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Optimal Photovoltaic Capacity Planning for Windfarm Expansion

Hamsadhwani V., Mohanrajan S. R.

***Abstract:** The hybridization of solar-wind projects is necessary to harness maximum potential of renewable energy resources. One of the ways to promote this is through optimizing the usage of land resources for solar and wind farms. It is acknowledged that the solar farms don't necessarily have good wind resources. But the on-shore wind farms are spread out over large areas, hence underutilizing the expensive land resource. This land area can be used to collect solar radiation cast in between the wind turbines to generate solar power.With the dramatic drop in solar photovoltaic technology and already existing electrical infrastructure in a wind farm, it would be economically advantageous to incorporate solar panels to an existing wind farm. The complementary characteristics of solar and wind energy resources also aids in smoothing the load curve, improving the operation economy. This paper presents a framework to optimize such an upgrade to maximize the energy harvested from hybrid wind-solar projects.*

One major constraint when placing the solar panels between the wind turbines is the shadowing of the wind turbines on the solar panels. It is hence required to calculate the area available for the placement of solar panels which is unaffected by the shadow of the wind turbines. A case study of Bogampatti wind farm is done to calculate the area available and maximum energy that can be extracted.

Index Terms: synergy, hybrid solar-wind, solar angles, shadow of wind turbine.

I. INTRODUCTION

Energy was treated as a commodity in the 20th century. Now, in the 21st century, energy is treated as an infrastructure. The history of commercial energy growth can be viewed in three phases: It started with dispersed micro-systems which were site-specific and manually operated. This moved on to centralized large power plants which are depleting resource based and not environment friendly. The third stage is much more advanced and centrally planned, automated and integrated distributed generation systems, predominantly targeting for renewable energy-based power production. Energy security is currently regarded as an important parameter in a country's well-being. For achieving this energy security, it is to be understood that increased power production is not the only solution. Sustainable power production as well as judicious use of the energy resources is more important. This has caused a paradigm shift on the power grid. The depletion of fossil fuels and the threats of climate change have limited the growth of centralized generation. Therefore, the penetration of renewable energy into the grid has been gradually increasing with time. Power generation from renewable energy resources is becoming more feasible as the technology improves. Solar PV has gained grid-parity and its installation is rapidly accelerating as the prices have dropped significantly in the recent past. India is blessed with adequate sunshine and a balanced wind speed. Hence there is greater scope for development of hybrid solar wind projects.

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***** Correspondence Author (s)

Hamsadhwani V., M. Tech student, Department of Electrical and Electronics Engineering, Amrita School of Engineering,Coimbatore, Amrita Vishwa Vidyapeetham, India.

Mohanrajan S. R., Assistant professor, Department of Electrical and Electronics Engineering, Amrita School of Engineering,Coimbatore, Amrita Vishwa Vidyapeetham, India.

II. GEOGRAPHICAL LIMITATIONS OF RENEWABLE ENERGY PROJECTS

The need of the hour for emission reduction and energy security has led to the much-needed advancement in power generation from renewable energy resources, especially wind and solar. Although we have developed enough technological know-how to generate power from these renewable resources individually, we still have not explored the full potential and optimized use of these resources. It is observed that the wind farms are spread over large areas to reduce the impact of wake effect. For micro-siting of wind farms, it is important to ascertain minimum distances between the individual wind turbines. Study shows that it is required to have a minimum spacing of three to five times the rotor diameters in the cross-wind directions and six to eight times the rotor diameters in the main wind direction between each of the turbines [3]. Also, to address the public criticisms of noise and shadowing, the wind farms are preferably placed far away from the residential areas. Although the sources of wind and solar are potentially infinite, the land availability for capturing these wind and solar resources is very much limited. With the alarming growth in population, the prices of land resources are expected to increase proportionately. Moreover, for an agriculture-based country like India, land is a highly priced and precious commodity. Ergo, land resource management is vital for economy and biodiversity conservation. One possible solution to the limited land availability is off-shore wind power plants. Although the off-shore winds are steadier and promising, the construction and maintenance of these off-shore plants are very expensive. The effects of the off-shore power plants on marine life is also of concern.

III. SYNERGIES OF SOLAR AND WIND POWER

Both solar and wind farms require vast areas of land to collect as much possible energy. The only difference is that in a solar farm, the solar panels are placed in far more proximity as compared to the wide expanse of the wind turbines.

