

Modeling reflected irradiance in urban environments – a case study for simulation-based measurement quality control for an outdoor PV test site

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MODELING REFLECTED IRRADIANCE IN URBAN ENVIRONMENTS – A CASE STUDY FOR SIMULATION-BASED MEASUREMENT QUALITY CONTROL FOR AN OUTDOOR PV TEST SITE

Ádám Bognár¹, Roel Loonen¹, Roland Valckenborg², Jan Hensen¹

¹Building Physics and Services, Eindhoven University of Technology, Postbus 513 5600 MB, Eindhoven, the Netherlands

²Solar Energy Application Centre (SEAC), High Tech Campus 21, Eindhoven, the Netherlands

ABSTRACT: The increased application of PV in urban environments goes together with a growing awareness of the need to consider the influence of partial shading and reflected irradiance on PV performance. Most of the conventional PV simulation tools do not have the capabilities to account for the possible additional PV yield due to reflected sunlight. On the other end of the spectrum are complex ray-tracing tools that can accurately model reflected irradiance, but require a large amount of input data, are computationally intensive and have limited or no PV modeling algorithms. In this work, as a step towards quantifying uncertainties due to reflected irradiance in urban settings, the potential of a modeling strategy using building energy simulation software, with intermediate complexity is investigated using a case study of an outdoor PV test site.

Keywords: Simulation; Solar radiation; Pyranometer; Building integration, EnergyPlus

1 INTRODUCTION

The growth of the solar market in the 2010s exceeded most expectations. In 2017 (99.1 GW), the installed new PV capacity was almost as large as the total capacity in 2012 (100.9 GW) [1]. The main driving factors for such growth are ground-mounted utility-scale solar applications, which are becoming an increasingly attractive investment due to the decreasing prices of PV modules and system components. State-of-the-art PV simulation software are well-suited to predict the performance of such applications, partly because they are typically installed in an ideal location, chosen to be well-suited for maximizing PV yield. The situation of PV integration in the urban environment, on the other hand, is quite different. The European Energy Performance of Buildings Directive (EPBD) requires all new buildings in the European Union to be “nearly zero energy” buildings by 2020 [2]. Such government-induced requirements are pushing building designers to apply passive (energy demand reduction) and active (on-site energy generation) building energy performance measures. The former often requires the preparation of a building energy model to conduct simulations in order to optimize the energy performance of the building [3, 4]. The latter leads to increased use of Building Integrated Photovoltaic (BIPV) applications in an urban environment, where the irradiance conditions are more complex (due to shadows, diffuse and specular reflections) than in the case of ground-mounted PV farms. Consequently, it is a likely scenario, that a state-of-the-art building design, that satisfies the nearly zero energy requirements, is optimized using building energy models and relies on PV for on-site electricity generation. Therefore it is a logical step, to investigate the capability of building energy simulation software to cope with the complex irradiance conditions of the urban environment.

In this work, EnergyPlus [5], a whole building simulation software is investigated regarding its ability to predict the occurrence of specular reflections. The detection and classification of reflection events is demonstrated on the case study of an outdoor PV test site, utilizing the irradiance models of EnergyPlus and post-processing with Python programming language [6]. Using the reflection event classification and irradiance transposition models, filtering the effect of unwanted specular reflections from measured irradiance data at an outdoor PV test site is demonstrated.

2 IRRADIANCE SIMULATION APPROACH

EnergyPlus is an open-source whole building energy simulation software, primarily developed for the aim of conducting thermal simulations. However, during its development, more detailed solar irradiance models were added to the software, making it capable of conducting the investigation presented in this paper. In this section, the necessary simulation model settings are described in order to be able to model the occurrence of specular reflections on irradiance sensors and active surfaces.

In order to decrease the computational time, EnergyPlus by default calculates an average daily solar path and shadow coefficients in every 20 days. This setting can be overridden and set to timestep frequency, that is, the calculation of the solar position and shading factors is executed at every timestep of the dynamic building energy simulation. The maximum timestep frequency is 60 iterations per hour.

