NUMERICAL ANALYSIS OF THE IMPACT OF ENVIRONMENTAL CONDITIONS ON BIPV SYSTEMS, AN OVERVIEW OF BIPV MODELLING IN THE SOPHIA PROJECT

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ABSTRACT: The advantage of BIPV systems is to obtain multifunctional building envelope by adding functions such as weather impact protection in addition to electro-technical properties. Based on the results of the BIPV task of SOPHIA research program, the main purpose of this work is to analyze the thermal related electrical behaviour of BIPV systems according to environmental conditions.

Various steady state and dynamic numerical models have been realized by the partners. CEA INES developed in TRNSYS software a 2D steady-state model of PV modules integrated into roof. AIT uses different approaches of modeling: a stochastic volumetric path tracing of spectral light, infrared and visible absorption and emission of surfaces, local average of illumination respecting local climate, surrounding buildings.

Fraunhofer ISE realized a steady-state temperature model for BIPV systems, including the dependence on the cell operation mode. In order to evaluate all relevant aspects in BIPV applications, a real-time power balance model has been developed at Fraunhofer IWES in holistic approach. In order to evaluate the accuracy and the relevance of numerical models, they present an overview and an analysis of the existing optical, thermal and electrical models.

Keywords: Rooftop, Modeling, Module Integration

1 INTRODUCTION

The research program called SOPHIA is a European project aiming to the numerical and experimental analysis of PV modules installation and the dissemination of knowledge.

Based on the results of the BIPV task of SOPHIA project, the main purpose of this work is to study the thermal related electrical behaviour of building integrated PV modules (BIPV). The principle of a BIPV system is to replace or modify the existing building envelope element by a photovoltaic (PV) component in order to add functions for example weather impact protection, mechanical rigidity, and thermal insulation to electro-technical properties. These PV modules could be put in façade, in roof, in canopy or in curtain wall, for example as a multifunctional element. Thus, there is a TC 82 CENELEC draft, at the moment under the enquiry procedure step, specifically addressed not only to the electrical but also to the building requirements BIPV systems depending on the way they are integrated into the building. This standard proposes six kinds of categories.

The partners involved in this task are CEA INES, Fraunhofer ISE, Fraunhofer IWES, AIT, TECNALIA, JRC and ENEA. More precisely, our objective is to evaluate the behaviour of PV modules temperature in BIPV systems according to environmental conditions. Various steady state and dynamic numerical models of BIPV systems have been developed by the partners. Thus, in order to evaluate the accuracy and the relevance of these models numerical parametric studies have been realized by using ICT conditions and finally benchmarks.

In this paper which is the first step of our work, we present an overview of the existing numerical models by analyzing the influence of all parameters required for modeling of power and energy rating of the BIPV systems. Firstly, an optical analysis by studying the incident irradiation on tilted surface and the reflection losses was performed. Then, the different models used to simulate the electrical and thermal behaviors of a Building Integrated Photovoltaic system were identified.

2 OPTICAL ANALYSIS

The optical analysis found in the literature concerns numerical and experimental studies. They aim, most of the time, to determine first the optimal tilt angle for BIPV systems for a building design and then, the solar irradiation according to the system tilt angle by proposing accurate correlations or accurate sensors. For BIPV systems optical analysis is important since modules can have additional functions such as glazing, sun shading daylight. Contrary to free-standing PV plants, PV modules in building-integrated applications can be installed at orientations that do not lead to the maximum of generated electricity yield. Especially vertical orientations are very common due to façade applications. It is important for some applications to evaluate the amount of energy and even of light that a module reflects or transmits.

2.1 Numerical studies

The global and the diffuse irradiances on a horizontal plane can be measured at first and then the data is processed to a model that simulates the irradiance on the tilted surface.

In literature, there are different models usually good for free-standing applications. However, it has to be analyzed in which extent the equation is also valid for vertical orientations. Not only the higher fraction of diffuse irradiation, but also the higher incidence angles may lead to higher errors.