Granted that the solar farms don't necessarily have good wind resources, but the wind farms do have vast areas of underutilized land between the turbines [2].

Hence, it is proposed that the land areas between wind turbines in a wind farm be used for placement of solar panels. The land and electrical infrastructure account for almost 25% of the investment in any renewable energy project. By sharing the land and electrical infrastructure and operating at a common point of grid connection, a synergy of solar and wind power can earn better returns [8].

It is well known that the intermittency of solar and wind energy is a critical challenge for grid stability. However, the wind and solar energy resources have different diurnal cycles. The solar power is more pronounced during the day and the winds are stronger during the evenings. The peak operating times of solar and wind not only complement daily, but also seasonally. Hence, the synergy of wind-solar resources not only reduces the dependency on one resource, but also provides reliable power round the clock [4], thus reducing the primary drawback of intermittency. A better generation profile can be achieved from a hybrid power plant than standalone plant [9].

Considering the falling trend in the prices of solar photovoltaic systems, it is attractive to capitalize on the synergies of solar and wind power plants.

IV. SHADOWING OF WIND TURBINES

The major constraint for the placement of solar panels in between the wind turbines is the shadowing of the wind turbines on the solar panels. Shadowing on photovoltaics modules has a devastating impact on their performances since it degrades the electricity production from the PV module [7]. Even a partial shading on the solar panels can virtually obliterate the output of an entire string. To avoid this inconvenience, it is essential to study the movement of sun's position in the sky and quantify the effects of shadowing of the wind turbine. Consider the plane in which the shadow of the wind turbine falls. In tropical regions, this shadow falls on all directions around the wind turbine. In subtropical regions, the shadow falls only in one half of the plane. By taking the location and time into consideration, the area around the wind turbine with possibility of shadowing is first calculated. The mathematical background required for this is presented in Section V and is experimentally verified in Section VI. With this, the shadow area is calculated in Section VII. For the calculated available area, the plant capacity of the hybrid solar-wind farm is then estimated in Section VIII. The sun's position in the sky shifts continuously in the East-West and North-South directions. Accordingly, the turbine's shadow will vary throughout the day and year. The length of the turbine's shadow depends on how high or low the sun is in the sky. This is the foremost consideration for the placement of solar panels in the shadow regions. The effect of partial and dynamic shading of solar panels is critical for the solar panel's performance as well as the reduction in output power produced.

The turbine shading is of two types:

A. Tower shading

This is the most significant shadow. It varies with the movement of the sun in the sky. The losses due to this partial shadowing is worthy of consideration. Although some degree of shading is inevitable in a hybrid solar-wind farm, the area around the wind turbine where the shadow is most likely to fall should be discarded for placement of solar panels.

B. Flickering

Blade shadow called flickering, which changes rapidly with time. Flickering refers to the alternating in light intensity due the rotation of wind turbine blades. The effect of flickering is far less when compared to the tower shading. Hence, the losses incurred due to shadow flickering would not undermine the viability of a hybrid wind-solar project. In this paper, only the effect of tower shading is considered for shadow calculations.

V. MATHEMATICAL FORMULATION

The axial tilt of Earth, its rotation about its axis and revolution around the sun are responsible for changes in the sun's position in the sky all over the day and year.

Accurate determination of the sun's position is very much essential in order to quantify the shadow cast by the wind turbines, which changes in length and direction throughout the day and year. This can be assessed using various angles that have been defined to locate the sun's position at any time of the day throughout the year. Since the shadow patterns repeat on a yearly basis, the shadow calculations are also done for a year.

This section consists of two parts:

The first part defines the solar angles used in the shadow calculations. There are four significant solar angles – Solar Altitude angle, Solar Declination angle, Solar Hour angle and Solar Azimuth angle.

The latter part discusses the formulae for shadow calculations.The shadow of wind turbine on the ground is almost rectangular in shape. So, the area of the shadow at one time is the product of length and width of the shadow. The width of the shadow depends on the width of the turbine itself and is constant. The length of the turbine varies throughout the day and year.

To calculate the entire shadow area around the wind turbine, the shadow directions at all time instances is also required.

