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Dynamic prediction of a building integrated photovoltaic system thermal behaviour

Ya Brigitte Assoa[a,*], Leon Gaillard[b], Christophe Ménézo[b], Nicolas Negri[a], François Sauzedde[a]

[a] Univ Grenoble Alpes, CEA, LITEN, DTS, LCEB, INES, F-38000 Grenoble, France
[b] University Savoie Mont Blanc, LOCIE CNRS UMR5271, F-73376 Le Bourget du Lac, France

HIGHLIGHTS

- A dynamic thermal model of the solar system was developed and validated.
- A detailed analysis of accuracy of the thermal model was performed.
- The correlations in the thermal model are adequate for the configurations studied.
- Ross coefficient was used to evaluate the level of heat dissipation of modules.
- The thermal model is adapted for fully and partially integrated configurations.

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ABSTRACT

A dynamic numerical thermal model has been developed for rooftop building integrated photovoltaic systems, considering a fully or partially integrated configuration, their integration structure and an insulated air gap at the underside. The two-dimensional mathematical model was validated using a test bench representing a residential partially integrated photovoltaic system. The accuracy of the model was studied by deriving the equivalent thermal resistance (or Ross coefficient). Values obtained with the developed model were compared to a nominal operating cell temperature thermal model based on manufacturer datasheet, and the measured data. The results were indicative of a well ventilated air gap and an appropriate choice of Nusselt number. The model was additionally tested for a fully integrated photovoltaic system to demonstrate its utility for different integration architectures. The mean absolute error of the model was evaluated to 2.71 °C for module temperature. It could, therefore, be useful for design studies requiring the prediction of thermal behaviour, as may become important for future regulations and business models such as self-consumption. Future work will consider façade photovoltaic systems, shading elements and coupling to an electrical model. Preliminary results indicate an accuracy of 4.7% in electrical energy production using a simplified electrical model.

1. Introduction

Building integrated Photovoltaic (BIPV) arrays are those where the PV modules constitute a building component that serves a function such as shading, daylighting, thermal insulation, primary weather impact protection, security, or shelter and safety [1], and thus removing the installation would compromise the building envelope [2,3].

The advantage of photovoltaic building integration is to exploit the area available on building envelope for an energy production. In France, a further distinction is made between BIPV systems depending upon the type of sealing function, for the purposes of allocating feed-in tariffs. Systems in which only PV modules ensure the water and air tightness of the roof and are at most 2 cm above the roof plane are said to be fully-integrated whereas those in which the sealing function is provided mainly by other elements than the PV modules are classed as partially integrated. In both configurations, PV modules must be parallel to the roof plane. Elsewhere in Europe, various financial schemes and supporting mechanisms have been defined and implemented such as self-consumption business models, where the main requirement is that the BIPV installation is well designed in order to cover all or most of the customer's electrical energy needs.

Models used in the design phase of BIPV systems are for the most based on linear or NOCT (nominal operating cell temperature) models. These existing models give a reasonable estimation of the PV module

* Corresponding author.
E-mail address: ya-brigitte.assoa@cea.fr (Y.B. Assoa).

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Nomenclature

Symbols

a, b, c, k	parameter
AC	alternative current
Ci	specific heat of air at node i (J/kg·K)
DC	direct current
d_{wind}	wind direction (°)
dx	finite volume length (m)
G, Gi, Gt	solar total incident radiation (W/m^2)
Gr_f	Grashof number in the air gap (–)
h, $h_{i,j}$	heat transfer coefficient between nodes Ti and Tj ($W/m^2 \cdot °C$)
INOCT	Installed Nominal Operating Cell Temperature condition (–)
k	ross coefficient ($°C \cdot m^2/W$)
$K_{i,j}$	thermal conductance between nodes Ti and Tj (W/K)
L	characteristic length of the air gap (m)
Nu	Nusselt number (–)
Pr_f	Prandtl number in the air gap (–)
Qi	absorbed solar radiation at node i (W)
qm	air mass flow rate (kg/s)
Ra_f	Rayleigh number (–)
rc	ratio of cells area to aperture area (–)
$S_{i,j}$	heat transfer surface between nodes Ti and Tj (m)
t	time (s)
T_c	cell temperature (°C)
T_i	temperature at node i (°C)
TNOCT	nominal operating cell temperature (°C)
V_{wind}	wind velocity (m/s)

