Sensitivity analysis of the effect of forced convection on photovoltaic module temperature and energy yield

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Abstract — With the growing competition of utility-scale photovoltaic (PV) plants to provide electricity to the grid, accurate energy yield simulation is becoming essential. Apart from irradiance, forced convection can have an equally significant impact on solar cell temperature, which in turn affects the power output, hence the energy yield. As a consequence, the wind must be taken into account for an accurate estimation of PV installations' energy yield. However, no earlier studies have systematically investigated the impact of wind on precise energy yield simulation. In this study, we investigate how sensitive is PV module's output to forced convection. First, we reveal a significant deviation between the simulated PV module's energy yield and cell temperature compared to experimental results in case dynamic wind effects are neglected. Secondly, for controlled incremental forced convection with a steady state scenario, we show that for higher wind speed the change of PV module's cell temperature and power output is small with different forced convection. Whereas, for the low wind speed, small changes of forced convection imply a larger variation of the PV module's cell temperature and power output. This shows that for high wind speed region energy yield estimation is less sensitive on modelling errors. Whereas for the low wind speed region it is highly sensitive.

I. INTRODUCTION

Photovoltaic (PV) market has seen tremendous growth in the last few years. In 2017 the total installed solar PV worldwide was 398 GW which contributed to 2% of the global power output. Utility-scale plants account for over 60% of the installed capacity [1]. In parallel, the swift decrease of the localized cost electricity has driven the growing interest in better understanding and precisely estimating the energy yield of PV installations. Besides irradiance, the performance of PV modules is strongly influenced by its operating temperature. It is established that the efficiency of the crystalline silicon PV module is inversely proportional to cell temperature [2]. The cell temperature of the PV module depends on a combination of heat conduction, convection and radiation from within the module towards the environment. Many studies already showed the significant effect of wind on solar cell temperature [2], [3]. Wind removes heat from the top and bottom of the solar PV module by forced and natural convection. The type of convection that dominates also varies in function of wind speed and direction. Several published studies describe heat

transfer characteristics from the module towards the environment in scenarios with varying wind flow condition and mounting structure [2], [4]–[6]. Moreover, that heat transfer characteristic is spatially variable over the PV module subjected to wind [7].

Although extensive research has been carried out on the effect of wind on PV, there is a lack of understanding on how sensitive PV module's temperature and energy yield estimation are to changes in wind conditions [2], [3]. That is also directly related to the sensitivity to potential errors, which provides essential insights to develop accurate energy yield simulation. Therefore, this study focuses on the sensitivity of the PV module's temperature and energy yield to forced convection. First, we present our Electrical Optical and Thermal (EOT) PV system Modelling framework, and the experimental setup is described briefly. Secondly, we extract the difference between simulated and measured PV energy yield and cell temperature at different timescale, either considering wind or no wind conditions. Finally, considering wind effects on PV module, further investigation is done to study at which wind conditions PV module's power output and cell temperature are most sensitive to changes. In this case, the PV module's power output and temperature are simulated in steady-state conditions with incremental changes of forced convection. The finding of this latter simulation will be used to understand what degree of accuracy for the heat transfer coefficient induced by forced convection is required for an accurate simulation of the energy yield.

Fig. 1. Experimental setup in Oldenburg University

Fig. 2(a). Relative energy yield rmse for wind and no wind effect 2(b). Absolute temperature rmse for wind and no wind condition

II. SIMULATION FRAMEWORK: ELECTRICAL OPTICAL AND THERMAL MODEL

Imec's Electrical-Optical-Thermal simulation framework allows estimation of the energy yield of silicon solar PV module [3]. The inputs of this model are irradiance, ambient temperature, wind speed and wind direction, next to module material and cell properties. The EOT model simulates electrical output and solar cell temperature as a function of illumination, sky temperature, ambient temperature, wind speed, wind direction, thermal state and electrical operation point with a fine spatial and temporal resolution. We simulated the output of a 72-cell multi-crystalline silicon module for 176 days and compared this to measurement results from the experimental setup installed in the Oldenburg University, located at latitude 53.1523°N and longitude 8.166°E at an inclination 54° facing south [3]. The wind speed and direction were measured with an anemometer installed next to the PV module. This measurement setup is shown in Fig. 1.

$$\begin{aligned} \text{Absolute RMSE} &= \sqrt{\frac{\sum_{i=1}^N (M_i - S_i)^2}{N}} \\ \text{Relative RMSE} &= \sqrt{\frac{\sum_{i=1}^N (\frac{M_i - S_i}{M_i})^2}{N}} \end{aligned} \quad (1)$$

III. SENSITIVITY OF PV MODULE ENERGY YIELD AND TEMPERATURE TO FORCED CONVECTION OVER A DIFFERENT PERIOD

The EOT model was adapted to simulate two conditions. In Scenario one, simulation includes heat transfer coefficient as a function of wind speed and direction. In Scenario two, constant heat transfer (10 Wm⁻²K⁻¹) over the PV module is simulated, based on the assumption that wind speed and direction do not affect the heat transfer. The measured PV

module back sheet temperature and energy yield were compared with simulated solar cell temperature and energy yield.