A. Solar Angles for Shadow Calculation

1) Solar Altitude Angle

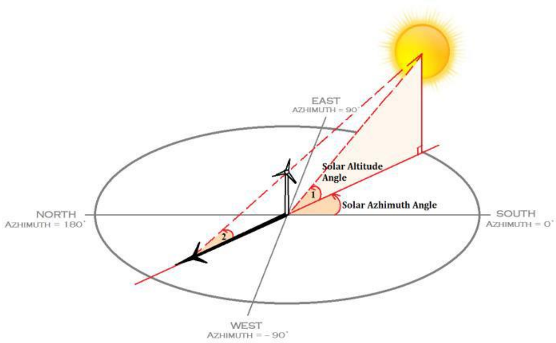

Fig 1. Solar angles for determination of Sun's position

The solar altitude angle or the solar elevation angle is the angle between the horizontal plane and the center of the Sun's disc. It is a measure of how high the sun is in the sky. It is denoted by α.

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For a latitude L and declination angle δ, the maximum value of altitude angle α is given by the following equation (1).

$$\alpha = 90° + L - \delta \quad (1)$$

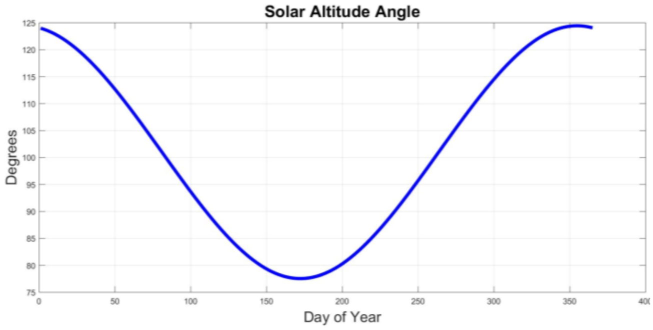

Fig 2. Variation of Maximum values of Solar angle atlatitude 11 °N

2) Solar Declination Angle

The declination angle is denoted by δ and it varies seasonally due to the tilt of the Earth's axis and revolution around the sun. The Earth is tilted by 23.45° and so the declination angle varies with this angle. The solar declination angle relates the position of the sun with respect to the tilt of the Earth's axis, for a day n of the year.
The notation *n* denotes the number of the day in a year. For the date of January 1, *n* = 1.
The solar declination angle is given by

$$\delta = 23.45 \ \sin\left[(284 + n) \times \frac{360}{365}\right] \quad (2)$$

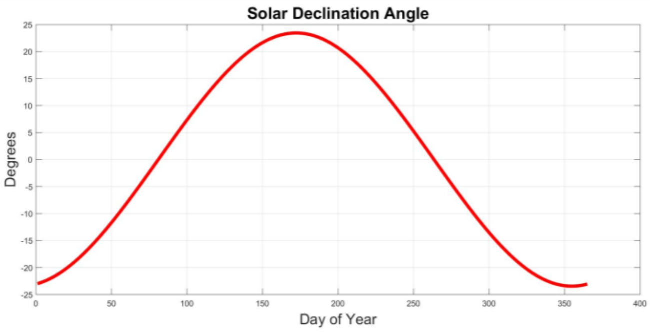

Fig 3. Solar Declination angle over a year

3) Solar Hour Angle

The hour angle converts the local time into the number of degrees which the sun moves across the sky. The hour angle is 0° at solar noon. Since the Earth rotates 15° per hour, each hour away from solar noon corresponds to an angular motion of the sun in the sky of 15°.

The hour angle is necessary to track the sun's position throughout the day. Considering that potential irradiance for solar power production is available only from 6 a.m. to 6 p.m.

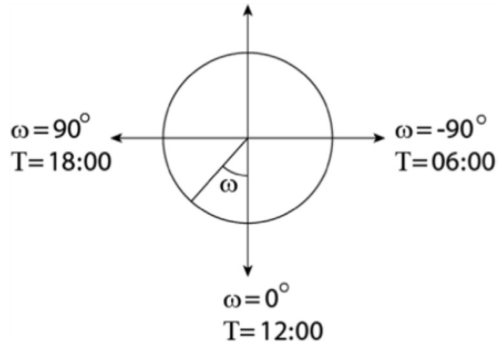

Fig 4. Solar Hour Angle

The solar hour angle ω is calculated using the formula:

$$\omega = 15T - 180° \quad (3)$$

4) Solar Azimuth Angle

The azimuth angle is the direction of facing the sun directly. It is defined as:

$$\theta_z = \cos^{-1}\left(\frac{\sin\delta\cos L - \cos\delta\sin L\cos\omega}{\cos\alpha}\right) \quad (4)$$