The irradiance on a tilted surface (G_{poa}) is calculated according to Equation 1:

$$G_{poa} = G_d * \cos\theta * SF + G_{sd} * F_s + G_{gd} * F_g, \quad (1)$$

where G_d is the direct normal solar irradiance, θ is the angle of incidence of direct irradiance on the tilted surface, SF is the shaded fraction calculated by the shading module of EnergyPlus. G_{sd} is the sky-diffuse irradiance, calculated with the Perez-model [7], G_{gd} is the ground reflected diffuse irradiance. F_s and F_g are the surface-sky and surface-ground “angle factors”.

EnergyPlus has a simple, single-bounce ray-tracing method to calculate external specular and diffuse reflections on building surfaces, originally developed for daylighting and heat-transfer calculations, and rarely used for solar energy applications. Validation studies of this model for predicting reflected irradiance from exterior building surfaces could not be found in literature. For every exterior surface, EnergyPlus assigns four receiver points (see Figure 1), to calculate the incident solar radiation reflected from neighboring surfaces. The reflecting surfaces can be specularly reflective (e.g. glass surfaces), diffusely reflective (opaque surfaces), and the mixture of the two (shading surfaces). Table I summarizes the settings needed to be set in the EnergyPlus Input Data File (IDF) in order to conduct the simulation case studies described in Section 3.

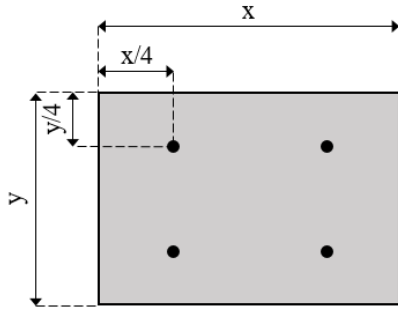


Figure 1: Receiving points on a rectangular surface.

Table I: IDF object settings to model reflected irradiance with EnergyPlus

IDF object	Value
Timestep	60
Building:SolarDistribution	FullExteriorWithReflections
Shad.Calc.:Calc.Method	TimestepFrequency

3 CASE STUDY DESCRIPTION

The SolarBEAT outdoor PV research facility (Figure 2) [8] is located on the top of the Vertigo building at the Eindhoven University of Technology (TU/e) and operated by the Solar Energy Application Centre (SEAC). Similar PV test sites can be found at numerous research institutes across the globe [9]. The site is elevated from the ground, there is no near shading and it has a clear view of the south sky hemisphere. Nevertheless, effects of the built environment can never be eliminated completely. On the North of the test site, there is an elevator shaft whose curtain wall has a reflective coating that is currently covered by a banner, to prevent specular reflections. The curtain wall will be changed in the future to a semi-transparent PV facade that despite the anti-reflection coating, might cause minor specular reflections on the test site. When local reflection events cause differences between irradiance received at PV surfaces and the neighboring irradiance sensors, this can negatively impact the reliability of PV performance metrics calculated from the measurements.



Figure 2: SolarBEAT outdoor PV research facility.

To aid the analysis of experiments, and to maintain the high quality of the measurement data collected at SolarBEAT, a simulation-based method is developed to indicate and classify momentary specular reflection events on the test site. The approach is to simulate the reflected irradiance on the PV surfaces and at the irradiance sensor points on the test site under clear sky conditions using the EnergyPlus software. The geometry of SolarBEAT was generated with Euclid, a SketchUp plugin for EnergyPlus geometry input. The reflective surfaces (elevator shaft and the façade of the Vertigo building) were modeled with shading surfaces (see Figure 3), the active surfaces were modeled as roofs and the pyranometers were modeled as 0.1x0.1m rectangles in plane of the sensors.

