METHODS FOR QUALITY CONTROL OF MONITORING DATA FROM COMMERCIAL PV SYSTEMS

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The aim of this work is to develop and test new methods for quality control of data from commercial monitoring systems for small and medium sized PV installations. Such installations often have limited or non-existent maintenance of their monitoring systems. Quality issues in e.g. irradiance and temperature measurements will cause errors in the analysis of the PV system performance and might lead to non-optimal maintenance of the system. To determine the condition of the sensors and the monitoring system based on the measured data itself is therefore essential to improve performance analysis algorithms and to understand historical data from these types of PV systems, and consequently this is of significant economical and practical value. In this work, we use data from both commercial and research systems in Norway to assess the robustness of the methods in a real-world scenario. We demonstrate that drift and deviations in the sensitivity of irradiance sensors, in addition to misalignment of the sensors, can be accurately quantified and detected based on comparison with clear sky irradiance modeling. Furthermore, we show that analysis of temperature data potentially can be used to detect snow cover of modules, in addition to identification of detached temperature sensors.

Keywords: monitoring, PV system, data quality

1 INTRODUCTION

Regulations and irradiation conditions greatly influence the size and type of PV systems installed in a given market. In Norway, as in other northern climates, moderate solar irradiance and incentives for self-consumption has resulted in a market dominated by relatively small PV systems with installed capacity less than 1 MWp. Moderately sized commercial systems constitute a significant fraction. Typically, these systems have a simple monitoring system, measuring both electrical and environmental data. Most commonly, the electrical data is collected from the inverter, the plane of array (POA) irradiance is measured by a reference cell, and there are sensors measuring ambient temperature and the module temperature. In addition to the typically low accuracy of commercial monitoring solutions [1,2], often very little maintenance is performed on these systems, as the cost of maintenance of distributed monitoring systems may exceed the expected benefit if local personnel are not available. In most cases, necessary maintenance like cleaning of the irradiance sensors and visual inspection of the system and sensors is not performed, and the sensors are not regularly recalibrated. Drift in sensors, dirty irradiance sensors and detached module temperature sensors can lead to significant misinterpretation of the PV system performance, and consequently also suboptimal or unnecessary maintenance of the PV system. The distribution of the systems, combined with little local competence and small economic incentives, makes increased manual supervision an unrealistic solution. A more realistic path ahead is quality control of the sensor data based on data analysis. In addition to saving money by reducing the need for maintenance, this approach also enables validation of the quality of historical data for any system, independent of previous monitoring system maintenance routines.

Data-based evaluation of the condition of the sensors and the monitoring system is not widely discussed in the literature. The quality control work done today is mostly limited to detecting abnormal points (i.e. outliers and data exceeding physical possible limits) [3–5], as opposed to detecting permanent changes in the measurement over longer periods. In this work we suggest a new data-based method for detecting changes in the quality or accuracy of the irradiance measurements. We also discuss a method for quality control of module temperature measurements and how this method can be used to identify snow cover on the modules. Analysis is performed using data from commercial PV systems in addition to scientific test sites to assess the robustness of the methods in a real-world scenario.

The challenge of missing maintenance and supervision of irradiance sensors is also discussed by Jordan et al. [6], who proposed to calculate PV system degradation based on clear sky irradiance simulations instead of measured irradiance. However, ground measurements provide valuable additional information on the performance of the PV system under cloudy conditions and enable a more comprehensive analysis of PV systems. This is particularly important for locations with few clear sky days.

In this work we use clear sky irradiance simulations to assess the reliability and quality of the measured irradiance. This has previously been suggested by Reno et al. [7], but is to our knowledge not tested before. The method is assessed for both high and low-quality irradiance sensors.

