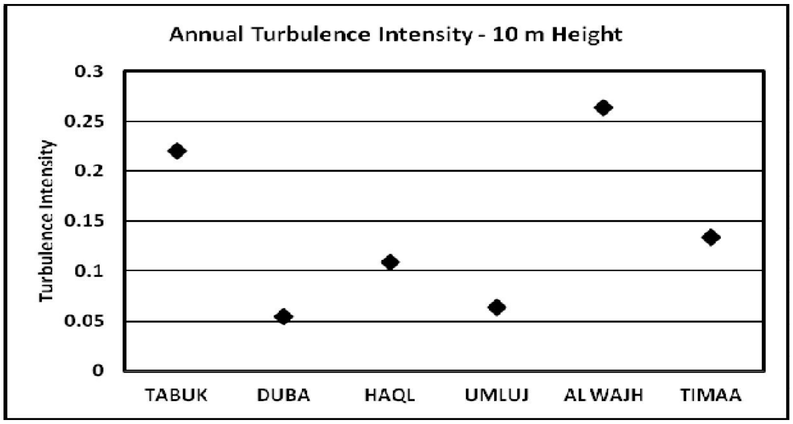


Figure 4: The Annual Turbulence Intensity for all the Stations

(e) Effect of hub height on wind energy production: In order to assess the effect of hub height, wind energy calculations are made at 30,40,50,80 and 100m above ground. The wind velocity at each height is calculated using the $1/7^{th}$ power law. Figure 5shows the extrapolated wind velocity at 10m, 20m, 30m, 40m, 50m, 80m and 100 m.

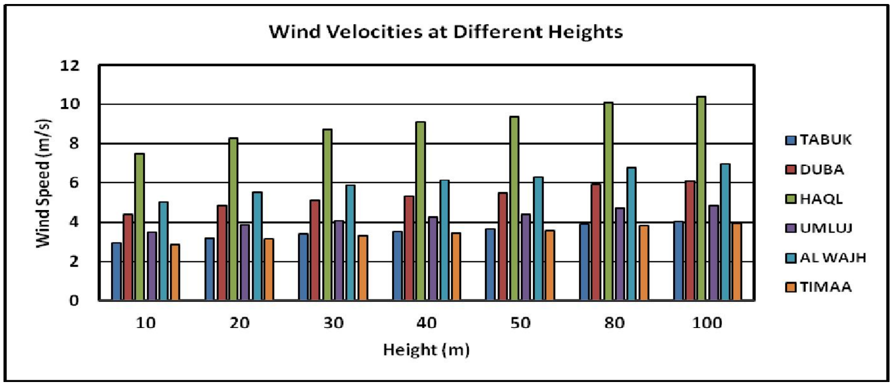


Figure 5: The Extrapolated Wind Velocity Values at Different Heights

The figure shows that at 100m Haql can expect winds of the order of >10m/s, which is a potentially high wind for wind energy generation.

Figure 6 shows the corresponding wind power densities at different heights. The inland stations of Tabuk and Timaa do not show significant power density even at a hub height of 100m. Umluj shows a WPD of 52.11 W/m^2 at a hub height of 50m. Duba, Al Wajh and Haql have wind power densities more than 100 W/m^2 above 40m height.