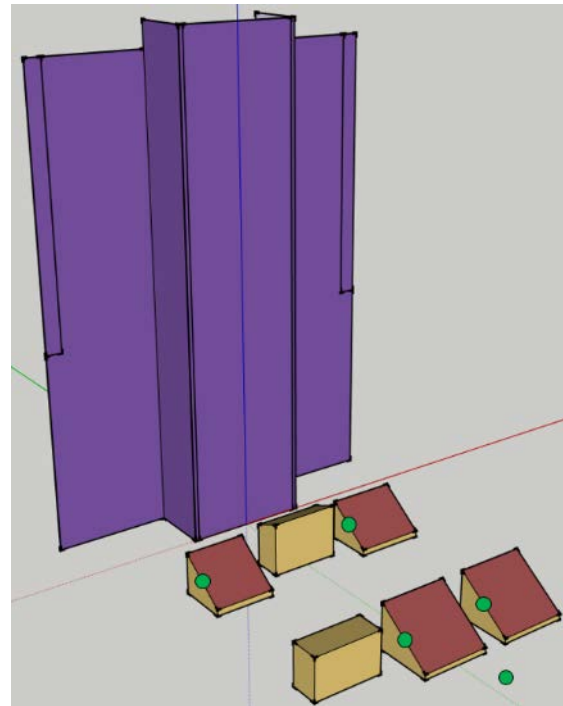


Figure 3: SolarBEAT modeled in SketchUp. The reflective surfaces are purple, the active surfaces red and the irradiance sensors are marked with green.

The clear sky weather file for the simulation was generated with the `get_clearsky` function of the PV_LIB Python library [10], using the Ineichen clear sky model. By simulating the reflected irradiance with a clear sky weather file, all time periods can be identified and classified, when specular reflections can possibly occur.

4 CLASSIFICATION OF REFLECTION EVENTS

4.1 Classification approach

The steps to classify and flag the reflection events on the test site are as follows:

- 1) Create an accurate geometry of the test site (active surfaces, irradiance measurement points and obstructions) in SketchUp and EnergyPlus with the assumed reflection properties of the nearby surfaces.
- 2) Create a weather file with only clear sky conditions.
- 3) Run a yearly simulation with minutely resolution using the clear sky weather file and register the reflected irradiance on the active surfaces and irradiance measurement points.

4) Classify the reflection events with the rule table (see Table II) and flag them in a yearly time series assigned to the individual measurements on the test site.

Measuring plane of array irradiance and generated power of the PV provides the basis to calculate derived performance metrics, such as Performance Ratio (PR). The effect of the reflected irradiance on the calculated metrics can be categorized to three different reflection events (see Figure 4): Reflection on Active Surface (RoAS), Reflection on Irradiance Sensor (RoIS), and Reflection on Active Surface and Irradiance Sensor (RoASIS).

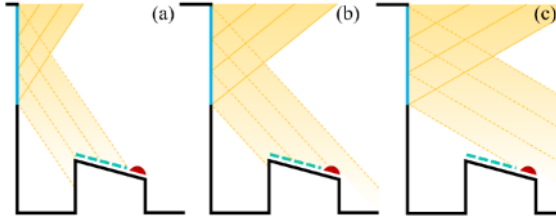


Figure 4: a) RoAS, b) RoASIS, c) RoIS reflection-events

Table II: Reflection-event rule table

Reflection detected		Flagged reflection event		
Active surface	Irradiance sensor	RoAS	RoIS	RoASIS
0	0	0	0	0
1	0	1	0	0
0	1	0	1	0
1	1	0	0	1

In the latter case, the point-like irradiance measurement might represent well the irradiance on the PV surface, but not the weather conditions on the site. It is also difficult to interpret properties like incidence angle, when the active surface sees the sun and the reflected image of it at the same time. In the case of a RoAS reflection event, the power output of the PV might increase, while measured irradiance does not, causing an error in the calculation of performance metrics, such as overestimation of PR. In the case of a RoIS event, PR would be underestimated.

