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Vertically mounted bifacial photovoltaic modules: A global analysis

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ABSTRACT

Bifacial PV (photovoltaic) modules have recently come to increasing attention and various system designs have been investigated. In this paper, a global comparison is made between vertically mounted bifacial modules facing East–West and conventionally mounted mono-facial modules. An analytical method is used to calculate the radiation received by these two module configurations. It is found that the answer to the question which of these two module configurations performs better strongly depends on three factors: (i) the latitude, (ii) the local diffuse fraction and (iii) the albedo. In a subsequent part of the paper, the minimum albedo required to result in a better performance for vertically mounted bifacial modules is calculated for every place in the world. The calculation is based on measured data of the diffuse light fraction and the results are shown in the form of a global map. Finally, the albedo requirements are compared with the measured global albedo distribution. The calculation allows a distinct decision which module configuration is more suitable for a certain place in the world. The result is also shown as a map defining the corresponding areas.

1. Introduction

The fast depleting of conventional energy sources and increasing energy demand are encouraging the development on PV (photovoltaic) technologies [1]. Among different kinds of PV technologies, interest in bifacial PV modules is increasing in recent years [2,3]. There are several reasons for this. Glass–glass PV module construction technology seems to have more benefits in terms of durability compared to glass-backsheet module construction [4]. Advanced solar cell manufacturing methods such as ion-implantation and heterojunction technologies not only result in high efficiency solar cells, but also naturally result in bifacial solar cells, unlike the aluminium back surface field solar cells which dominate the PV (photovoltaic) market today [5–8]. The structures of mono-facial and bifacial p-type substrate crystalline silicon solar cells are shown as an example in Fig. 1. The local contact on the back surface of bifacial solar cells allows them to absorb light from both the front side and the back side. Their corresponding module structures are also included in Fig. 1. Instead of having backsheet on the back of mono-facial PV modules, bifacial modules have glass on their back side which allows them to make use of the light coming from both sides. Depending on the installation, bifacial modules can produce up to 20% more energy in side-by-side comparisons than equivalent mono-facial modules [9], and the cost of a bifacial PV module is equal to the cost of a conventional mono-facial module with the same front surface [10]. Bifacial modules can be installed vertically facing (East–West), which, depending on the application, can save space, and depending on several factors, can, in this orientation, produce as much energy per Watt as conventionally mounted mono-facial PV modules (tilted at latitude towards the equator) [11,12]. The generation profile of such a vertically mounted bifacial PV module is significantly different to that of a conventionally mounted mono-facial module (see Fig. 3). The VMBM (vertically mounted bifacial module) facing East–West produces more energy in the early morning and late afternoon than CMMM (conventionally mounted mono-facial modules). With increasing penetration of PV electricity generation in a grid (e.g. in Germany), this rare double-humped "bactrian camel" of Central Asia, is far more valuable than the single-humped "dromedary camel" of Arabia. VMBMs also have further advantages. They can, for example, be installed as sound barriers along roadsides and they are less prone to be covered by snow. For these reasons it is necessary to investigate how the performance of VMBM is affected by the environmental factors and how it compares with CMMM.

In this paper, MATLAB-based simulation is used to investigate factors affecting and influencing the amount of energy which can be produced by a VMBM. Also, a global comparison is made

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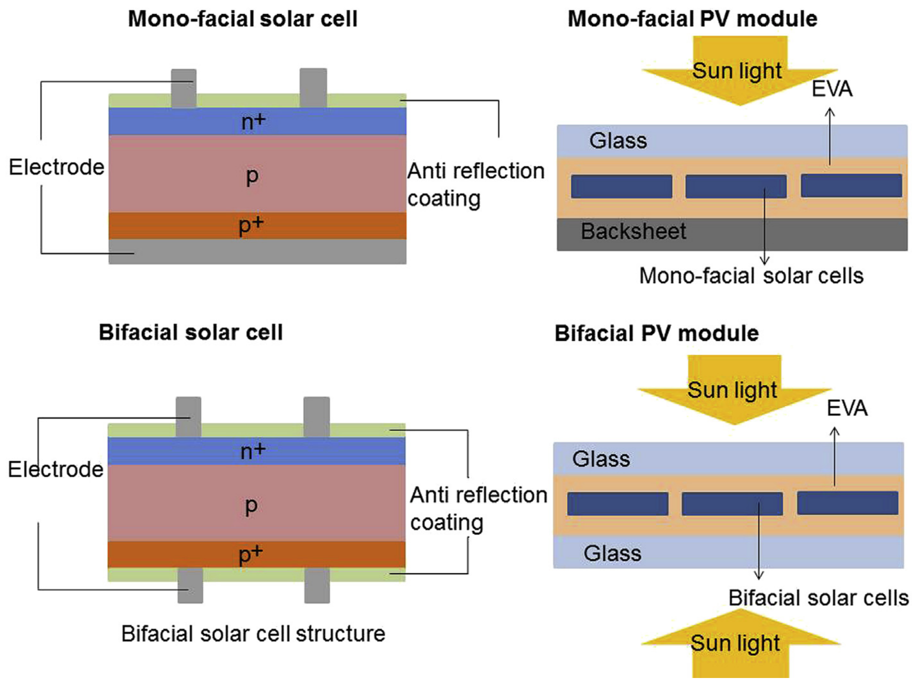