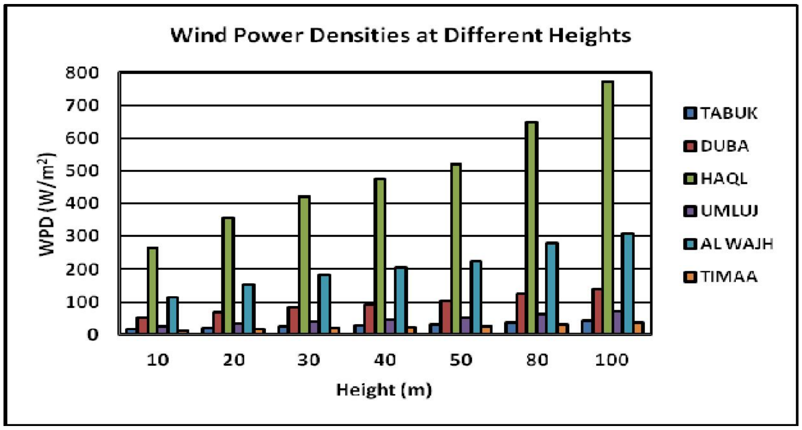
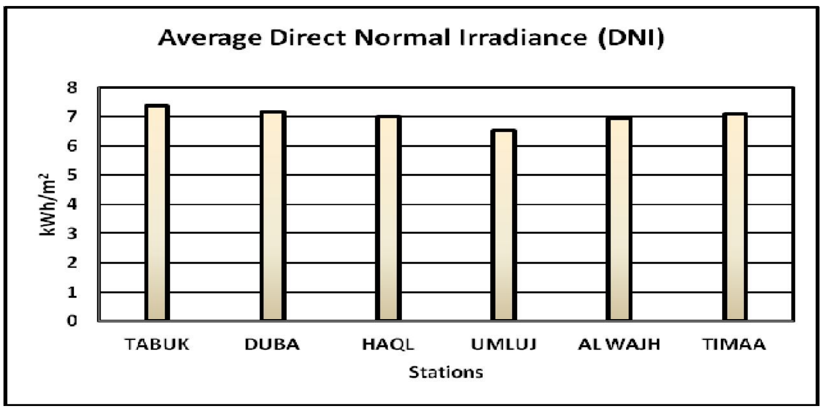
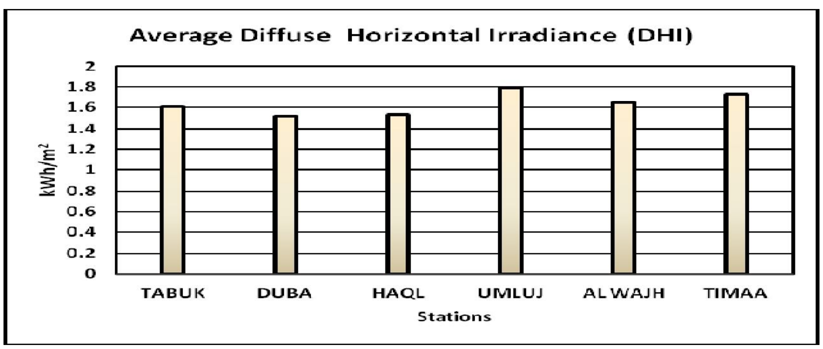


Figure 6: The Wind Power Density Calculated at Different Heights for all the Stations

Solar Data

To get an overview of the solar energy potential in the Tabuk province, the monthly and annual average values of the 3 components like DNI, DHI and GHI are analyzed for all the 12 months and are shown in Fig 7 and 8.





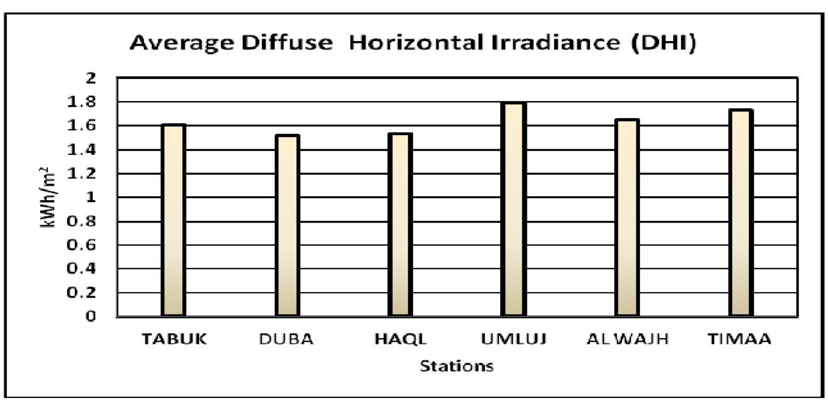


Figure 7: The Average Annual Components of Solar Radiation in Tabuk Province

The minimum DNI was observed at Umluj and maximum in Tabuk. For the diffuse part of the solar radiation, the maximum was observed in Umluj and minimum in Duba. The total radiation was maximum in Tabuk and minimum in Haql

Figure 8 shows the monthly averaged components of solar radiation during the period.