A relatively common problem with measurements of module temperature, is detachment of temperature sensors, which are normally attached to the back sheet of the module. This could be detected by monitoring the difference between the module and the ambient temperature. To our knowledge, this method has not been tested beyond the observations presented by Woyte et al. [8]. In this work we test this method for two different types of PV installation, and assess it for a new application; snow detection. The possibility of detecting
snow coverage using measurement equipment that already exists on-site, could improve both the monitoring algorithms for PV system fault detection and the energy generation forecasts by separating snow events from other failures. Additionally, it will also simplify the analysis of historical data, with respect to estimation of performance and validation of snow loss models. In previous studies, the probability of snow cover on PV modules is estimated by detecting when the PV production is low relative to irradiance or estimated irradiance in combination with evaluation of other parameters, including ambient temperature [9], predictions of snow depth and temperature [10], and satellite observations [11]. Using ambient temperature alone will not separate snow events from e.g. total black outs or other serious failures [12]. The aim of this work is to increase the accuracy of snow detection at a specific location by also using the module temperature sensor data.

2 METHODS

2.1 Test of irradiance measurements based on clear sky irradiance simulations

Global horizontal clear sky irradiance is simulated using the Ineichen and Perez clear sky model based on zenith angle, air mass, elevation and Linke Turbidity [13]. The model error has been shown to have low dependency of time of the day and day of the year compared to other clear sky models [7]. The simulated clear sky irradiance is then transposed to a tilted plane by calculating beam, reflected and diffuse irradiance in the plane. The sky diffuse irradiance is calculated using the isotropic sky model [14], where the sky diffuse irradiance in the plane of the PV array is found using the diffuse horizontal irradiance, the tilt angle of the plane of array, and the assumption that the sky is a uniform source of irradiance. Periods with measured irradiance equivalent to clear sky conditions, i.e. a smooth irradiance curve, was detected using the algorithm proposed by Reno and Hansen, which compares GHI time series statistics to the Ineichen clear sky model [15]. The length of the clear sky time periods selected are at least two hours, to optimize between amount of data and correct selection of clear sky periods. All models are implemented in compliance with the methods in the Matlab version of the PV_LIB Toolbox [16], using the default Link turbidity values provided by SoDa in the clear sky modeling.

The modeled clear sky irradiance is in this case used as a reference, and the measured data is compared to the modeled results in the periods with irradiance equivalent to clear sky conditions. The relative difference (ΔI) between measured (I\text{meas}) and modeled irradiance (I\text{CS}) is given by:

$$ΔI = (I\text{meas} - I\text{CS})/I\text{meas}$$  \hspace{1cm} (1)

To evaluate how the measurements change relative to the model from year to year, a scaling factor (α) is estimated for every year by minimizing RMSE between measured and clear sky irradiance, given by [15]:

$$RMSE(α) = \sqrt{\frac{1}{m} \sum_{t=1}^{m} (α \times I\text{meas}_t - I\text{CS})^2}$$ \hspace{1cm} (2)

2.2 Method for detection of sensor detachment and snow

The difference in module and ambient temperature is strongly correlated with the irradiance (Eq. 3) [17]. Hence, by monitoring this correlation, signatures of temperature sensor detachment can be identified [8]. We have tested this method for two different installation configurations, by investigating the changes in linear regression fits of hourly values of temperature difference and irradiance for different weeks. Additionally, we have tested if the same approach can be used for snow cover detection.

$$T\text{meas} - T\text{amb} = I \times e^{a+b \times \text{Wind speed}}$$ \hspace{1cm} (3)

Where a and b are coefficients compensating for site specific configurations.

2.3 Measurement sites

The proposed method for quality control of irradiance sensors was tested for the uncorrected raw data, given as 10-minute averages, measured by an old pyranometer installed at the supervised weather station at the Norwegian University of Life Sciences. The method was also tested on a commercial flat roof PV system, where the POA irradiance was measured by tilted reference cell and given in 5-minute averages. The tilt of the system and the reference cell is 10°, and the orientation of the modules is south-east and north-west.

The method for detection of sensor detachment is tested for two different types of PV installations: South-orientated modules installed in an open-rack configuration with a tilt of 28°, and modules installed on a roof with a tilt of 35°. The module temperatures are measured by a resistant thermometer attached to the back sheet of the modules, and the POA irradiance is measured by reference cells. For the rack installation, the ambient temperature sensor is installed under the modules, and for the tilted roof installation the ambient temperature is measured by a weather station at the same location.

