Sensitivity analysis of the state of the art silicon photovoltaic temperature estimation methods over different time resolution

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***Abstract*— Precise PV energy yield estimation is critically dependent on an accurate temperature estimation method. This paper experimentally investigates the accuracy of three commonly used thermal modelling methods. Detailed sensitivity analysis of yearly, monthly, daily and intraday time resolution reveals that the actual data are clearly dependent of day-type and weather parameters. However, the proposed methods struggle to estimate temperature with varying irradiance or wind speed. During the summer months, on intermittently cloudy days the intraday mismatch can be as high as 25°C, whereas on clear sky days it can be below 10°C. Applying these methods for short term estimation of any day type can lead to a large error in energy yield estimation. Further adaptation is required to propose estimation methods which can properly handle different day types and weather fluctuations.**

Keywords— PV Cell Temperature, Temperature estimation, Yearly outdoor data analysis

I. INTRODUCTION

Within the renewable energy industry, solar photovoltaic power has seen unprecedented growth in recent years. It is forecasted that PV capacity increase in 2023-25 may range from 130 GW to 165 GW, accounting for 60% of renewable energy market expansion [1]. There is an increasing interest in precisely understanding PV energy yield for short-term forecasts, as the technical inputs and assumptions have a large impact on the financial models [2].

Instantaneous PV power reflects the meteorological conditions, which can vary strongly, such as irradiance, ambient temperature, wind speed, and wind direction. Among the meteorological inputs, second to irradiance, the PV performance is highly influenced by cell operation temperature [3]. This operation temperature is dependent on multiple factors like heat conduction, convection, and radiation from the PV to the environment, where the module technology and mounting conditions play a large role. Heat transport from the module varies in both space and time [3]–[5], which is why it is arguably challenging to propose estimation methods to precisely predict the operating cell temperature fit for all scenarios and temporal resolution. A comparative analysis was performed over two widely used methods in various climatic zones [6]. It provided

Fig. 1. Experimental site in KU Leuven, Ghent Campus

an insight into yearly temperature mismatch over a broad climatic region. However, that experiment used PV backsheet measurements.

To test the sensitivity of some of the state-of-the-art PV cell temperature estimation methods, this paper compares over different timeframes, from yearly, to monthly, and then daily to intraday. This can provide insights into the scenarios where these estimation methods perform well, and where improvement would be necessary. This study's sensitivity analysis clearly shows that further refinement of state-of-the-art temperature estimation methods is required, especially for short-term periods where less averaging out occurs. This study's finding can be used to understand widely implemented temperature estimation methods' accuracy and sensitivity. This would support the

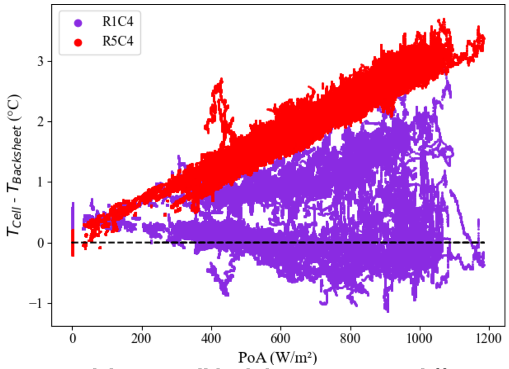

Fig. 2. Measured daytime cell-backsheet temperature differences for two positions, top centre (R1C4) and centre of module (R5C4), on 1 May-31 Dec 2015.

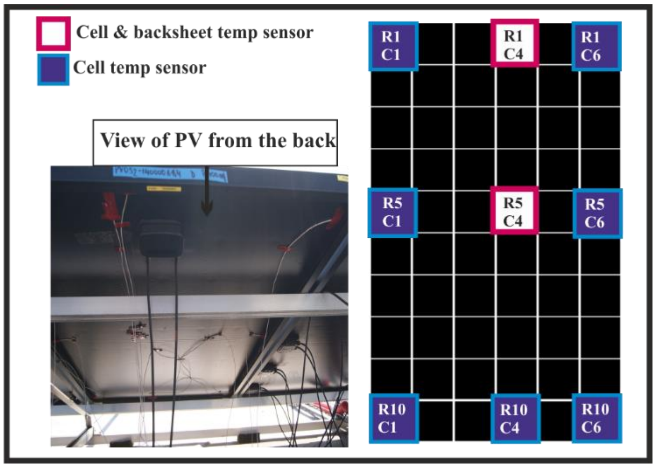

Fig. 3. PV cell and backsheet temperature sensor locations of studied module, notation is sunny side up

preparation of a robust temporally and spatially resolved temperature estimation method.

