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Shadow analysis of wind turbines for dual use of land for combined wind and solar photovoltaic power generation

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ABSTRACT

Wind and solar energies are among the main renewable energy sources. Large wind and solar farms are designed separately for each type of energy. Dual use of the land for wind and photovoltaic energies may save land area and will result in matching the utility load better than with wind or solar alone. Shading by wind turbines on photovoltaic panels may affect the output power. The amount of shading and its pattern are of interest for deployment of the photovoltaic panels in the wind farm land. The present article deals with the calculation of shadows cast on the land area by wind turbines during the year for two latitudes, 32° and 50°. The calculations show that the average percentage "loss" of land for photovoltaic panels due to wind turbine shading is less than one percent.

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1. Introduction

Renewable energy sources, particular wind [1–6] and photovoltaic (PV) energies have been of interest in policies of government, academia and industry. Off grid applications of small wind turbines and photovoltaic systems are known. Large scale wind farms and large scale PV systems are widely used all over the world, each application on a separate land. Dual use of land for large scale wind farms and solar power has not been dealt much with in the literature, and only recently has been examined [7–11]. Wind and solar plants generate energy at different times of the day and, therefore, will supply a more stable energy to the grid. In addition, the transmission lines will be utilized more efficiently than by either wind or solar alone. Recent reduced prices of PV panels make the option of dual use of land more attractive in the future. Ref. [7] deals with combining wind farms with solar thermal power plants and Ref. [8] deals with combining wind energy with solar photovoltaics.

Wind turbines may be deployed in rows and columns (gridwise structure) or in discrete units, depending on the local terrain. The horizontal axis wind energy turbine is the most popular. Each farm consists of hundreds of turbines over hundreds of square kilometers generating electricity on large scale. Most wind farms are installed in agricultural regions where the land can still be used for other purposes, like pasture and growing crops. However, land occupied by wind turbines in desert regions, are not utilized for combined wind and solar power generation. In wind farms of

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grid-wise structures, the spacing between the turbines is determined by the rotor diameter and the local wind conditions. Typical turbine spacing in wind farms is placing the towers 5 rotor diameters in the crosswind direction and roughly 10 rotor diameters in the downwind direction. The shadow cast by a turbine may be of the order of a few hundred square meters. Photovoltaic panels are sensitive to shading. Unlike a solar thermal panel which can tolerate some shading, PV panels may suffer significant loss in the energy production. The purpose of the present article is to analyze the ground shading area and the shadow pattern of wind turbines that may affect the photovoltaic energy output in a dual use of land for wind and photovoltaic energies. Ref. [11] deal with the same topic, although the approach is different and less detailed than the present article. Ref. [11] concludes that for extreme shading conditions this still leaves approximately 93 percent of the total wind farm area suitable for PV panels. A study carried out by the institute mentioned in [12] concludes that in the same land area (wind and PV), twice the amount of electricity may be generated, and the shading cast by the wind turbines accounts for 1–2 percent loss in the PV energy. No detailed calculations are given in the reference. A study on an optimal design of a solar photovoltaic field is performed in [13] taking into account the mutual shading by adjacent collector rows.

2. Shadow of a vertical pole

Fig. 1 shows the shadow components of a pole of height H at the origin. The sun is at elevation angle α and azimuth γ with respect to south. The shadow length F on the ground is given by:

$$F = H/\ \tan\alpha \tag{1}$$

The sun elevation angle given by:

$$\sin\alpha = \ \sin\phi\ \sin\delta + \ \cos\phi\ \cos\delta\ \cos\omega \tag{2}$$

The east-west shadow component is given by [14]:

$$F_x = H\frac{\cos\delta\ \sin\omega}{\sin\phi\ \sin\delta + cos\phi\ \cos\delta\ \cos\omega} \tag{3}$$

and the north-south shadow component is:

$$F_y = H\frac{\sin\phi\ \cos\delta\ \cos\omega - \ \cos\phi\ \cos\delta}{\sin\phi\ \sin\delta + \ \cos\phi\ \cos\delta\ \cos\omega} \tag{4}$$

where ϕ is the latitude, δ is the declination angle and ω is the hour angle.

