Theoretical Analysis of a Solar PV-Wind Hybrid Power System for Energy Generation in Kutch Region

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Abstract. - Solar PV-Wind Hybrid Power System that uses renewable sources to supply power to grid to meet the power requirement. Theoretical Mathematical Modeling and its Generation analysis showed that solar radiation and wind are the most important physical variables for the Solar PV-Wind power system design. The study proposes Solar PV-Wind based system, affordable by local government standards to respond to the electricity demand of that state, is the one with an irradiance between 2.6 to 7 kWh/Day/m² and wind speed between 6.6 to 15.5 miles per hour. The annual average daily yield, annual average monthly yield and total average Capacity Utilization Factor (CUF) are 5 kWh/kWp/Day, 157 kWh/kWp/Month and 21 % Respectively for solar pv-wind hybrid power system total Generation for Kutch region. The model shows that with the help of Solar PV-Wind Hybrid Power System we can forecast the energy generation of minimum 30 % and maximum 70 % energy generation which can be utilize in state with the modification of existing infrastructure hence infrastructure cost can be saved and waste land between the wind mills can also be utilized.

1. Introduction
India has set an ambitious target of reaching 175 GW of installed capacity from renewable energy sources by the year 2022, which includes 100 GW of solar and 60 GW of wind power capacity. Various policy initiatives have been taken to achieve this target. At the end of 2017-18 the total renewable power installed capacity in the country was almost 70 GW. Solar and wind power being variable in nature pose certain challenges on grid security and stability. Studies revealed that in India solar and wind resources are complementary to each other and hybridization of these two technologies would help in minimizing the variability apart from optimally utilizing the infrastructure including land and transmission system. Superimposition of wind and solar resource maps shows that there are large areas where both wind and solar have high to moderate potential. The existing wind farms have scope of adding solar PV capacity and similarly there may be wind potential in the vicinity of existing solar PV plant. [1]

In Kutch region, the summers are short, sweltering, muggy, and windy; the winters are short and comfortable; and it is dry and mostly clear year-round. Over the course of the year, the temperature typically varies from 53°F to 101°F. [4]
Fig 1: Color contour plot showing average hourly temperature through the entire year. The horizontal axis is the day of the year, the vertical axis is the hour of the day, and the color is the average temperature for that hour and day. The average hourly temperature, color coded into bands. The shaded overlays indicate night and civil twilight.

![Image of color contour plot]

Figure 1. Average hourly temperature

1.1 Solar Energy
This section discusses the total daily incident shortwave solar energy reaching the surface of the ground over a wide area, taking full account of seasonal variations in the length of the day, the elevation of the Sun above the horizon, and absorption by clouds and other atmospheric constituents. Shortwave radiation includes visible light and ultraviolet radiation.

Fig 2 caption: Average daily solar energy in the location (Kutch). The brighter period of the year lasts for 2.7 months, from March 24 to June 14, with an average daily incident shortwave energy per square meter above 6.9 kWh. The brightest day of the year is May 13, with an average of 7.4 kWh. The darker period of the year lasts for 2.5 months, from November 10 to January 25, with an average daily incident shortwave energy per square meter below 5.2 kWh. The darkest day of the year is December 20, with an average of 4.6 kWh.

![Image of average daily solar energy graph]

Figure 2. Average daily solar energy

The average hourly wind speed in Kutch Region experiences extreme seasonal variation over the course of the year.

1.2 Wind Energy
The windier part of the year lasts for 4.7 months, from April 15 to September 7, with average wind speeds of more than 11.1 miles per hour. The windiest day of the year is July 1, with an average hourly wind speed of 15.5 miles per hour. The calmer time of year lasts for 7.3 months, from September 7 to April 15. The calmest day of the year is November 5, with an average hourly wind speed of 6.6 miles per hour.

Figure 3 discusses the wide-area hourly average wind vector (speed and direction) at 10 meters above the ground. The wind experienced at any given location is highly dependent on local topography and other factors, and instantaneous wind speed and direction vary more widely than hourly averages. The predominant average hourly wind direction in Kutch Region varies throughout the year. The wind is most often from the west for 8.2 months, from February 21 to October 28, with a peak percentage of 94% on May 14. The wind is most often from the north for 3.8 months, from October 28 to February 21, with a peak percentage of 69% on January 1.[4]

Solar PV-Wind Hybrid Power Systems have several advantages like

- We can save a billion dollars if we can manage a grid power generation and distribution.
- Solar PV-Wind Hybrid Power Systems could solve the energy crisis. It is “energy security” to the power industry.
- The Solar PV-Wind Hybrid Power System allows one to decrease overall costs and emissions without requiring any change in daily lifestyles.
- Viable for regions with developing infrastructures.

