Solar Energy 146 (2017) 113–118

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Modelling the performance of amorphous and crystalline silicon in different typologies of building-integrated photovoltaic (BIPV) conditions

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 2 July 2016
Accepted 20 February 2017
Available online 3 April 2017

Keywords:
BIPV
Performance ratio
Energy-yield
Amorphous silicon
Crystalline silicon
Modelling

ABSTRACT

In this work we use and further elaborate a previously proposed model to describe the daily performance ratio of amorphous (a-Si) and crystalline silicon (c-Si) photovoltaic solar modules under real operating conditions. For both technologies, the model was validated against three years of data collected from the outdoor test field at Supsi for a conventional ventilated free-rack mounted installation (south-facing, 45°-tilt). In the present work, we expand the simulations to model the performance of the same technologies for the same location and to include building integrated (BIPV) installation conditions. For simplicity, we consider two extreme cases: (a) a south-facing façade installation (90°-tilt) and (b) a perfectly horizontal one (0°-tilt). The angle-of-incidence response of the modules is then used to quantify reflection losses, which are very significant in summer and winter for the façade and horizontal installation, respectively. Further, compared to ventilated ones, fully integrated PV modules exhibit average operating temperatures that can reach an offset of +20 °C in days of clear sky conditions. This offset is used to model the operating temperatures – and performance losses – of the BIPV modules.

The model, whose main limitation is the focus on days of clear sky conditions, allows assessing the distinguished contributions, and peculiar time-phases, of each effect to the yearly energy performance of the devices under test.

1. Introduction

In 2015, several sources report new installations of solar photovoltaic (PV) electricity worldwide to be in the range of 55–60 GWp, of which only a minor portion has been used in the built environment as a full constituent of the building envelope (i.e. Building Integrated PhotoVoltaics, BIPV). However, in the coming years particularly in Europe BIPV installations are expected to boost mainly thanks to policy drivers. Specifically, the *Energy Performance of Buildings Directive* (Directive 2010/31/EU, 2010) requires all new buildings to be nearly zero-energy by the end of 2020. All new public buildings must be nearly zero-energy by 2018. Nearly Zero-Energy consumption Buildings (NZEBs) are buildings in which the energy consumption and production – by means of renewable sources – needs to be balanced. Therefore, BIPV installations in Europe are expected to grow considerably beyond the present niche market.

In this work, we model the energy performance (DC-side) of single-junction amorphous (a-Si) and crystalline (c-Si) silicon photovoltaic (PV) modules for different typologies of Building Integrated PV (BIPV) installations. For both technologies, which captured our attention due to their peculiar counter-seasonal oscillations (Virtuani et al., 2015; Minemoto et al., 2009; Ye et al., 2012; Makrides et al., 2013; Marion et al., 2014), the model has previously been validated against three years of data collected from the outdoor test field at Supsi (Lugano, CH, 46°N) for a conventional ventilated free-rack mounted installation (south-facing, 45°-tilt, see Virtuani et al., 2015).

In the paper, we briefly recall the model, which has a daily resolution, and focus on days of clear-sky conditions only, and, for the test site of Lugano, we expand the simulations to model the performance of the same technologies to include Building Integrated PV (BIPV) installation conditions.

For simplicity, we consider two extreme cases of full integration: (a) a south-facing façade installation (90°-tilt) and (b) a perfectly horizontal one (0°-tilt).

For these typologies of installation, besides the strong influence of the module's angle-of-incidence (AOI) response introducing

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http://dx.doi.org/10.1016/j.solener.2017.02.035
0038-092X/

reflection losses, another parameter having a strong influence on the energy output of the module is the operating temperature of the cell/module, which for fully integrated modules is considerably higher. A third parameter, having potentially a strong influence on the energy performance (and lifetime) of BIPV installations is the presence of shadows, which are much more likely to appear in a built environment. We do not address this latter point in this work, but we want to stress the fact that shadowing issues may be mitigated by the use of the appropriate smart electronics (i.e. power optimizers or micro-inverters).

2. The model

The performance ratio PR of a PV system or single module varies as a function of daytime and can be averaged on a daily basis (International Electro-technical Commission, 1998). The daily PR_d is defined as:

$$PR_d = \frac{E_d/P_{STC}}{H_d/G_{STC}} = \frac{\eta_{en}}{\eta_{p\_STC}} \tag{1}$$

where E_d (Wh) and H_d (Wh/m^2) are, respectively, the daily energy production (DC-side in this work) of the module and the insolation to which the module is exposed; P_{STC} (W) is the measured power at standard test conditions (STC: 25 °C, AM1.5, 1000 W/m^2, normal incidence) and G_{STC} (W/m^2) is the irradiance at STC. In other words, PR expresses a ratio between the efficiency η_{en} (in terms of energy) of the module/system exposed to real operating conditions ($\eta_{en} = E_d/H_d$) and the efficiency η_{p_STC} (in terms of power, $\eta_{p\_STC} = P_{STC}/G_{STC}$) of the same device at STC. Therefore, providing an indication of how the device will perform under real operating conditions compared to STC ones.