Greek

α_{cell}	solar absorptance of PV cell (–)
βr	temperature coefficient (K^{-1})
β	slope of the solar collector (°)
Δt	time discretization (s)
ε	emissivity (–)
η	efficiency of the PV module (–)
τ_{glass}	transmissivity of the glass cover (–)

Subscripts

c	sky
calc	calculated
cell	photovoltaic cells
e, amb	ambient air
in	air at the inlet of the gap
Isol	insulation layer
laconv	convective air node in the gap
larad	radiative air node in the gap
m	mean
meas	measured
ox, oy, oz	coordinate axis
pv	photovoltaic

performance, however, greater accuracy is needed in the context of the design of Net Zero Energy Building (NZEB) and 2010 energy policies [4]. Such NZEB projects combine both a high level of energy performance and a balance of its energy needs by on-site or nearby renewable energy sources, and among the various solutions available, solar BIPV systems is the most widely considered. In this context, it is necessary to improve the accuracy of predictive BIPV models which is strongly dependent upon the thermal interaction between PV modules and the building, [5]. The development of numerical models complying with these requirements is therefore essential in the short term, as has been, highlighted recently by Raza et al. [6] through an innovative approach based on Bayesian model averaging to generate forecast output.

Various physical numerical modelling approaches have been undertaken and validated with experimental analyses. Their aim has been to achieve an improved prediction of both the thermal behaviour and the electrical performance of an integrated photovoltaic (PV) system in comparison to simple linear thermal models. These studies focus for the most part upon the impact of key parameters such as the integration configuration (roof, facade, sun shading systems…), weather conditions, orientation of the PV component and partial shading by nearby structures, or the thermal coupling to the building for integrated systems (BIPV) compared to rack-mounted PV modules. The cooling of PV and BIPV components by natural convection at the rear side of the module has been investigated by various researchers with the overall aim to optimize the development of thermal models based on detailed correlations of heat transfer in an air gap or equivalent thermal resistance values (or Ross coefficient). In 2013, D'Orazio et al. realized a comparative analysis of PV modules heating level according to their system configuration, considering two BIPV modules differentiated by their air gap width and a rack-mounted PV module, taking also into account the Ross coefficient value [7]. Maturi et al. presented an overview of the equivalent thermal resistance values of rack mounted PV modules according to their operating conditions and technology [8]. In 2011, Huang et al. compared their developed thermal model of a crystalline silicon BIPV system based on a linear regression method and weather data with PV module temperature models of Ross and Smokler [9] and of Skoplaki and Palyvos [10]. The accuracy of their model is satisfactory, nevertheless, they highlighted the importance to develop high prediction thermal models since the PV module temperature influences the electrical power production prediction [11]. Despite their quality and accuracy, the majority of existing models require detailed modelling of the PV module and its integration architecture using computationally-expensive analytical models and computational fluid dynamic approaches leading to a refined level of discretization and extrapolations. These models are most of the time strongly related to a specific BIPV systems configuration and are not suitable for other configurations. Amongst other factors, the accuracy of these models depends upon their high level of discretization, demanding a detailed knowledge of system geometry which are most of the time unknown or inaccurate. Furthermore, linear models and NOCT models are inadequate for the analysis of building integration effects (reduction of electrical performance due to higher temperature operating conditions, and in the long run, ageing issues), despite providing a relevant estimation of the PV module temperature for energy production [5]. Indeed, these models are based on weather data and on a constant NOCT temperature which is estimated either by the manufacturer in the datasheet or from measured data. In the present work, a dynamic mathematical model of a BIPV system was developed, comprising opaque polycrystalline solar photovoltaic modules with a naturally ventilated insulated air gap at the underside and an integration structure. The model was validated with experimental data obtained from a test bench of a partially integrated rooftop BIPV system monitored during one year in the framework of the ANR HABISOL "Performance BIPV" research program located at the National Solar Energy Institute (INES) in France. Then, in order to optimize the modelling of convective and radiation heat transfer in the air gap, heat dissipation from the BIPV system to its surroundings was estimated through the comparison of the equivalent thermal resistance (or Ross coefficient) of the BIPV system obtained using the developed thermal model, a NOCT thermal model based on manufacturer datasheet and measured data. Finally, in order to assess