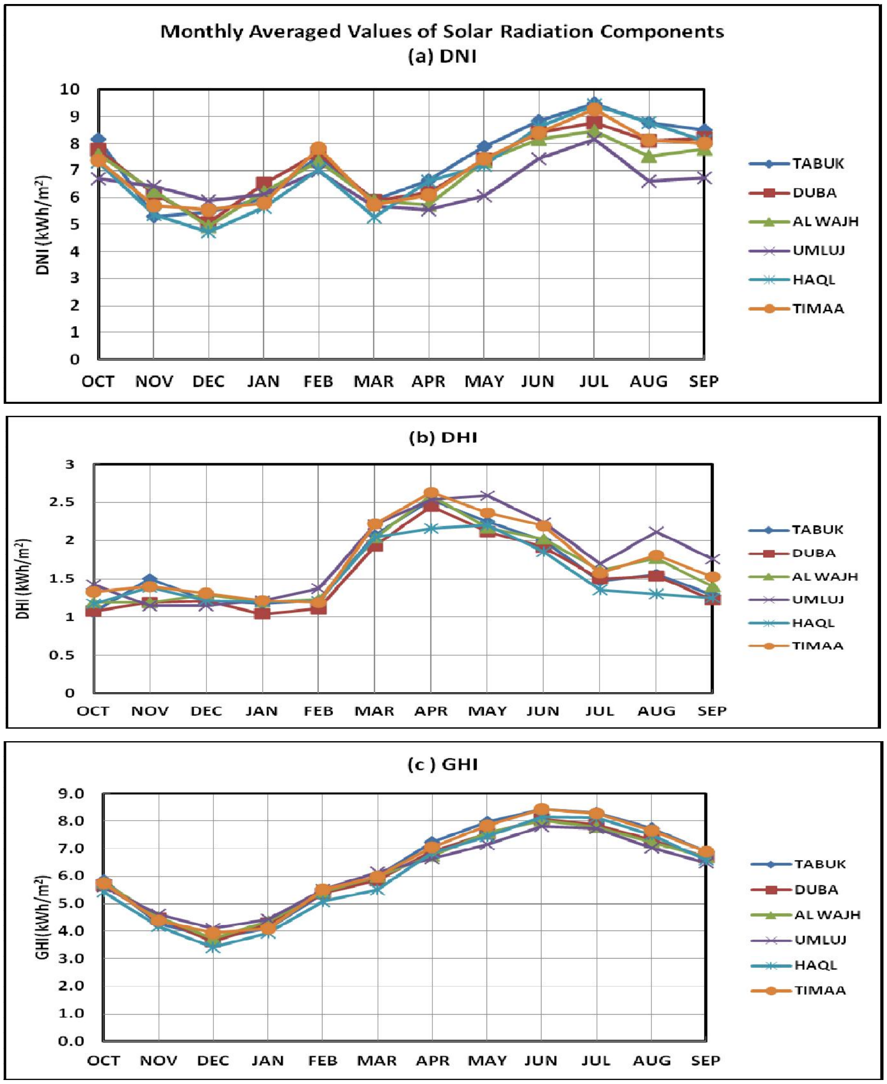


Figure 8: Seasonal Variations of DNI, DHI and GHI in the Tabuk Province

The direct component of the solar radiation is found to start increasing by March and reaches a maximum in the summer peak of July. Tabuk record the maximum during this time. There after it decreases till December and a secondary peak is observed during February. The diffuse part increases after the month of February and reaches a maximum in April. There after it also decreases and reaches a minimum in July. Again there is a slight increase during the month of August and after that it continues to decrease. The same pattern is followed in all the stations.

For the total part, irradiance is found to be a maximum during summer months of June-July and minimum during winter months.

Discussion

The main aim of this study was to review and identify the potential renewable energy resources in the Tabuk region. The earlier studies on similar fields identified Tabuk to have the minimum solar radiation in Saudi Arabia. However, measurements with the solar and wind resource monitoring stations in 29 stations spread over Saudi Arabia, shows that Tabuk is the station with maximum DNI, along with other stations in the Tabuk province. Measurements also shows that July 2014 was the sunniest month recorded in many stations since its establishment in 2013.

The areas with the highest DNI readings for July 2014 are in northwest Saudi Arabia in the stations of Tabuk, Haql and Timaa.

The direct normal irradiance shows a seasonal pattern. Generally summer months experience highest solar radiations due to longer days and clear skies. During winter, the days are shorter and the sun is lower in the sky which makes the sunlight travel longer distances through the atmosphere, and getting scattered by the atmospheric particles. This explains the maximum and minimum radiations in July and December respectively.