For simplicity, our approach to model the PR_d of the modules focuses on days of clear-sky conditions and on four main *losses/gain mechanism* only: (1) **temperature**, (2) **spectral-effects**, (3) **reflection**, (4) **irradiance losses**. With the addition of the **Staebler-Wronsky effect** (SWE, Staebler and Wronski, 1977; Virtuani and Fanni, 2014) for a-Si, a reversible degradation and regeneration of the electronic properties of the absorber material promoted, respectively, by exposure to light and by thermal annealing.

Due to the large noise and scatter in PR_d data, cloudy and overcast days are filtered, allowing us to recognize a clear trend in the measured data. The criteria used in the filtering process are multiple, the more relevant of which is, however, the clear-sky ratio. In order to classify a day as a clear-sky one (and hence use it in our calculations), we have defined, a clear-sky ratio $Hs = G_{diff}/G_{poa}$ (with G_{diff} and G_{poa} the diffused and plane-of-array irradiance, respectively). Clear-sky days are the ones with $Hs < 0.2$. By focusing on clear-sky days only, other effects (e.g. the diffuse-to-direct irradiance ratio, humidity, etc.) which may have an influence on PR_d for days with different climatic conditions (or instantaneously on PR(t)) are here neglected or averaged out by the model. More details about the model are given in Virtuani et al. (2015).

2.1. Module characterization

From the device side the model requires a limited characterization of the device under test (Virtuani et al., 2011), which we performed at SUPSI's ISO-17025 accredited testing laboratory: IV measurement at STC (Wp), temperature coefficients, spectral (SR) and angle-of-incidence (AOI) response, and low-irradiance dependence. A full characterization of the devices, whose performance is modelled in this work, is given in Virtuani et al. (2015).

The indoor tested power P_{max} of the devices, used for the PR_d calculation, was 100.2 W_p (stabilized) and 216.2 W_p for a-Si and c-Si, respectively.

The modules' P_{max} temperature coefficients were measured indoors ($\gamma_{rel} = -0.18\%/°C$ for a-Si and $-0.43\%/°C$ for c-Si), as well as the spectral response (SR) of the device (Virtuani et al., 2010). The SR is used to simulate the air mass (AM) dependence of the devices ($\alpha_{sp} = -6.44$ and +2.05%/AM for a-Si and c-Si, respectively), as described in Virtuani et al. (2015), using as a reference global irradiance spectra generated with SMARTS (Gueymard, 2001) for the test site of Lugano. These data are briefly summarized in Table 1. The input to model reflection losses is the module's performance P_{AOI} (power or current) vs AOI, which we take from literature data for conventional a-Si and c-Si modules (Martin and Ruiz, 2001). P_{AOI} (Θ) is fitted well with a 6th-grade polynomial fit and, for AOI's between 0° and 50°, reflection losses for both devices can be nearly neglected.

Further, both devices exhibit an excellent low-light behaviour (see Virtuani et al., 2015).

2.2. Processing solar and meteorological input parameters

Input for our simulations are *daily aggregate data* weighted on the irradiance for the module's temperature T_{mod}, the plane-of-array global irradiance G_{poa}, the Air Mass AM, and the Angle-of-Incidence AOI. AM and AOI (with respect to the module's normal) are geometrical parameters which are available or can be calculated for any location. T_{mod} requires a direct monitoring (as for Lugano), or the use of approximate relations based on NOCT between T_{mod} and the ambient temperature T_{amb} (Ross, 1980; Koehl et al., 2011; Alonso Garcia and Balenzategui, 2004).

In this work we use directly monitored T_{mod} and G_{poa}, values from the open-rack modules at 45° tilt and model the corresponding parameters for the simulated BIPV installations.

Daily weighted average values are calculated by multiplying per the irradiance profile G(t) (i.e. G_{poa}) and normalizing over the full insolation of the day $H_d = \int G(t) \cdot dt$. For the AM ($\overline{AM_d}$):

$$\overline{AM_d} = \frac{\int AM(t) \cdot G(t) \cdot dt}{\int G(t) \cdot dt} \tag{2}$$

All other input parameters are processed accordingly. As all these parameters are instantaneous values, the idea of focusing on aggregate values - weighted on the irradiance - reflects the fact that in a single day the energy production of a solar module is perfectly phased with the irradiance profile (i.e. the highest amount of energy is produced in the central part of the day). So that, in order to model the daily energy performance of a PV device, values of T_{mod}, G, AM, and AOI are given a higher weight around noontime.

2.3. Losses/gains and relative performance factors

We model then the relative daily average *performance losses* (or *gains*) ΔP_i with respect to STC (in %) for the devices and each single contribution by inserting the daily input parameters in the following expressions:

Table 1
Indoor characterization of the PV modules used in this work.

Module	Stabilized P_{max} (Wp)	Temp. Coef. (%/°C)	Spectral Coef. (%/AM)
Single-junction a-Si Nexpower NH-100-AX-1	100.2	−0.18	−6.44
c-Si Conergy, PowerPlus 15	216.2	−0.43	+2.05