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Electricity yield simulation for the building-integrated photovoltaic system installed in the main building roof of the Fraunhofer Institute for Solar Energy Systems ISE

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ABSTRACT

The generated electricity of a rather complex building-integrated photovoltaic system, installed in the main building of the Fraunhofer Institute for Solar Energy Systems, is analyzed in detail. For this purpose, the measured irradiance on the tilted surface, the temperatures of the PV modules, the DC power and the AC power are compared with the results of an advanced electricity yield simulation program that has been developed at the institute. The chosen building-integrated photovoltaic (BIPV) system allows detailed investigation of complex shading patterns, improved electrical cell connection and the temperature characteristics of building-integrated photovoltaic modules when they simultaneously function as insulating glazing units with a low *U* value. The comparison of simulated and measured AC power shows that the consequences of partial shading, the consequences of the integration as a thermally insulating component of the building envelope and the electrical properties of the PV system are understood well.

1. Introduction

During the last few years, substantial efforts have been undertaken to develop an electricity yield simulation program with the aim of understanding the consequences of partial shading, the layer structure of the BIPV module, the electrical connection of the PV cells to each other, the choice of inverter and many other effects on the generated electrical power of a BIPV system (Sprenger, 2013). The efforts were motivated by the awareness that a BIPV system can best be optimized when the DC power output can be reproduced in a simulation. Also, the functionality of already installed PV cells and modules of a BIPV system can be verified most easily if the generated electricity is compared to the results of a detailed electricity yield simulation program. Also, the sensitivity of BIPV system optimization to different material parameters can best be analyzed with the help of a complete computer simulation chain. To illustrate the achieved degree of understanding of the factors that determine the generated electricity, a rather complex BIPV system is analyzed in detail in this paper.

2. State of the art in simulating BIPV systems

For free-standing PV systems, many commercially available simulation programs exist to calculate the time-dependent electricity yield, typically for a whole year. Generally, the accuracy of these programs when applied to building-integrated photovoltaic systems is limited due to the fact that simplified models had to be used in order to minimize the computation time. Most of these PV simulation programs restrict the calculation of the irradiation to one value per time step, which allows accurate determination of the electricity yield for most free-standing PV systems but makes it impossible to accurately represent the consequences of partial shading. Some commercially available PV simulation programs allow partial shading calculations on the level of PV modules, which at least provides the possibility to optimize the electrical interconnection of the PV modules. An accurate representation of the power output under partial shading conditions is not the intention, as this calculation would exceed practicable calculation duration limits. Furthermore, the agreement of the assumed power output with measurements strongly depends on the shadow pattern. The assumptions implemented by commercial PV simulation programs are generally not accessible.

A good review of the specific physical properties that need to be analyzed for BIPV systems can be found in Norton et al. (2011). In addition to the aspects discussed above, a simulation procedure with the purpose of calculating the electricity yield for the general case of building-integrated photovoltaics needs to take into account at least four further topics.

First, a BIPV system is almost always inhomogeneously irradiated, either due to several different module orientations, due to partial shading or due to higher irradiation caused by

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Nomenclature

α	fraction of the incident (effective) irradiation that is absorbed in the PV layer
$\alpha_{I_{SC}}$	temperature coefficient of the short circuit current
$\alpha_{P_{MPP}}$	temperature coefficient of the maximum power point
$\alpha_{V_{OC}}$	temperature coefficient of the open circuit voltage
Δt	time interval (within this publication: 5 min)
$\dot{q}_{abs}$	heat absorbed in the PV layer
$\dot{q}_{cap}$	capacitive heat from the last time step
$\dot{q}_{i,j}$	heat transfer from layer i to layer j
η_{STC}	efficiency of the PV module at standard test conditions (STC)
λ_i	thermal conductivity of layer i
ρ_i	density of layer i
a_R	variable in the angular response model of Martin and Ruiz (2001)
c_i	heat capacity of layer i
d_i	thickness of layer i
d_{wind}	wind direction when projected onto the horizontal plane
E_{eff}	"effective" irradiance (with angular correction according to Martin and Ruiz (2001))
h_{ext}	external heat transfer coefficient
h_{int}	internal heat transfer coefficient
I_{ph}	photocurrent (source current in the electrical circuit of the two-diode model)
I_{s1}	saturation current of the first diode in the two-diode model
I_{s2}	saturation current of the second diode in the two-diode model
k_B	Boltzmann constant
L_{mod}	length of the PV module from the top to the bottom (as a basis for the calculation of the resistances in the electrical connections of each PV submodule)
N	number of analyzed time steps
n_1	ideality factor of the first diode in the two-diode model
n_2	ideality factor of the second diode in the two-diode model
pyr_{30°	global irradiance measured by a CMP11 pyranometer with southern orientation and a tilt angle of 30°
pyr_{45°	global irradiance measured by a CMP11 pyranometer with southern orientation and a tilt angle of 45°
q_{el}	charge of the electron
R_m	resistance per connector length of the laminated connection paths within the PV module
R_p	parallel resistance in the two-diode model
R_s	series resistance in the two-diode model
T'	temperature of the PV cell in the previous time step
T_{amb}	ambient temperature, measured at the local meteorological station
T_{mod}	temperature of the PV module (if the temperature is considered to be constant throughout the PV module)
U_{gap}	bandgap of silicon
V_T	thermal voltage as defined in the text
v_{wind}	wind speed when projected onto the horizontal plane