While the direct irradiation on the tilted surface can be directly calculated from the direct irradiation fraction on the horizontal plane, the diffuse component – or, leading to the same knowledge – the global irradiance on the tilted plane needs to be simulated in detail.

With vertical orientations, also the albedo gains importance. The albedo of various surfaces of ground has been analyzed by A. Angstrom in 1925. While common PV simulation tools assume a value of 0.2 as ground albedo, this number has to be discussed in more detail for vertical orientations [1].

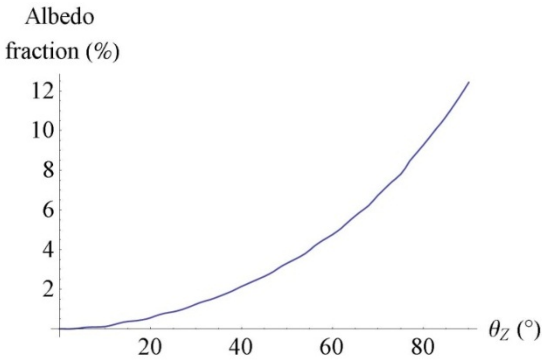

Figure 1: Albedo fraction of the annual irradiance total for different tilt angles in southern direction for the location of Freiburg/Germany [1].

The Figure 1 shows the albedo fraction for different tilt angles in southern direction for the location of Freiburg/Germany. Assuming an albedo of 0.2, the irradiance fraction due to ground reflection exceeds 10% for south-vertical orientations.

Furthermore, STC measurements are performed only with the global AM1.5 spectrum. The spectral distribution on vertical orientations is blue-shifted due to the higher fraction of diffuse irradiation. This is especially important for the competition between different PV technologies: materials with a higher band gap show higher photon absorption. It has to be analyzed in which respect the change of spectral distribution is important for the BIPV yield simulation.

For a fixed orientation, the optimum tilt angle β is obtained through an equation depending on solar irradiation and time [2].

For BIPV systems, PV modules are usually placed according to the facade shapes and architecture arts, so that analyzing the yearly performance with azimuth and slope angles is quite valuable as illustrated in Figure 2:

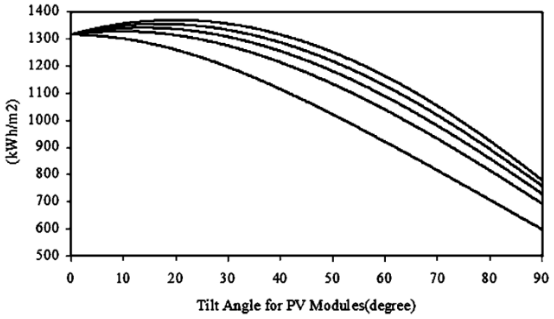

Figure 2: Effect of tilt angles on yearly absorbed solar radiation on PV panels, upper to lower curves: (γ=0, −30, −45, −60, −90 deg).

This study could be interesting during the building design in order to determine the optimal façade orientation for BIPV systems.

Sprenger et al [3] developed a new methodology for simulating the electricity yield of complex BIPV systems. It permits a detailed optical analysis of the surroundings of the BIPV system by separating the time-independent ray-tracing of the given geometry from the time-dependent sky simulation when an irradiation on a photovoltaic element is calculated. Furthermore, also more complex BIPV façade elements can be treated in the optical simulation, like the PV element called "PVSHADE", which was developed by the same group (see Fig. 3). The PV element consists of two layers of photovoltaic material (amorphous silicon) in the form of stripes.