Researchers all over the world are making huge efforts to study Solar PV-Wind Hybrid Systems and to construct test beds and demonstration sites, while the classification of Solar PV-Wind Hybrid Systems and relevant key technologies need to be addressed. In this paper, we have discussed the concept of energy generation using Solar PV-Wind Hybrid Systems based on their respective integration levels into the grid, their different responsibilities, relevant key technologies in the deployment of Solar PV-Wind Hybrid Systems.

2. Theoretical Mathematical Analysis

2.1. Theory and Assumption: Solar Energy

2.1.1. Total Radiation tilted surface

The Radiation on a tilted surface of the collector will be the sum of direct, diffuse and reflected radiation

\[ I_{T} = I_{b}r_{b} + I_{d}r_{d} + (I_{b} + I_{d}) I_{r} \]  

(1)

Where \( I_{b} \), \( I_{d} \) and \( I_{r} \) are the instantaneous values of beam, diffuse and direct radiation, respectively, and \( r_{b} \), \( r_{d} \) and \( r_{r} \) are the tilt factors for the beam, diffuse and reflected radiations, respectively.
2.1.2. Annual average solar radiation on tilted panels (shadings not included)

To estimate the amount of solar radiation falling on a solar collector at a given time and location, the direct or beam radiation and diffuse radiation should be either measured or estimated using empirical equations. The monthly average daily global radiation on a horizontal surface $H_{ga}$ is

$$
H_{ga} = {a + b / c}
$$

Where

$H_{oa}$ = monthly average extra-terrestrial solar radiation at horizontal surface

$S_a$ = monthly average daily sunshine hours

$S_{max}$ = maximum possible daily sunshine hours at a given location.

$a$ and $b$ are constants.

2.1.3. Performance Ratio

Performance ratio (PR) is defined as the ration of the Energy injected to the Grid ($Y_f$) to the energy generation for the number of peak sun hours per day ($Y_r$). Performance ration indicates the overall effect of losses on the rated output of PV system due to Soiling or Component failure, Inverter inefficiency, PV module temperature loss, wiring mismatch etc. and is expressed as

$$
PR = Y_f/Y_r.
$$

2.1.4. PV module efficiency

The instantaneous PV module efficiency is given by [2-3].

$$
\eta = \left( \frac{P_{oc} / G * \eta_m}{100} \right)
$$

As a function of temperature, it can be represented as [2-3].

$$
\eta_T = \eta_{T_{ref}} \left[ 1 - \beta_{ref} (T - T_{ref}) \right]
$$

where,

$\eta_{T_{ref}}$ = Efficiency of PV module at reference temperature

$\beta_{ref}$ = the temperature coefficient of power

$T_{ref}$ = Reference temperature

$T$ = the cell temperature and is given by

$$
T = T_{amb} + 1.25 \times 10^{-3} G_t (NOCT-20)
$$

where, $T_{amb}$ is the ambient temperature, NOCT is Nominal operating cell temperature of module declared by the manufacturer and $G_t$ is the total in plane solar irradiation. One can reach in nominal incident condition under an irradiance of 800 W/m$^2$ and ambient temperature of 20 °C [2-3].

2.1.5. Estimation of the electricity generated in output of a photovoltaic system

$$
E = A_t * \eta * H_{ga} * PR
$$

$E$ =Energy (kWh)

$A_t$ =Total solar panel Area (m$^2$)

$\eta$ =Solar panel efficiency (%)

$H_{ga}$ =Annual average solar radiation on tilted panels (shadings not included)

$PR$ = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.7)

2.2. Theory and Assumption- Wind Energy

The fundamental equation governing the mechanical power of the wind turbine is given by

$$
P = \frac{1}{2} \rho \cdot A \cdot V^3
$$
Where,
\( C_p \) = Power Coefficient (0.593, also known as Betz’s coefficient.)
\( V \) = Wind Speed (m/sec)
\( \rho \) = Density (kg/m\(^3\))
\( A \) = Swept area of rotor (m\(^2\))

Base on the Equation number 7 we can calculate the theoretically Solar Energy Generation and similarly for the Wind Energy Generation from equation number 8. The result of the calculated wind, Solar PV, and Solar PV-Wind Hybrid system energy generation is shown in the Table 1.