The relation between the hour angle ω and the solar time T(at $T = 12:00,\ \ \omega = 0^\circ$) is given by (see Fig. 2):

$$\omega = 15T - 180 \tag{5}$$

Figures 2 and 3 in [14] show the shadow components F_y/H and F_x/H, respectively of a pole calculated by Eqs. (3) and (4) for Tel Aviv area (latitude $\phi = 32^\circ 00'$ N) for some typical months.

3. Shadow of a turbine tower

A turbine tower is a pole with a finite width casting shadow on the ground during the day as seen in Fig. 3. The tower height is related to the blade length or to rotor radius R, and may vary between about 1.5R to about 2.5R. The total height (tower plus blade) may vary between about 3R to about 3.5R, and the tower height is between 80 m to 150 m and above; all dimensions corresponding to a range of turbine powers. Also, the wind farm dimensions (the spacing between the towers), in an array like grid-wise deployment (rows and columns), are given in relation to R. Fig. 4 shows a wind farm with a spacing of 6R in the north-south direction and 20R in the east-west direction for a west-east wind

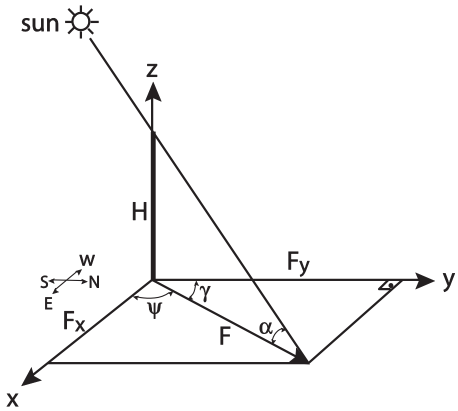

Fig. 1. Shadow components of a vertical pole.

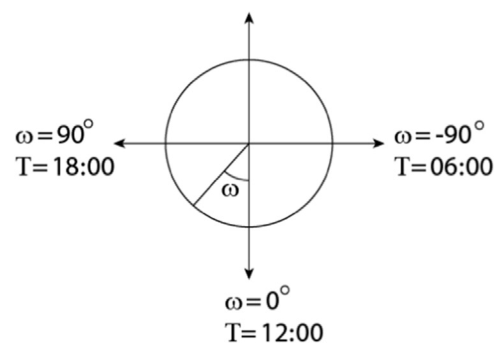

Fig. 2. Relation between the hour angle ω and the solar time T.

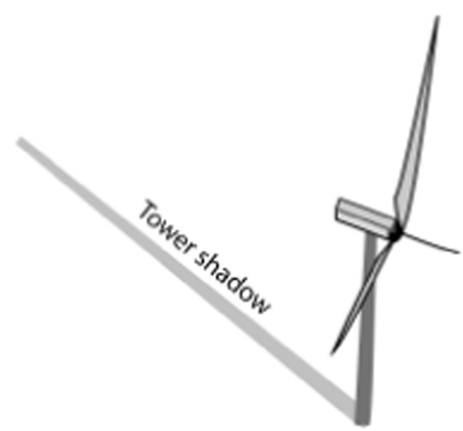

Fig. 3. Tower shading.

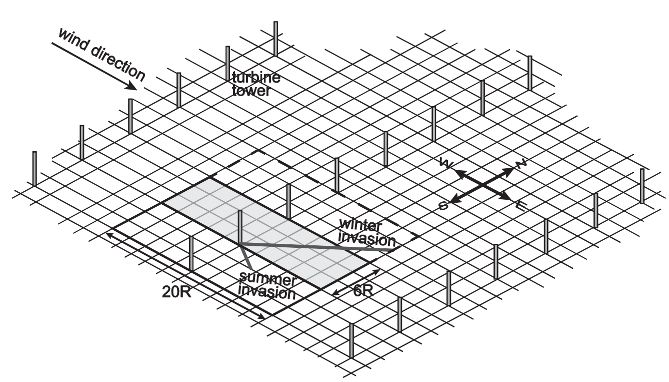

Fig. 4. Wind farm layout.

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