B. Shadow Calculations

1) Shadow Length

If α is the angle of elevation of the sun from the ground, then the length of the shadow for a given wind turbine can be determined using the formula:

$$Shadow\ length = \frac{Turbine\ height}{\tan\alpha} \quad (5)$$

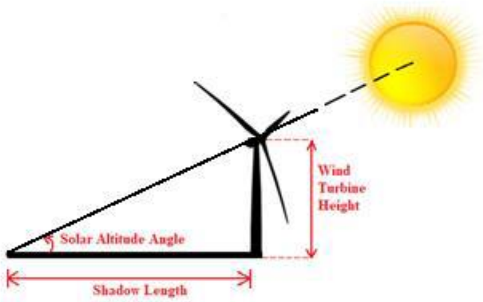

Fig 5. Determination of Wind Turbine Shadow Length

It is to be noted that the shadows are shorter with large altitude angles, i.e., when sun is at the top of the head. At these times, the shadows are also sharper. As the altitude angle decreases, the shadows become longer and lesser in intensity. The shadow calculation considers only the umbra and not the penumbra. Umbra is the darker part of shadow with defined outlines and the penumbra is the indistinct lighter outer part of the shadow with lesser light intensity.

2) Shadow Width

From equation (5), the shadow length can be calculated. Now to calculate the area covered by the shadow the tower dimensions are required. Generalizing for various power levels of wind turbines, the tower height and width can be expressed in terms of the rotor diameter, R [3].

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The average wind turbine tower height = 2.5*R
The average wind turbine tower width = R/16
where R is the radius of the swept area of the rotor blades of the wind turbine.
The product of tower width and shadow length gives the shadow area.

3) Shadow Direction

Shadows always fall in the opposite direction of the sun. Similarly, the wind turbine shadow direction is exactly opposite to the direction of facing the sun. The direction of facing the sun is given by azimuth angle. So, the shadow direction is in line with this angle, but in the opposite direction.
Therefore, shadow direction = θz+180°

VI. EXPERIMENTATION AND RESULTS

The verification of the above formulae is done experimentally by measuring the shadow lengths of objects of known length.

Table 1. Calculations of Experimental Pre-Requisites

Data	Known values	Calculated values
Date	April 10, 2018	n = 100, δ = 7.534
Time	15:55 hrs	Ω = 47°
Location	Ettimadai, Coimbatore	L = 11.016855 °N

Substituting for the given data,

$$\alpha = 43.518°$$

Hence the shadow length is calculated as,

$$Shadow\ length = \frac{Object\ length}{\tan\alpha}$$

$$Shadow\ length = \frac{8\ cm}{\tan 43.518°} = 8.425\ cm$$

Table 2. Experimental Verification of Shadow Length

Time	Object Length	Shadow Length
15:35 hrs	8 cm	8.425 cm
15:40 hrs	15 cm	15.35 cm

It is observed that the calculated shadow lengths match closely with the observed and measured shadow lengths. The error is less than 1% and deviation is due to misperception of differentiating the umbra from penumbra.

The closely matching values of shadow lengths verifies the formulae for calculating the shadow lengths from sun's position. This calculation can be extended to the shadow calculations of any number of turbines for any time of the day in a year.

Fig 6. Shadow plot of a wind turbine with rotor diameter 82 m and hub height 78.5 m for the whole year at 11° N latitude [15]

VII. AREA UNDER SHADOW

With this mathematical background, it is possible to determine the area under shadow and the remaining area available for placement of solar panels. In order to assimilate this, a case study of Suzlon wind power plant located in Bogampatti, Coimbatore is presented in this section. Bogampatti wind farm is an operational onshore wind farm with a total nominal power of 1200 kW [17].

Table 3 gives the pre-requisite data from the wind farm required to calculate the available area in the wind farm forplacement of solar panels [16].

Table 3. Wind Turbine details of Bogampatti Windfarm

Wind Turbine Label	S82 – 1.5 MW
WT location	10.886611 °N, 77.123083 °E
WT Hub height	78.5 m
WT Hub rotor diameter	82 m

For the above considered wind turbine, the radius of the swept area of the blades

$$R = \frac{Rotor\ Diameter}{2} = \frac{82\ m}{2} = 41\ m$$

During mornings and evenings, the sun is low in the horizon, causing the shadows to be longer. But these shadows have less umbra in them as the sun is at the farthest distance. It is the umbra that must be strictly avoided for placement of solar panels. Fortunately, the shadows that have more umbra occur at midday, when the sun is at its peak and these shadows are shorter. This gives the benefits of irony that sharper shadows are shorter and indistinct shadows are longer.