For both systems, the same approach is tested for snow cover identification. Additionally, snow cover identification is tested for the flat roof system used in the irradiance quality control tests. For this system, the cell temperature of a reference cell is used as an estimation of module temperature, the ambient temperature is measured by a PT-1000 element, and irradiance is measured by a ventilated pyranometer. Normally, the reference cell is covered by snow in the same period as the modules because of the low tilt angles, and the pyranometer is less affected, most likely because of the ventilation and a more elevated installation position. Both roof installations are commercial systems, while the open rack system is a scientific test site. Hourly averages are used in the analysis.

3 RESULTS AND DISCUSSION

3.1 Quality control of irradiance measurements

The irradiance measurement control method was tested on raw data from the pyranometer at the Norwegian University of Life Sciences. As presented in Figure 1, the relative difference between measured and modeled irradiance is scattered and high, especially in periods with low irradiance. In periods with low irradiance and high angle of incidence, the relative errors
of both the measurements and the modeled results is probably higher [7,18].

To improve the analysis, the periods with low irradiance were filtered out. The difference between measured irradiance and modeled clear sky irradiance when the measured irradiance was more than 500 W/m² is given as a function of time in Figure 2. The sensor was recalibrated and adjusted in 2008, after this there were no significant changes in sensitivity for two years, followed by a decrease in sensitivity by 1% per year in a four-year period (2010-2014). The pyranometer was replaced in 2014, which lead to an increase in the sensitivity of the irradiance measurements at the site of 6%. All these alterations were detectable through comparison with clear sky modeling. The shift in measured irradiance relative to the modeled irradiance at the time of the sensor adjustment and the pyranometer replacement is clearly shown in Figure 2. After the sensor replacement, the scaling factor \( \alpha \) also increased by 6 percentage points. The analysis indicates a degradation of the sensor of 1% per year in the period 2010-2014, the same as the independent instrument calibration, based on a reduction of \( \alpha \) of 1 percentage point per year.

We observe that the modeled irradiance is slightly biased and most of the time is lower than the measured irradiance, as expected for higher latitudes when using the Ineichen and Perez model [7]. Additionally, the variations between single points is high, indicating that this method cannot be applied for quality control of individual measurements. However, the ability of the method to indicate drift or other permanent changes in the irradiance measurements over time is remarkable.

It is well known that pyranometers are subject to a thermal offset during clear sky periods [19]. This introduce a bias in the comparison between the clear sky model and the measurements. However, as it is the change and not the absolute value that is of importance, this effect is assumed negligible in this context. A more relevant challenge is changes in atmospheric conditions with respect to transmission and scattering. Changes in air pollution are one of the major contributions to what is referred to as global brightening and dimming, which may have an effect of a magnitude that might influence long time PV performance analysis [18]. More practical challenges related to this method for commercial systems, is the low time resolution data these types of systems often have, and potentially also the number of clear sky hours through the year at the specific location.

### 3.2 Quality control of tilted reference cell measurements

The quality control method for irradiance measurements was also tested for tilted reference cells measuring the POA irradiance of a PV system in a north-west, south-east configuration with a tilt of 10°. Reference cells are, as mentioned earlier, common for medium sized PV systems with monitoring. The uncertainties are however higher than when pyranometers are used. The relative difference between the measurements and the clear sky modeling for irradiance above 500 W/m² is presented in Figure 3. The scaling factor between the measured and modeled irradiance is approximately constant from year to year for the irradiance measured in the north-west direction, with a reduction of less than 0.1 percentage points. This is lower than expected degradation for a c-Si reference cell [8].

![Figure 1: Relative difference between GHI measurements and clear sky irradiance modeling at different irradiance levels.](image1)

Figure 1: Relative difference between GHI measurements and clear sky irradiance modeling at different irradiance levels.