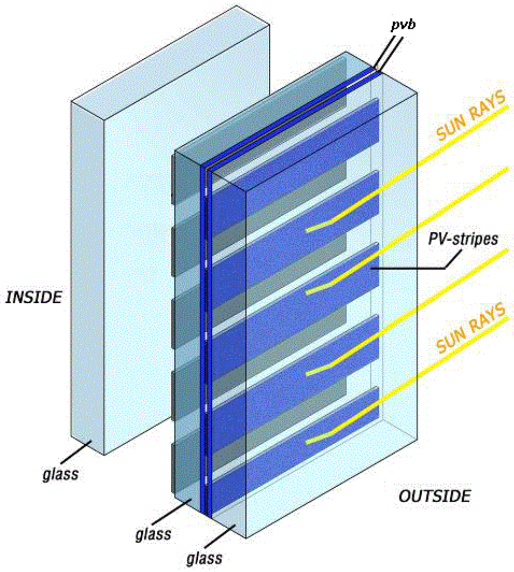

Figure 3: The PVSHADE module. The photovoltaic layers of two a-Si:H modules are ablated into stripes with special lasers; after that procedure, both modules are laminated together [3].

As an example, the irradiative loss due to an east-facing wall to a south-facing PV module is analyzed, leading to the irradiance course shown in Figure 4.

The inclusion of shading alone reduces the irradiation total of one particular day by 33.7%, whereas consideration of both shading and reflection by the wall results in a reduction of only 13.7%. Thus, taking into account the shading but not reflection, corresponding to methods based on solid-angle approaches, results in an error of 23.1% for the daily global irradiance (see Fig. 4).

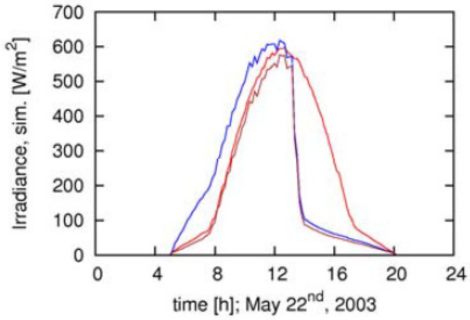

Figure 4: Time-dependent irradiance for the geometrical configuration of Figure 3. Red: Simulation without the shading wall; brown simulation with shading by the east facing wall, but without considering its reflectance; blue: with shading and taking a reflectance of 0.65 into account (corresponding to a grey-white external wall).

The loss of radiation due to shading by a wall adjacent to a façade suitable for BIPV is shown to be partly compensated by radiation reflected from the wall. The effect has already been discussed and quantified in [3].

2.2 Experimental studies

The irradiance on the tilted PV surface can be measured with a pyranometer or a reference solar cell. However, there is a difference between the measured irradiance and the irradiance relevant for the PV module that is especially important for vertical orientations. If the incidence angle of the direct sunlight exceeds 60 degrees, a considerable amount of the irradiance is reflected, but still measured by the pyranometer or reference solar cell.

The accuracy of the prediction of power and energy rating is dependent on irradiation measurement. There are several studies which compare different technologies of irradiation sensors with each other. This shows that the initial calibration coefficients cause discrepancies in the measurement of irradiance of about 4.5%. This has to be taken into account during modeling. Moreover depending on the technology of the reference solar cells, discrepancies can be measured as well. The comparisons show that not only different irradiations sensors but also different technologies can lead to discrepancies for measuring irradiation and further modeling.

The optical analysis is one of the most important elements for thermal and electrical modeling of BIPV systems. Thus, the correlation used for optical behavior, such as irradiance equation will influence the temperature of the PV modules and so the electrical production.

3 THERMAL ANALYSIS

The main difference between BIPV modules and conventional building products is the higher operating temperature. The cell temperature depends on several parameters, such as the thermal properties of materials used, the type of cells, the module configuration, the installation methods and the environmental conditions, etc. In a nutshell, a study of the literatures expressing operating temperature of PV cell (T_C) as a function of pertinent weather variables and irradiation yield can be explained with a large number of NOCT, implicit and explicit models [4].