reflections from surrounding buildings or inhomogeneous optical properties of the ground. The results described in Sprenger et al. (2011) strongly suggest that a ray-tracing procedure is needed to analyze the irradiation on the PV cells involved in a BIPV system, and the results also implicitly recommend the application of CAD programs to define the geometrical configuration of the building and the surroundings.

The required processing the calculated irradiance data leads to the second additional topic, the necessity of calculating the *I–V* characteristic curves at the PV cell, PV module and PV system levels. An accurate simulation approach for the *I–V* curves is especially necessary due to the fact that the operating conditions of the PV cells in BIPV applications deviate more from standard test conditions than for free-standing PV plants.

The third topic that needs to be addressed in an electricity yield simulation tool for building-integrated photovoltaic systems is the operating temperature of PV cells and modules, depending on the installation type. In the frequent case of semitransparent BIPV facades and roofs, the BIPV modules often provide the function of thermal insulation in the building envelope, reducing the heat transfer to the back surface of the complete BIPV component. In BIPV insulating glazing units with many glass panes involved, also the heat capacity of the PV module plays a role for the calculation of the time-dependent electricity yield.

The fourth important topic is the analysis of the inverters electrical specifications and their impact on the electricity yield. Building-integrated photovoltaic systems show wider variety in DC voltage and DC power than free-standing PV systems, which can lead to non-optimal MPP tracking and to power losses. In addition, the greater DC power variation within a single BIPV system also leads to a lower total inverter efficiency, which needs to be analyzed in the simulation process.

The validation of an electricity yield simulation procedure for BIPV systems requires detailed monitoring of a real BIPV system that addresses the listed four topics. To the authors knowledge, a validated yield simulation tool on the basis of representing the PV cells DC circuit was first published in the scientific literature in Sprenger (2013). The earliest efforts were undertaken by Kovach and Schmid (1996), who already applied a combination of ray-tracing and *I–V* curve calculation at the PV cell level, but without considering the two-dimensional layer structure of the PV modules, and without validation of the generated AC power at the system level. Kelly (1998) published a general simulation procedure for electrical DC circuits on the basis of a simplified diode model, but with only limited validation (based on laboratory measurements of a PV module).

Some publications focus on the analysis of partial shading but use simple PV systems (with PV modules that do not provide a building function) as a basis for validation, like Picault et al. (2010). An early review on the topic can be found in Woyte et al. (2003). The remaining publications in the research field that came to the knowledge of the authors apply simulation procedures based on more simplified assumptions, and none of them includes the calculation of the electrical mismatch at the system level. The publication of Yoo and Manz (2011) shows a detailed temperature calculation based on computational fluid dynamics, but without calculating the consequences of the resulting module temperatures on the electricity yield. The publications of Fath et al. (2015), Lam et al. (2006) and Fry (1998) use parameter models at the module or system level to reflect the electrical behavior at low-light conditions, which excludes partial shading calculations. In the publications of Saber et al. (2014) and Mondol et al. (2005), the one-diode model in TRNSYS has been applied for low-light conditions, but without mismatch calculations or validations at the system level. The simulation approach chosen by Lu and Yang (2010) is similar. Still more simplified approaches are applied in Yoon et al. (2011) and Yoo and Manz (2011).