![Figure 2: Relative difference between GHI measurements and clear sky irradiance modeling at measured irradiance above 500 W/m². Time of adjustment of the sensor, pyranometer replacement, and the period where 1 % decrease per year was measured is marked.](image2)

Figure 2: Relative difference between GHI measurements and clear sky irradiance modeling at measured irradiance above 500 W/m². Time of adjustment of the sensor, pyranometer replacement, and the period where 1 % decrease per year was measured is marked.
It should be noted that the north-west orientation results in lower irradiance and fewer data points with irradiance values above 500 W/m². This could potentially affect the robustness of this result. For the irradiance measured in the south-east direction, the difference between measured and modeled irradiance appeared to be season dependent. It was found that this sensor was misaligned, which could be an explanation for this behavior.

This misalignment also gave a shift between the position of the measured and modeled irradiance curves (as well as the PV power curve), as shown in Figure 4. A consequence of this was unlikely high performance ratios for the PV system in the morning, as the irradiance sensor measured less irradiance than what the PV modules received, and opposite in the evening.

3.3 Control of module temperature sensor detachment

The linear relationship between module and ambient temperature difference and irradiance is presented in Figure 5 for two different types of installations. Data was selected from four different weeks and different months and years to highlight some important aspects: The correlation between the temperature difference and the irradiance is almost linear and it typically has relatively small variations from year to year and month to month for the ground mounted open rack system, and to some degree also for the roof mounted system. This indicates that it is possible to detect detachment of the module temperature sensor by monitoring changes in the slope. If detached, or partially detached, the module temperature sensor measure a value closer to ambient temperature, and the slope would be less steep or zero. The scattering of the data points is greater for the close roof mounted system and this system also experience the highest temperature difference. One natural explanation for this is the cooling effect of the wind, which is not taken into account in the analysis. Lack of rear side ventilation or heat leakage from the building itself may also be influential. The slope of the regression lines of the close roof mounted system is twice as steep as for the rack mounted system, in agreement with the experimental results of King et al. [17].

Figure 5: Absolute difference between module and ambient temperature as a function of measured irradiance. Data from four different weeks is shown.

3.4 Use of temperature sensors for snow detection

Snow cover on the PV modules will, like the sensor detachment, have an effect on the slope of the temperature/irradiance regression line. As presented in Figure 8-10, when snow is covering the modules, the correlation between the temperature difference and the irradiance will change substantially, as the module surface and back sheet will be significantly less heated. For the rack mounted system the measured module temperature is lower than the measured ambient temperature. The difference is increasing with increasing irradiance and ambient temperature. For the roof systems, the module temperature is higher than the ambient, most likely because the snow has an isolating effect.

Generally, it might not be possible to separate situations with partly snow-covered modules from situations with low irradiance, or situations when snow is covering the irradiance sensor. The figure showing the snow-covered modules at the tilted roof system, illustrates how it can be challenging to separate periods
with low irradiance from periods with snow cover.

The placement of the temperature sensors is of importance, as this will define the ability to detect partly covered modules, and give different temperature difference characteristics (i.e. positive, negative or zero). The temperature difference characteristics can also be studied through night time values.

4 CONCLUSION

In this work, a method for detection of permanent changes in irradiance measurements has been tested, as well as a method for detection of module temperature sensor detachment and how the latter can be used to improve detection of snow cover on the PV modules.

Quality control of irradiance measurements based on data analysis has been performed for different PV systems with high and low-accuracy irradiance sensors. We show that by using this approach it is possible to accurately detect both abrupt changes, as well as slow gradual changes such as the yearly drift of 1%.

A method for detection of module temperature sensors detachment and snow cover was tested for typical commercial installation configurations in Nordic climates, including open rack mounted, close roof mounted and tilted flat roof mounted systems. The linear relationship between temperature differences and irradiance proved to be stable enough to indicate sensor detachment and snow cover. The robustness of this method might depend on reliable irradiance measurements, sensor placement and installation configuration. Periods with low irradiance and partly snow-covered modules appeared to be challenging. However, in combination with other methods, the presented results show that the use of module temperature sensor increase the confidence and accuracy of forecasting and fault diagnostics with respect to snow cover events.

REFERENCES