3. Results and Discussion
The analysis is based on the above theoretical mathematical analysis section. The Month wise energy generation is as per below parameters used in the calculation of the system performance are given in Table 1.

| Table 1. Monthly Solar PV-Wind Hybrid Energy Generation |
|--------------------------------------------------------|
| **Month** | **Wind Energy (kWh)** | **Solar Energy (kWh)** | **Solar PV-Wind Hybrid Total Energy (kWh)** |
|-----------|------------------------|------------------------|---------------------------------------------|
| January   | 90                     | 144                    | 234                                         |
| February  | 81                     | 141                    | 222                                         |
| March     | 152                    | 154                    | 306                                         |
| April     | 303                    | 143                    | 446                                         |
| May       | 363                    | 156                    | 518                                         |
| June      | 292                    | 117                    | 408                                         |
| July      | 289                    | 60                     | 350                                         |
| August    | 248                    | 57                     | 305                                         |
| September | 100                    | 118                    | 219                                         |
| October   | 91                     | 154                    | 245                                         |
| November  | 108                    | 142                    | 250                                         |
| December  | 128                    | 139                    | 267                                         |

From Table 1, it can be seen that the Total Energy has a significant effect in increasing the Solar Radiation as well as Wind Speed. With the help of the both Solar and Wind energy source at one place we can get the monthly energy between 200 kWh to 500 kWh. Because high solar radiation and good wind speed in Monsoon we can get the minimum 300 kWh energy to Maximum 500 kWh energy between March to August month. Annual Total Wind Energy, Solar PV Energy and Solar PV-Wind Hybrid Generation are 2245 kWh/kWp, 1525 kWh/kWp and 3770 kWh.
Figure 4. Solar PV, Wind and Solar PV-Wind Hybrid power system daily energy(kWh)

Figure 4 shows Daily Solar PV Energy, Wind energy, Solar PV- Wind Hybrid Total Energy, Solar PV- Wind Hybrid Average Energy generation varies between 2 to 5 kWh, between 3 to 12 kWh, between 8 to 17 kWh and between 4 to 8 kWh respectively. Between April to June Wind energy Generation is double compare the Solar PV energy.

Figure 5. Solar PV, Wind and Solar PV-Wind Hybrid power system monthly Energy(kWh)

The Monthly Solar Energy generation varies between 57 to 156 kWh and Monthly Wind Energy generation varies between 81 kWh to 363 kWh. From the Total annual 3770 kWh Solar PV-Wind Energy generation around 2300 kWh energy generated between March to August. Between March to August 62 % energy generated of total energy. Between September to February Solar PV monthly generation is 30 % to 60 % higher compare to Wind monthly generation.

The CUF of Energy generation of Solar PV, Wind, Solar PV-Wind Hybrid Total Energy and Solar PV-Wind Hybrid Average Energy are presented in Figure 6. In October to February Solar Energy generation CUF is higher than Wind Energy generation CUF similarly In April to August Wind Energy Generation CUF is higher than Solar Energy generation CUF while in March and September both CUF are almost equal. Figure 6 shows that the theoretically calculated value of Monthly Solar Energy CUF varies between 8% to 21 % and Monthly Wind Energy CUF varies between 12 % to 49 % kWh.
Figure 6. Solar PV, Wind and Solar PV-Wind Hybrid Power System Monthly CUF (%)

Solar PV-Wind Hybrid Total Energy CUF varies between 30 % to 70 % and Solar PV-Wind Hybrid Average Energy CUF varies between 15 % to 35 %. This is a very conservative calculation for those countries which have Desert and coastal area. Higher Solar PV-Wind Hybrid Power System energy production is expected during the summer and rainy season (i.e. March to August) due to the higher radiation & wind speed during this period the CUF of Solar PV-Wind Hybrid Power System varies minimum 41 % to maximum 70%. Annual Average Daily Yield, Annual Average Monthly Yield and Annual Average CUF are 5 kWh/kWp/Day, 157 kWh/kWp/Year and 21 % respectively for Solar PV-Wind Hybrid Power System Generation for Kutch Region.

4. Conclusion

This work presents a theoretical analytical model to predict the performance of Solar PV-Wind Hybrid power system which can be installed in those countries which have Desert and costal area. The model showed excellent agreement with theoretical work. 1 kW of Solar PV and Wind Hybrid power system can generate together minimum 7 kWh to maximum 17 kWh daily. The model shows that with the help of Solar PV-Wind Hybrid Power System we can forecast the energy generation of minimum 30 % and maximum 70 % which can be utilize in the state with modification of existing infrastructure hence infrastructure cost can be saved and waste land between the wind mills can also be utilized.

5. References

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