3.1 Simple Model

The nominal operating cell temperature (T_{NOCT}) is defined as the average temperature of PV modules for free-standing outdoor applications under Standard Operating Conditions – SOC (solar radiation - 800 W/m², ambient temperature (T_{amb}) - 20°C, tilt angle - 45°, wind speed - 1m/s and open circuit operation) [IEC-61215]. Generally, the T_{NOCT} value is an inherent property of each individual module, but its value can still vary from one module to another. It is commonly used to estimate the cell temperature (T_C) of BIPV modules (see Eq. 1). Therefore, the simplest correlation model for real-time operating cell temperature (T_C) can be calculated with function of solar irradiation (G_T) (see Eq. 2) [5], [6]. Davis et al [7] has also tried to explain the cell temperature with consideration of average module efficiency (η_c), solar transmittance as a function of the incident angle (τ) and absorption of PV cell (α) values of PV module have also been taken into account (see Eq. 3).

$$T_{NOCT} = (T_C - T_{amb})_{SOC} + 20°C \qquad (1)$$

$$T_C = T_{amb} + (T_{NOCT} - 20°C).(G_T/800) \qquad (2)$$

$$T_C = (T_{NOCT} - T_{amb,NOCT}).(G_T/800).(1 - \eta_c/\tau\alpha) + T_{amb} \qquad (3)$$

In order to get better operating temperature in BIPV applications, INOCT (Installed Nominal Operating Cell Temperature) and NOST (Nominal Operating Specific Temperature) are also other possibilities. INOCT is defined as PV cell temperature of an installed array at NOCT conditions. It characterizes the thermal properties of the module and its mounting configuration [8]. NOST is defined as a site and mounting specific module temperature at NOCT conditions [9].

Cell temperature and back-surface module temperature (T_M) can be distinctly different. Knaup tried to estimate the precise operating cell temperature from backside surface temperature and the amount of solar irradiation for glass-glass and glass-backsheet modules (see Eq. 4), while King added up temperature difference between back-surface module temperature and ambient temperature [10], [11]. The temperature difference is typically 2 to 3°C for flat-plate modules in open rack-mounted PV systems for glass-glass and glass-backsheet, respectively. This difference is nearly zero for a thermally insulated back surface.

$$T_C = T_M + (G_T/1000)\ (T_M - T_{amb}) \qquad (4)$$

3.2 Explicit methods

From the mathematical point of view, the correlations for the PV operating temperature are sometimes explicit in form, thus giving T_c, directly based on some parameters related to historic measured data.

The Sauer model is the simplest explicit model to explain the operating temperature (see Eq. 5). This model considers only the linear correlation between operating temperature and solar irradiation, without any consideration of the influence of wind. Normally the parameter a could be neglected, while parameter b can be achieved by measurement from individual location. They are dependent on mounting system and regional wind characteristics. Table 1 shows the parameter b based on location of Germany [12].

$$T_M = T_{amb} + a + b.G_T \quad (5)$$

Table 1 Parameter b in Sauer model based on Germany locations

Mounting type	b (°C.m²/W)
Facade-integrated, poor ventilation	0.055
Limited ventilation, large surface	0.035
Roof-integrated, large surface	0.025
Freestanding	0.015

However, there are numerous explicit models, trying to express the cell temperature with different parameters by considering solar irradiation (G_T) and different mounting systems; [13], [14]. Moreover, Sandia-Lab and IEC-61853-2 also use this explicit model to express the cell temperature by considering solar irradiation together with wind speed [15], [IEC-61853-2].

3.3 Implicit models

These implicit models can be calculated by involving variables related to physical characteristics of PV-module itself, environmental conditions, etc. These are the instantaneous value of the PV module's operating conditions. Apart from the electrical power production of PV, the non-converted heat power has to be taken into account via heat dissipation mechanisms: conduction, convection and radiation, which leads to the estimation of different operating temperature (T_C).