The classification is done in post-processing the simulated and measured irradiance data with Python. Two conditions are needed to be simultaneously met, in order to classify an irradiance sensor or an active surface as being affected by reflections:

$$\frac{DHI_m}{GHI_m} \leq k_{Dt}, \quad (2)$$

and

$$G_{poa_ref_sim} \geq G_{poa_sim} * RTM. \quad (3)$$

Equation 2 is about the irradiance conditions on the site, it expresses the condition, that specular reflections are only possible, if there is direct light. DHI_m and GHI_m are the site measured diffuse and global horizontal irradiance. k_{Dt} is the diffuse fraction threshold. For this investigation $k_{Dt} = 0.95$ was used. Equation 2 expresses the condition, that a surface can be classified as affected by specular reflections, if the simulated specularly reflected clear sky irradiance ($G_{poa_ref_sim}$) surpasses a given value. G_{poa_sim} is the simulated clear sky irradiance on the surface in question, RTM is the reflectance threshold multiplier. An $RTM = 0.05$ was used in this investigation.

4.2 Case study results

Figure 5 shows measured and simulated clear sky irradiance on an irradiance sensor at SolarBEAT, from

August 2015, when the banner covering the reflective elevator shaft was not installed yet. The simulated reflected component is plotted separately as well, with the threshold for indicating a reflection event. Figure 6 shows the classification of reflection events for a whole year.

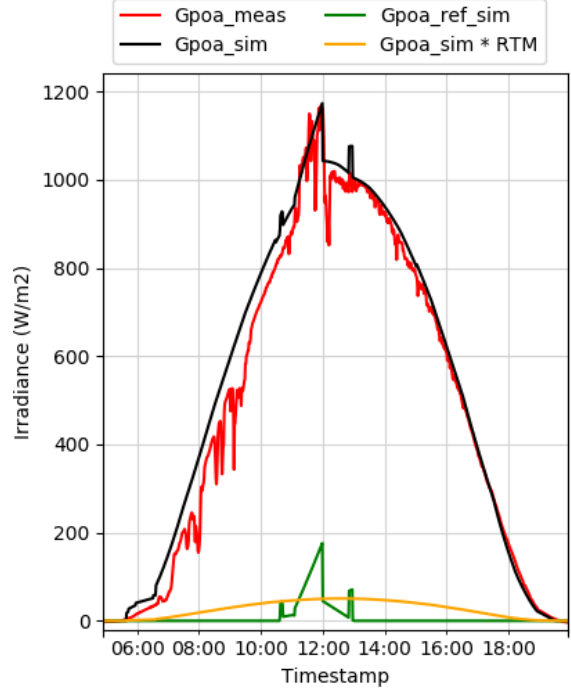


Figure 5: Simulated and measured irradiance of a pyranometer in 22th of August, 2015.