GHI also shows similar seasonal pattern like DNI. Local weather conditions have a significant effect on the seasonal and short term solar radiations. A sudden decrease in DNI values is observed during the month of March. March is part of the spring season between the winter and summer seasons in Saudi Arabia. Thunderstorms and cloudy days are common in the northern regions during this season. This would have obstructed the direct radiations from reaching the ground and resulted in the sudden decrease of DNI. A weather consolidation based on the data for Tabuk recorded at the Tabuk International Airport in 2014 shows that the *cloudiest month of* 2014 was March, with 10% of days being more cloudy than clear. The increase in the diffuse component also can be explained based on this. The seasonal variations in solar radiation seems to have a positive correlation with the energy demand during summer where a peak demand in electricity is observed.

Wind energy is a form of solar energy which is caused due to change in pressure in the lower atmosphere, due to uneven heating of the earth's surface. It is known that the wind speed is the most essential part of predicting the available wind energy potential in a location. Hence modeling the wind speeds for predicting the winds is an important part of the study on wind energy potential.

The monthly averaged wind speeds from all the stations does not exhibit seasonal trends. It is been found that except Haql and Al Wajh, all the other 4 stations show almost steady winds throughout the one year period. Haql records the maximum wind speed followed by Al Wajh and Duba. The high altitude stations of Tabuk and Timaa shows only small wind velocities. The vertical wind profiles are also estimated, since in the design of wind turbine, information on the different heights is very important. Moreover, it helps to determine the appropriate hub height of the wind farms.

Normally winds with velocities more than 4.5 m/s are considered important in the wind energy assessment. In this study it is seen that winds in Haql and Al Wajh experience wind velocities more than this at 10m height itself. Winds in Duba attain this velocity at 20m and above, while Tabuk and Timaa does not show wind speeds > 4.5 m/s even at 100m. Umluj shows a wind speed of ~ 4.8 m/s at 100m. For a wind speed of 6m/s, Al Wajh hub height has to be above 30m. However in Haql, the wind speeds increase to 8.27 m/s in 20 m itself and the maximum wind speed that can be expected at 100m hub is around 10.42 m/s.

The corresponding wind power density also shows that in the high altitude stations of Tabuk and Timaa, the wind energy potential is very less. This is due to the low wind velocities and also the decreasing air density due to high elevation. It can be seen that at 50m, the wind power density becomes almost 60 % of its value at 10m for Haql and Al Wajh and almost 3 times at the hub height of 100m. An increase of 33% in the energy value can be achieved even if the hub height is increased to 20m. This increase in energy with increase of hub height is already been studied by different researchers, M. Alam et.al (2011), M Schwartz and D Elliott (2005). A common practice in wind energy assessment is to analyze data from shorter heights and extrapolate it to turbine hub heights for wind farm designs. This kind of an extrapolation using standard power law normally gives a good representation of the winds below 80m.

Wind normally remains steady from year to year, but short term fluctuations are normal. Since the power density equation is a cubic speed relation, it is necessary that one has to use all the data available without any average like the monthly or annual average. Since hourly wind values were not available for all the stations, the monthly average value of wind speed is used in this study. To overcome this limitation, the modified power density equation including the Energy Pattern Factor is used.

A good wind resource requires strong winds. Wind speed is determined by atmospheric conditions and terrain. Even in areas that are generally windy, local conditions may determine whether the wind resources are adequate or not. A detailed wind resource assessment can only provide the information necessary to determine whether wind is a viable source of renewable energy at a location. A detailed assessment requires information like where it is windy, and at what time of the day and year it tends to be the strongest.

This study was planned to review the solar and wind energy potential in the Tabuk region of Saudi Arabia. From this study with the limited data set of 12 months from the 6 major regions in the Tabuk province, it can be concluded that Haql has the highest potential of wind energy with the maximum wind speed throughout the year. Al Wajh is the next station with an annual average wind speed of 5.04m/s. Duba and Umluj are also found to have some potential of wind power provided the hub height is above 50m. The other two regions of Tabuk and Timaa are not having adequate wind speeds for tapping the wind energy. When it comes to solar energy, Tabuk and Timaa show the maximum solar irradiance in both the normal and total components. Duba and Haql also show almost same potential for solar power.

In conclusion, Haql is the most suitable station for wind energy potential and Tabuk and Timaa stands out as the major regions from which solar energy can be harnessed.

Acknowledgements

The authors would like to thank the Deanship of Scientific Research, University of Tabuk and his office for providing an opportunity and support to take up this research project. The total work is financed by the Deanship of Research, University of Tabuk. We acknowledge our gratitude to the Team Atlas of the King Abdulla City for Atomic and Renewable Energy (KACARE) Riyadh for providing the solar and wind data for this study.

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