The simplest power balance model could be described by equations 6, where τ the transmission coefficient of front glass (%), α the absorption coefficient of PV-Cell (%), η_C the cell efficiency (%), α_{coeff} the temperature coefficient of PV cells (%/K), U_{PV} the total thermal transmission coefficient of BIPV element (W/m²K). The model assumes that both sides of the module have the same ambient temperature and total thermal dissipation coefficient is constant.

$$T_C = \frac{U_{PV}\cdot T_{amb} + G_T[(\alpha\tau) - \eta_{STC} - (\alpha_{PV}\eta_{STC}T_{STC})]}{U_{PV} - (\alpha_{PV}\eta_{STC}G_T)} \quad (6)$$

Mattei et. al have combined the used of temperature dependent PV cell efficiency (see Eq. 6) into this power balance. He found that the value of UPV of 28.8 W/m²K is in a good agreement with measurement [16]. However, Misara has found out that total U_{PV} at front and backside of 31.5 W/m²K, 32.7 W/m²K and 19.14 W/m²K show a good agreement of operating temperature with glass-backsheet, glass-glass and glass-glass-insulation PV modules, respectively [17]. Duffie tried to combine simplest power balance model together with the model under NOCT-condition by replacing the η_{STC} with zero (open circuit) (see Eq. 7) [18].

$$T_C = T_{amb} + \left(\frac{G_T}{G_{NOCT}}\right)\left(\frac{U_{PV,NOCT}}{U_{PV}}\right)\cdot \left(T_{NOCT} - T_{amb,NOCT}\right) + \left[1 - \left(\frac{\eta}{\tau\alpha}\right)\right] \quad (7)$$

Barker et al [19] used the thermal model proposed by Ingersoll [20] to estimate the PV module thermal behaviours for four mounting configurations (see Fig. 5).

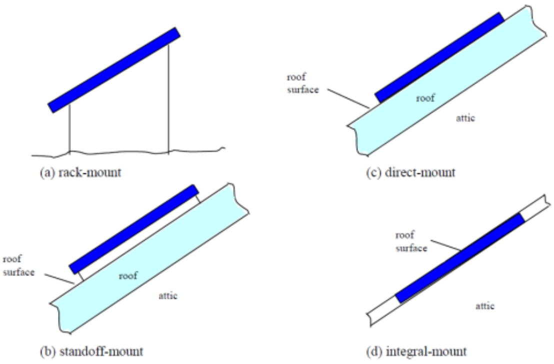

Figure 5: Four typical mounting configurations

There are still many research works try to precisely describe the module temperature with explicit and implicit methods [SKO'09].

3.4 Deficits

In the NOCT model, the operating cell temperature (T_c) is linearly proportional to solar irradiation (see 3.2). However, Stultz detected that the operating cell temperature (T_c) is linearly proportional to the solar irradiation above 400 W/m² [22]. In addition, the heat loss coefficient to the surrounding has not been considered in this model. Moreover, modeling has been done in the free-standing conditions, where both side of the module faces to the same environmental conditions, whereas in BIPV applications, they face to different environmental conditions, such as different wind speed, ambient temperature and module configurations. Though, INOCT and NOST are defined at NOCT conditions under mounting specific array and certain site, these are not appropriate to BIPV applications due to variable environmental conditions (wind, ambient temperature and module configurations).

The explicit methods are quite easy and fast to estimate the operating temperature of PV. However, the accuracy will be varied from different locations, module configurations and mounting systems. Although the error of SNL-Model is only a half compared to NOCT-Model, the different coefficients could be found on different locations for better modeling [23]. These explicit methods are appropriate only for the standard PV-laminated glass, where the difference between cell and surface temperatures is max 2-3 °C. With high module configuration of BIPV from laminated glass to composite element with thermal insulation, the temperature difference become higher than standard PV laminated glass. The surface and composite elements with metal sheet, flexible interlayer, etc., hence, the coefficient have been adapted individually to certain BIPV module configuration and its mounting systems. There are no specific coefficients for BIPV module with different module configurations, mounting systems and locations. Moreover, the heat transfer coefficient (U_{PV}) is not always constant. It is constantly changing due to variable wind speed, surface and ambient temperatures, etc. [25]. Therefore, a different and real-time UPV can be expected for front and backside of BIPV modules.