Fig. 3. Simulated Vs Measured solar cell temperature for 11th Aug 2014. (a) Wind effect is included (b) wind effect is not included

There were significant differences observed between scenario one and scenario two for the whole data set of 176 days especially when compared in different time resolution, from daily (24 hours) to 10 sec. Root Mean Square Error (RMSE) (1) was used to calculate the deviation where M_i and S_i mean measured and simulated values respectively. In Fig. 2(a). For scenario one with complete EOT where wind effects are considered the relative RMSE of energy yield was 2.8%, which is, to best of our knowledge, currently the most precise energy yield estimation for PV. While for scenario two where no wind effect is considered it can be seen that daily energy yield RMSE is 50%. Such a vast difference between the two scenarios indicate that if the wind is not considered, there is going to be a significant error on energy yield estimation. Moreover, this deviation of energy yield increases with smaller time resolution, which suggests wind dynamics are important for higher accuracy.

This variation in energy yield estimation can be explained by incorrect cell temperature estimation. From Fig. 2(b)., solar cell temperature daily absolute RMSE was 1.2 K for scenario one. Whereas, for scenario two, with no wind effect included, the deviation is 7.4 K and the deviation increases in smaller time resolution. For 10 sec resolution, the absolute deviation is 10.3 K. This deviation of cell temperature is much more visible when seen for a whole day period. For such daily temperature comparison, measurements during one highly varying day (11th August 2014) were compared with simulated temperature. In Fig. 3(a). for scenario one, where wind effects are taken into consideration, the simulated solar cell temperature follows the trend of the measured PV module

back sheet temperature quite well. In contrast to that, in Fig. 3(b), where no wind effect is considered, there is a considerable difference of simulated and measured temperature.

IV. THE SENSITIVITY OF PV MODULE'S CELL TEMPERATURE AND POWER OUTPUT TO INCREMENTAL FORCED CONVECTION

For a further understanding of the PV module's sensitivities to different forced convection scenarios, a 60 cell glass-back sheet PV module's power output and cell temperature were simulated by the EOT model for different forced convection scenarios. To reduce complexities of different variable and to purely study the effect of forced convection on PV performance, few assumptions were made. In the case presented in this Section, it is assumed that there is negligible heat transfer from the back side of the module. So heat transfer by forced convection will occur only from the front side of the module. The ambient temperature and illumination were 25°C and 1000 W/m² respectively and simulations were performed in steady state condition. The effect of forced convection is translated as heat transfer coefficient. Hence, the power output of the module is simulated for the incremental heat transfer coefficient. The relationship between the heat transfer coefficient and wind flow near the surface of the PV module was estimated from wind tunnel measurements [2].

In Fig. 4. it is visible that for higher wind speed region, the changes in cell temperature with increasing heat transfer coefficient is quite small. Hence the power output in higher wind speed region is less sensitive to varying heat transfer coefficient. Whereas, in the low wind speed region, the cell temperature is quite sensitive to changes in the heat transfer coefficient. Hence, the power output is highly sensitive too. This indicates that, for lower wind speed region, a small error in modelling heat transfer coefficient would lead to large error in PV module power output estimation.

Fig. 4. PV cell temperature and power output for incremental forced convection

V. SUMMARY

Our study investigates the sensitivity PV modules energy yield simulation on forced convection. From the simulation and experimental comparison discussed earlier, the sensitivity of forced convection on the PV module's output can be seen. If no wind effects are considered then daily energy yield relative RMSE is going to be 50% compared to 2.8% when the wind is considered. Also when wind effect is considered, in the low wind speed region large changes in the PV module's power output and cell temperature occurs with small changes in forced convection. It is clear that wind effects have to be integrated into energy yield simulation framework. Especially, greater accuracy on the thermal network is necessary for lower wind speed region to gain better accuracy in the PV module's energy yield estimation. Additional studies will be included in the final version of this paper, to extend the sensitivity analysis to different illumination and forced convection scenarios.

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