II. Methods Selected for Sensitivity Analysis

For the sensitivity study presented here, the widely used temperature models by Ross [7], Faiman [8], and King [9] are selected. Although cell operational temperature is used to calculate the energy yield of a PV module or system, in usual experimental practice, the backsheet temperature on the PV module surface is measured, and converted to cell temperature with linear approximation with respect to irradiance [9]. Hence, the first step is to verify the sensitivity of cell and backsheet temperature relationship versus irradiance. Figure 2 shows that the relationship is influenced by the cell's position and the impact of wind speed and wind direction. The unequal wind cooling over the module surface, especially during rapidly changing weather conditions such as wind direction changes can result in the backsheet being temporarily hotter than the cell. Therefore, we have proceeded to verify the state of temperature estimation models with actual cell temperature measurements rather than backsheet measurements. Given that the three temperature estimation models analyzed here all assume or provide a module average or center-of-module temperature, the comparison is made with an average of all the cell temperature sensor measurements over one module.

Table 1: Comparison of model RMSE versus measured data

	Ross	Faiman	King	Dates (yyyy-mm-dd)
Yearly RMSE (°C)	3.82	3.06	2.43	2015-05-01 to 2015-12-31
Daily RMSE (°C)	9.67	3.84	3.95	2015-06-02 (variable irradiance day)
Daily RMSE (°C)	4.87	2.41	2.66	2015-07-24 (clear sky day)

III. Experimental Set-up Description

The PV set-up is located on the tallest roof of KU Leuven campus in Ghent, Belgium (51°03'12N, 3°43'49E). Figure 1 shows the test setup of the PV array. The PV array is oriented South (180°) with 18° tilt mounted close to the roof surface, with free access for the wind to the modules possible. The measurement of PV module power, and weather data is done in Labview, using an NI CompactRIO with appropriate measurement cards (e.g. NI 9217 for 4-wire Pt100 temperature measurements), with all data recorded at 1 Hz. Among the climatic properties, the plane of array irradiance, wind speed, wind direction, and ambient temperature is measured. For this study, one custom-made standard mono-crystalline PV module with 60 cells is selected, which has 9 Pt100 sensors laminated against the cell backside, per the positions shown in Figure 3. Two extra sensors are placed on the backsheet next to the encapsulated sensors of R1C4 and R5C4. More technical details of the data logging methods and equipment are provided in [10]. The available temperature measurements are from 1 May 2015 to 31 December 2015.

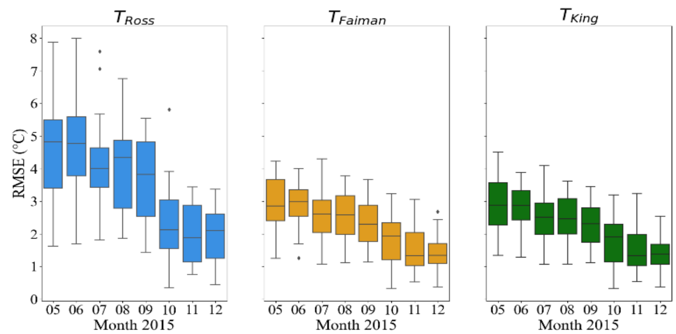

Fig.4. Daily RMSE of the temperature estimation methods

IV. Result and Discussion

A. Yearly vs daily temperature mismatch analysis

The measurement data is compared to the Ross, Faiman and King models for the different timeframes, with the data summarized in Table 1, using the root-mean-squared error (RMSE) as the key performance indicator. The yearly comparison exhibits higher RMSE than Olivera et al. in a similar climate [6]. This may be introduced from two factors. Firstly, in this study, the actual cell temperature is used to compare instead of the backsheet. Secondly, the missing days in the dataset are from the cooler months of January-April, where the RMSE mismatch is naturally smaller than the warmer months. This in