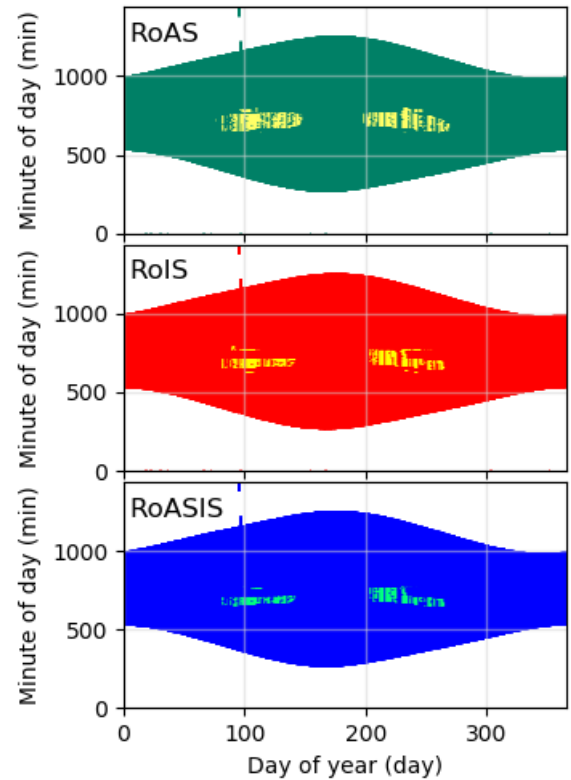


Figure 6: RoAS, RoIS and RoASIS reflection-events on a yearly heatmap. The background color indicates, when the sun is over the horizon, the contrasting colors show the occurrence of a reflection-event.

4.3 Irradiance corrections

A possible application of the flagging of reflection events is to aid the correction of irradiance measurements that are influenced by unwanted specular reflections. On the SolarBEAT test site, each experiment has its own plane of array pyranometer, that measures global irradiance. Moreover, there is a central measuring station, that provides detailed irradiance data, such as global horizontal, direct normal and diffuse horizontal irradiance. To filter unwanted specular reflections from an irradiance measurement, first a reflection-event detection should be conducted on the pyranometer in question and the central measuring station, which are situated approximately 40 meters from each other. It should be verified, that specular reflections do not occur at the same time on the two sensors. Once this is done, the detailed irradiance measured at the central measuring station can be transposed to the tilt and orientation angle of the pyranometer in question. For this the `pvlb.irradiance.total_irrad` function was used with the Klucher model [11] for transposing the sky-diffuse irradiance, implemented in Python. For the calculation of the ground-reflected component of the irradiance, an albedo value of 0.22 was used. Figure 7 shows, as the transposed irradiance replaces the measured at times, when it is affected by specular reflections.

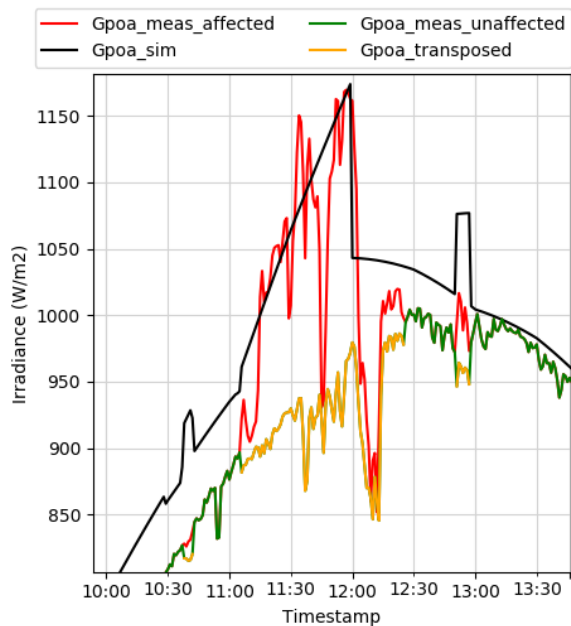


Figure 7: Simulated, measured and transposed irradiance pyranometer in 22th of August, 2015. The green and yellow lines give the corrected irradiance time series.

5 CONCLUSIONS

In this paper, it was demonstrated, that EnergyPlus is capable of simulating certain aspects of the complex irradiance conditions of dense urban environments. This finding provides supporting arguments for the use of EnergyPlus to simultaneously predict both building energy consumption as well on-site energy generation. With the use of a simulation case-study, it was shown how EnergyPlus can be used for classifying reflection events on an outdoor PV test site. With post-processing the irradiance data, using the flagged reflection events, a method was demonstrated, to filter the effect of unwanted reflections from irradiance measurements. Here we would like to note, that filtering the reflections from the measured

irradiance data is not always the best solution. It depends on the utilization of the measured irradiance data, that ignoring, replacing with NaN values or filtering the effect of reflections with the presented method is the best solution. The reflection-event classification presented in this paper can be used, to aid this decision.

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