For calculations, it is assumed that the shadow becomes sharp at 08:00 in the morning.

In the wind turbine location, the longest shadow of a wind turbine occurs on day n= 350, i.e., 16th of December.

Table 4. Shadow Area at the Wind Turbine location

Shadow Altitude angle	22.0752°
Calculated shadow length	193.5642 m
Calculated shadow width	= 41 / 16 = 2.5625 m

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Shadow area = Shadow length * shadow width	= 193.5642 * 2.5625 = 496.008 m^2

This is the largest shadow area of a wind turbine in a year.
In general, an area around the wind turbine within a radius of 193.5642 m is to be excluded from the placement of solar panels.
Thus, the area around one wind turbine which is not available for placement of solar panels due to shadowing is
$= \pi * (193.5642\ m)^2 = 1,17,706.36\ m^2$.

Table 5. Calculations for Availability of Area for Solar Panel Placement in the Wind farm

Wind Farm Land area (roughly)	70 km^2
Number of wind turbines in the farm	80 numbers
Shadow area of one WT	1,17,706 m^2
Shadow area of 80 WTs	9.416509 km^2
Area available for solar panel placement	= 70 – 9.416509 = 60.58349 km^2

Hence, the area available for placement of solar panels in Bogampatti wind farm is 60.58349 km^2.

VIII. ESTIMATION OF POWER OUTPUT FROM THE SOLAR PLANT

When it comes to planning and estimation of a solar project, the design variables are shadow consideration, load factor, meteorological data, site consideration, cost estimation and CAD layout. In this case, with the area available for placement of solar panels known, the solar power capacity in the available area can be calculated. Solar farms require large area for placement of the solar panels to capture the solar power from the sun. Typically, a solar farm requires 10 m^2 area for 1 kW capacity of solar power system [11].

Table 6. Power Calculation for the Wind Farm

Solar power available in 10 m^2 area	1 kW
Available area for solar panel placement in the wind farm	60.58349 km^2
Solar power available in Bogampatti wind farm	= 6058349 kW = 6058.349 MW

This is indeed a huge power, considering the present-day capacities of solar power plants. For comparison, the Adani solar project at Kamuthi has a nameplate capacity of 648 MW and it occupies area of 10 km^2. So, considering the vast expanse of land are available in the wind farm, this amount of solar power production is possible.

IX. CONCLUSION

This paper presents the idea of placing solar panels in existing wind farms. With such a huge area of land, the placement of solar panels in this area can increase energy production and profits made by the operating utility.

Placement of solar panels in a wind farm comes with the prime concern of shading of wind turbines on the solar panels. For addressing this, a mathematical formulation is done to track the sun's position and the shadow effects are verified experimentally. The area around the wind turbine where shadow is expected to fall during the year is excluded. The remaining area is suggested for placement of solar panels. For case study, the Bogampatti wind farm is considered. Of the total area, the actual area available for placing the solar panels is calculated. With the area available for solar panels, the energy output is estimated to be 6058.349 MW. Establishment of such a large rated solar power plant in the wind farm would increase the power output by several folds as compared to the original nominal power rating of the wind farm. For distributed generation, such a huge power production would improve the grid quality and economy of operation.

X. FUTURE SCOPE

There is room for further extension with more accurate calculation of shadow of a wind turbine with advanced software like SketchUp, PVsyst, PVsol, etc. Using such advanced software to obtain the terrain of the area can be more informative for decisions on placement of solar panels. Shadow analysis results from the above software can produce more accurate results which can aid in the calculation of shadow losses before actual placement of the panels in the field.

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AUTHOR'S PROFILE

Hamsadhwani V. is pursuing her master's degree in Power Electronics at Amrita Vishwa Vidyapeetham, Coimbatore, India. She received her bachelor's degree in Electrical and Electronics Engineering from PSG College of Technology, Coimbatore in 2016.

Mohanrajan S. R. currently serves as Assistant Professor (SR)at theDepartment of Electrical and Electronics Engineering,Amrita Vishwa Vidyapeetham, Coimbatore, India. His areas of research include Renewable Energy and Smart Grid.

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