Fig. 1. Structure of mono-facial solar cells (upper left), mono-facial PV modules (upper right), bifacial solar cells (lower left) and bifacial PV modules (lower right).

between VMBM and CMMM in order to evaluate which kind of PV module is more suitable for a certain location. The setups of the two modules are shown in Fig. 2. It is found that the performance of a bifacial module strongly depends on latitude, diffuse fraction and albedo, and the difference between the performances of VMBM and CMMM also strongly depends on these factors. Based on measured diffuse light fraction data, the minimum albedo required so that a VMBM performs better than a CMMM is calculated for every place in the world. The calculation is based on the annually received radiation and is therefore not specific to any kind of solar cell.

2. Theory and method

2.1. Simulation of direct and diffuse radiation

The method introduced in this part is used to calculate the radiation received by a PV module at a certain place in the world during a whole year for a certain fraction of diffuse light. The radiation received by a module can be divided into two parts: diffuse radiation and direct radiation. Each part is related to a certain fraction of radiation called diffuse and direct fraction. In this part, the direct and diffuse radiation is simulated under a certain transmittance coefficient τ.

In the first step, the extraterrestrial radiation, which describes the intensity of solar radiation directly outside the earth's atmosphere on a horizontal surface, is calculated with a yearly varying term [13]:

$$I_0 = 1367.7 \times \left[1 + 0.033 \times \cos\left(\frac{2\pi}{365} \times \mathrm{DOY}\right)\right] \quad (1)$$

I_0: extraterrestrial radiation; DOY: day of a year, DOY = 1 if the date is January 1st.

Direct normal radiation, which is defined as the solar radiation incident on a surface oriented normal to the solar radiation, can be calculated from the exterritorial radiation, which is a function of the transmission coefficient [14]. This relationship is based on a model developed by Liu and Jordan [15]. In this model, DNI (direct normal incidence) is calculated as a function of AM (air mass). Air mass is the path length which light takes through the atmosphere normalised to the shortest possible path length, which is described as:

$$\mathrm{AM} = \frac{1}{\cos(\theta)} \quad (2)$$

θ: zenith angle of the sun.

With a known air mass value, the direct normal incidence is calculated by:

$$\mathrm{DNI} = I_0 \times \tau^{\mathrm{AM}} \quad (3)$$

DNI: direct normal incidence; AM: air mass; τ: transmission coefficient for direct solar radiation.

If DNI is known, horizontal direct radiation (H_{dir}), which refers to the direct radiation incidents on a horizontal surface, can be calculated directly from:

$$H_{dir} = \mathrm{DNI} \times \cos(\theta) \quad (4)$$

In the next step, horizontal diffuse radiation (H_{diff}), which is defined as the amount of diffuse radiation incidents on a horizontal surface, needs to be calculated. Campbell and Norman developed a relationship between horizontal diffuse radiation and transmission coefficient based on Liu and Jordan's model, which is described by Ref. [16]:

$$H_{diff} = 0.3\left(1 - \tau^{\mathrm{AM}}\right) I_0 \cos(\theta) \quad (5)$$

However, this model is mostly used to model clear-sky condition when the transmission coefficient τ is larger than 0.45 and might not be very suitable for overcast conditions. Under overcast conditions, there are no existing models that directly relate diffuse radiation to the transmittance coefficient τ. However, there are many models that relate diffuse fraction k_d to clearness index k_t. Clearness index k_t can be used to generate synthetic solar radiation data and estimate the PV system performance [17]. The models that