Highlights

Performance of building integrated photovoltaic facades: Impact of exterior convective heat transfer

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- Impact of convective heat transfer on building-integrated photovoltaic facades
- A detailed analysis of the impact of building geometry, wind speed and direction
- Numerical analyses using a multi-physics model & computational fluid dynamics
- The local convective heat transfer significantly affects cell temperature and power
- Variations in cell temperature and power can go up to 42 °C and 17%, respectively

Performance of building integrated photovoltaic facades: Impact of exterior convective heat transfer

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Abstract

Building integrated photovoltaic (BIPV) applications are key to increase the share of renewable energy in the built environment. A large potential for BIPV deployment is related to building facades. The assessment of BIPV facades depends on the accurate modelling of exterior convective heat transfer coefficients (eCHTC). However, eCHTC models commonly used in BIPV modelling tend to be simplified. This paper proposes a simulation framework that combines detailed computational fluid dynamics with a multi-physics BIPV model to investigate the influence of eCHTC on the performance of BIPV facades (cell temperature and power). The evaluation is performed for different building geometries, wind speeds, wind directions, solar irradiations, and ambient temperatures. The results show that local variations in eCHTC can cause variations in cell temperature up to 42 °C between the BIPV modules across the facade. These temperature differences are associated with differences in power up to 17% across the BIPV facade. In general, lower temperatures and higher power output occur near the edges of the facade while higher temperatures (lower power output) occur at the middle and at the bottom of the facade. These findings are relevant for applications in which the knowledge of the local behaviour is important, such as degradation studies. Therefore, a detailed assessment of wind effects is recommended in order to verify the local operating conditions of the BIPV modules.

Keywords: Solar energy, Building integrated photovoltaic, Zero-energy buildings, Wind flow, Thermal degradation

1. Introduction

In 2018, the buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide emissions [1]. It is expected that the energy demand from buildings and construction continues to increase [1]. This growth is driven by several factors, such as improved access to energy in developing countries, greater ownership and use of energy-consuming devices, and rapid global growth in buildings floor area [1]. This trend in energy demand can further stress the energy system and increase greenhouse gas emissions, aggravating climate change [2, 3]. Therefore, the transition to a sustainable building sector is crucial to guarantee that urbanisation occurs at minimal environmental impact. The decarbonisation of buildings generally involves two measures [4–6]: (1) the implementation of energy efficiency measures to reduce the energy use of buildings, achieving nearly-zero, or even positive energy buildings, and (2) the deployment of local renewable energy sources to supply the remaining energy demand.

With consistent price reductions, the deployment of photovoltaic (PV) technology in the built environment is a promising path to guarantee renewable electricity supply [7–9]. Building facades hold an important share of the PV potential, with sufficient surface area to compensate for the reduced solar irradiation due to its vertical implementation [10]. In addition, the PV generation profile for facades corresponds better with the energy demand in buildings, helping to mitigate the “duck curve” problem that occurs due to the mismatch between supply and demand [10, 11]. However, the implementation of PV cells/films in facades requires special attention when it comes to aesthetics, as the building facade is essential to its identity [12, 13]. The use of PV as a building material provides new possibilities that enable the harmonious assimilation of PV into the building architecture, a concept referred to as building integrated photovoltaic (BIPV) [14]. As a building component, BIPV modules replace conventional building components, fulfilling one or more envelope functions, such as air and rain tightness, sound insulation, sun shading, and thermal insulation [15, 16].

The assessment of BIPV systems poses several challenges. One in particular concerns the thermal performance of BIPV modules. It is well known that the electrical efficiency of PV technologies usually decreases with increasing operating temperatures. For the crystalline Silicon (c-Si) technology, which

currently accounts for the largest share of the market [17], the power reduction is typically between 0.35-0.5% when the temperature increases by 1 °C above 25 °C at 1000 W/m² [18]. This means that a 20 °C rise in the operating temperature leads to a decrease in power in the range of 7-10%. Knowledge of the operating temperature is, therefore, essential to accurately assess the power output of a BIPV system. Furthermore, high operating temperatures accelerate degradation mechanisms in PV modules [19]. Degradation not only reduces the lifetime of the modules, but also jeopardises their aesthetic value due to corrosion, discoloration, delamination and breakage [20–22]. To reduce the operating temperature, BIPV modules usually include a ventilated cavity.

Different numerical approaches can be used to evaluate the performance of BIPV facades and roofs, as reviewed in Ref. [23, 24]. Numerical models based on energy balances are often used (e.g. [25–29]). In such models, the operating temperature of a BIPV module results from the balance between solar irradiance, power generation, and heat dissipation to the exterior environment, to the BIPV cavity, and ultimately to the building interior. Figure 1a shows a building with a BIPV facade. Figure 1b depicts the main heat transfer mechanisms involved in the energy balance of the BIPV module. Radiative and convective heat transfer takes place at the exterior surface, at the surfaces inside the cavity, and at the surface facing the building interior. Conductive heat transfer occurs through the material layers. In energy balance approaches, convective heat transfer is often represented by empirical correlations, radiative heat transfer is often based on the Stefan Boltzmann law, and conductive heat transfer is usually computed resistance-capacitance models. The generated power is generally taken into account by subtracting the amount of irradiance converted into power from the PV layer (i.e. as a heat sink at the PV layer). Accurately predicting the BIPV operating temperature is, therefore, a complex task as it depends on several parameters that govern the heat dissipation and power conversion mechanisms, which in turn are highly coupled as the power conversion depends on the operating temperature.