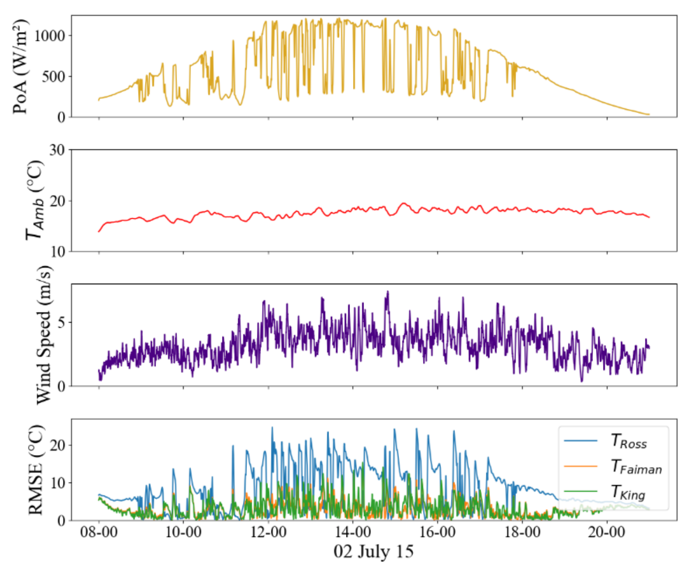

Fig.5. Weather profile and high temperature mismatch, high variability day

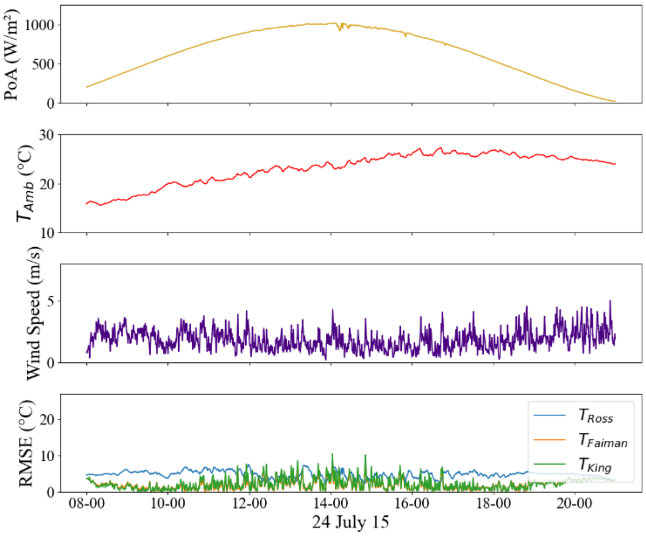

Fig.6. Weather profile and low temperature mismatch on clear sky day

turn lowers the RMSE mismatch for the entire year. The daily RMSE comparison from Figure 4 shows that the values from the three models can fluctuate over a range from 0.5°C to 8°C. Both the models by Faiman and King models perform better than Ross. This is expected, as the Ross model does not take wind speed or direction into consideration. From the daily RMSE analysis, both methods by King and Faiman do not exhibit any statistically significant difference.

There is seasonal consistency over the daily RMSE mismatch, but this is not true for the short-term intraday mismatch. The data analysis suggests a potential grouping of day type, contributing to a specific range of daily RMSE mismatch. Detailed analysis of different day types such as a cloudy hot day, clear sky hot day, cloudy cold day, and clear cold day will be provided in the full paper. In this abstract, what is presented here is the high contrast of temperature estimation mismatch between different types of days in the same season.

B. *Intraday temperature analysis in cloudy vs clear sky day in summer (High to Low mismatch)*

2 and 24 July 2015 represent days in summer with a highly variable irradiance and clear sky day respectively. Even though both days are within the same season with similar high irradiance, 2 July had one of the highest mismatches within the study. Table 1 provides the RMSE values for all the models where the Ross model has the largest daily RMSE mismatch. This can be explained by both irradiance and wind speed conditions, with Figure 5 visualising the primary weather input parameters and RMSE mismatch during the day. Due to moving clouds, the irradiance fluctuates between 100 W/m^2 and 1100 W/m^2. Most importantly, 2 July has higher wind speed than seen on 24 July. This results in the Ross model having an intraday RMSE mismatch of up to 25°C, due to the combination of the high irradiance fluctuations and the model disregarding wind inputs. The models by Faiman and King perform significantly better than Ross because of the additional wind component in their models. However, all three models exhibit large RMSE values due to highly fluctuating irradiance. These mismatches are averaged out if larger time resolution than the thermal constant of the module is taken, see [11].

In contrast to 2 July, 24 July in Figure 6 provides an entirely different picture for temperature estimation mismatch. It is a clear sky day with low wind speed compared to 2 July. In this day type, all the three models perform visibly better. Maximum intraday RMSE mismatch for all the models stays below 10°C. However, it is essential to note that even this mismatch of 10°C will lead to large energy yield estimation errors for the short term. Therefore, an improved model adapted for the shorter time horizon is necessary which would consider the actual energy losses from photon to the electron.

V. SUMMARY & FUTURE WORK

Among the compared temperature estimation methods, King's model shows the best yearly RMSE performance. When it comes to daily RMSE mismatch, Faiman and King follow a similar trend while the Ross model is far off. The primary reason for this is that these two models consider wind speed, yet a closer look at the intraday analysis over the season shows that the models still show mismatches on hot days with fast-changing irradiance of up to 15°C. On clear sky days in the summer, the maximum RMSE mismatch for all three models are below 10°C, while on winter days this can be as low as 0.2°C. In summary, the investigated temperature estimation methods are not universally accurate in all day types, especially when considering data at higher temporal resolution (1 s to 1 min), where heat transfer effects play an important role.

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