Under steady-state conditions for all methods above, the thermal capacity of the modules has not been taken into account. For the standard PV-laminated glass, the thermal capacity has been assumed to be low and can be neglected. Regarding higher module configurations and corresponding higher thermal capacity of BIPV module, a time-delay between operating temperature and solar irradiation can be occurred. Jones showed the time-lag of standard glass-glass module for more than 15 minutes between the operating temperature and fluctuated solar irradiance in a cloudy day [26]. Figure 6 exhibits the time-delay of two different module configurations; PV laminated glass (module-1) and PV laminated glass with thermal insulation on the backside (module-2). It can be seen that the time-delay of module-2 is longer than module-1. The temperature, which directly affects the amount of thermal dissipation, is dependent on the module configuration or conduction heat transfer of material used, respectively. The simulated operating temperature can be underestimated as much as 20K by using NOCT model in BIPV applications [24].

These implicit models are applicable on certain locations, where the parameters were calculated from measurement. For different configuration of BIPV modules, such as PV-laminated glass, PV-insulated glass

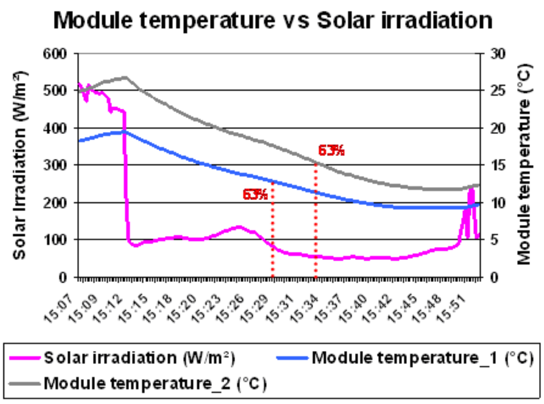

Figure 6: Solar irradiation and operating temperatures of two different module configurations; PV-laminated glass and PV-laminated glass with thermal insulation on the backside.

By using hourly average values, some dynamic effects could not be observed. Therefore, lower time resolution is needed under consideration of thermal capacity of PV-Modules, as described by Wang et al. [27].This effect is mainly needed for sizing of system components in the real-time grid-home-integration applications. However, this model is really complex. But, among all presented models, the dynamic model used by Wang et al [27] seems to be the most adapted for BIPV applications, as it permits to take into account the PV module back sheet temperature variation according to time.

4 ELECTRICAL ANALYSIS

One of the barrier to the widespread application of building integrated photovoltaic (BIPV) is the lack of validated predictive performance tools. Architects and building owners need these tools in order to determine the feasibility of a building integrated photovoltaic system and the potential energy savings obtained.

The power output of a BIPV system depends on several parameters, the cell temperature, the solar irradiance, etc. Each electrical model is based on all or part of these parameters according to its objectives. These parameters and the PV cells electrical circuit composition permit to classify the existing electrical models. Thus, Zhou et al [28] developed a simplified numerical model which only uses the solar irradiance and the PV module temperature to estimate the actual performance of the PV modules under varying operating conditions with acceptable precision. When solar radiation and cell temperatures are relatively high, Borowy et al [29] model, which takes into account the PV modules specifications, the I-V curve characteristic and the PV modules temperature, shall be appropriate. A model based on the atmosphere parameters of clearness index and air mass, and which considers independently each wavelength of the solar radiation spectrum is proposed by Martin and Ruiz [30]. A practical method to predict the energy generated by BIPV systems and to simulate its I-V and P-V curves using a one diode model was developed by Hernandez et al [31] (see Fig. 7).

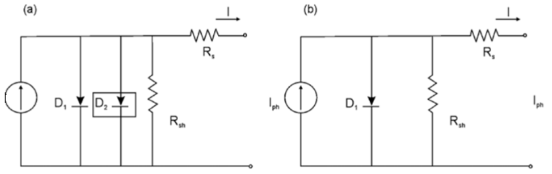

Figure 7: Equivalent circuit of the model of (left) two diodes and (right) one diode. [31]

In Lam et al [32] methodology, environmental parameters such as wind speed, ambient temperature and solar radiation, have been used to calculate the resultant power output from the PV system. (see Fig. 8)

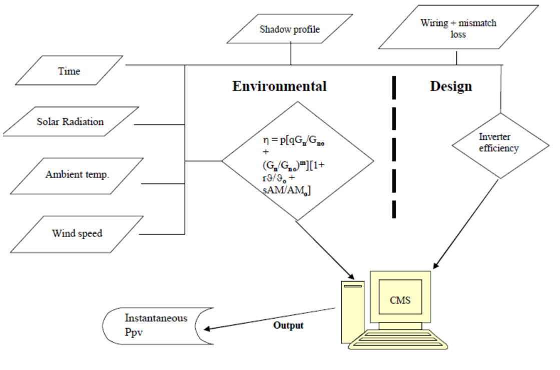

Figure 8: Schematic diagram of the BIPV dynamic model [32]

With respect to variation of Air Mass and corresponding spectrum distribution of solar irradiation, the module efficiency of each PV technology will be different based on its own spectrum response. [33]

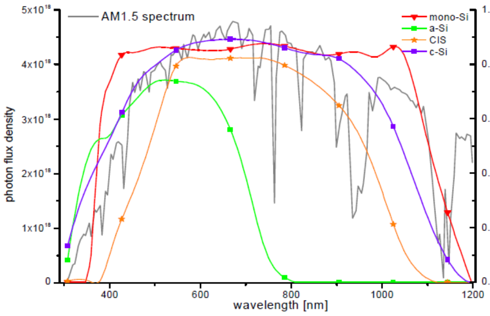

Figure 9: Spectral response for different PV modules [33].

These electrical models could be classified according to their outputs. Thus, most of the models aimed to determine the PV modules IV curve characteristics. Other models permit to calculate the PV modules electrical efficiency.

5 CONCLUSION

In this article, we present a critical analysis of BIPV numerical models existing in the literature by taking into account the optical, the thermal and the electrical aspects.

We identified all the parameters which influence the modeling of the optical and thermal behaviors and hence of the electrical performance of BIPV systems.

The optical behavior includes influences of parameters i.e. irradiance at the tilt angle, reflection losses, albedo, spectral influence as well as measuring effects according to type of irradiation sensors and photovoltaic technologies.

Modeling and calculation of different parameters and various approaches are included, i.e. hourly solar irradiance, ray tracing, shading and reflection effects.

Perez model is well defined for vertical orientations. Albedo measurements are especially important for BIPV since general dependence of the irradiance sums up on the orientation.

The module temperature, which influences the electrical performance of the BIPV system, is not only dependent on α_{coeff} the temperature coefficient of PV cells (%/K), τ_{glass} the transmission coefficient of front glass (%) and η_C the cell efficiency (%), but also on U_{PV} the total thermal transmission coefficient of BIPV element (W/m²K). U_{PV} changes due to variable wind speed, surface and ambient temperatures, etc.

The equations of the electrical balance are based on 4 or 5 parameters according to the PV module technology. Some studies showed that the one diode model is sufficient to study PV systems under solar irradiation higher than 100W/m². The differences between these models are mainly in the variables used in the correlations permitting to obtain the IV curve characteristics.

All these models are function of the PV modules temperature. Then, they seem to be adapted to BIPV application but further analyses are necessary to determine their advantages in this kind of configurations.

This literature overview will permit in the next step of our work, to evaluate the accuracy and the relevance of the partners' models by using numerically and experimentally ICT conditions and finally benchmark.

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