Compared to other PV applications, the assessment of BIPV facades is particularly challenging due to the complexity of the built environment. The building surroundings in an urban context is composed of several other buildings and other urban structures such as light poles, which cause shading on the BIPV modules, leading to power reduction. In addition, the wind flow around a building is significantly different from the wind flow occurring in a

power PV plant. In a PV power plant, the wind flow can be considered the same over the majority of PV modules, since the flow becomes fully developed after 6–7 rows of modules [30]. However, this is not the case for BIPV modules because the flow around a building is highly unsteady, as it depends on several parameters, such as building geometry, wind speed and direction, etc. The accurate representation of the wind flow around the building is important as it affects the convective heat transfer at the exterior surface of the BIPV modules and, thus, their capability to dissipate heat. While several studies focused on quantifying the reduction in solar potential due to shading in urban areas (e.g. [31–34]) and on improving cavity ventilation in BIPV modules (e.g. [35–38]), the effect of exterior convective heat transfer on the performance of BIPV facades has not been comprehensively investigated yet.

Figure 1: Schematic of (a) BIPV modules as part of a building envelope, and (b) heat transfer mechanisms in a BIPV module.

The exterior convective heat transfer at building surfaces is normally represented by exterior convective heat transfer coefficients (eCHTCs). Given the complexity involved in obtaining eCHTCs, a large number of empirical and semi-empirical eCHTC models have been derived for building performance assessment. Most of these eCHTC models are also commonly used in BIPV models based on energy balance approaches. Table 1 provides an

overview of the commonly used eCHTC models for BIPV assessment. However, the accuracy and reliability of the existing eCHTC models are of concern and their implementation may lead to incorrect results, for the following reasons:

(1) In most eCHTC models, it is assumed that a single value can represent the eCHTC distribution across the building facade/roof. This is the case for all BIPV models listed in Table 1. However, it has been demonstrated that the eCHTC values highly varies locally over the building facades [39–41]. This may be particularly critical for BIPV facades. For instance, a non-uniform temperature distribution over the facade may lead to non-uniform degradation between the BIPV modules, jeopardising the aesthetic integrity of the building. Moreover, local temperature variations may cause current/voltage deviations between neighbouring BIPV modules, which may have implications concerning the electrical architecture of the BIPV facade.

(2) In most eCHTC models, the individual and combined impacts of wind direction, building surroundings, and building geometry are taken into account either incompletely or not at all. None of the eCHTC models in Table 1 considers these factors. Moreover, models M2, M3 and M4 reported in Table 1 are based on wind-tunnel measurements on flat plates reported by Jürges [42]. However, the wind flow around buildings is more complex than the flow over flat plates.

(3) Many eCHTC models have been derived for specific building characteristics and specific meteorological conditions (wind speed and wind direction). For example, model M1 has been derived for leeward building facades [43]. However, it is applied to assess BIPV roofs in [25]. Similarly, some eCHTC models have been used for both roof and facade BIPV applications, e.g. model M2 in Ref. [27] and [44] (Table 1).

(4) The interaction between natural and forced convective effects on the exterior surface is not always considered in the existing eCHTC models. Compared to conventional building envelope materials, BIPV surfaces generally experience higher temperatures. In situations of low wind speeds (e.g. a sheltered building in an urban environment), it may be important to consider the combined effects of natural and forced convection [45]. The constant (intercept) in the linear models in Table 1 is sometimes described as a term that accounts for natural convection (buoyancy effects) [46]. However, these models do not take the surface temperature into account. Note that model M5 considers the surface temperature implicitly in the Ra_H number, but it does not consider wind effects.

More recently, computational fluid dynamics (CFD) simulations have also been used to derive eCHTC correlations (e.g. [40, 41, 46–50]). Compared to empirical methods, CFD has several advantages. First, CFD provides data on the relevant variables in every point of the computational domain. This means that the impact of local variations of eCHTC on the BIPV performance can be evaluated (in contrast to full-scale measurements that can only focus on a few positions across the building facade). Second, CFD allows a strong degree of control over the boundary conditions, which enables the assessment of the BIPV performance under different operational and meteorological conditions. Third, CFD is particularly suitable for parametric analysis to assess the individual and combined impacts of different parameters such as wind speed, wind direction and building geometries.

Table 1: Examples of eCHTC models commonly used for performance evaluation of BIPV roofs and facades (R = roof, F = facade, V_w = wind speed [m/s]). Note that this is a non-exhaustive list.

Model		Surface	Reference
M1 ¹	$eCHTC = 3.5V_w + 4.2$	R	[25]
M2	$eCHTC = 3V_w + 2.8, V_w < 7 \text{ m/s}$	R	[27] ²
	$eCHTC = 3V_w + 2.8$	F	[29] ³
M3	$eCHTC = 3.9V_w + 5.62$	F	[28] ³
M4	$eCHTC = 4V_w + 5.6, V_w \leq 5 \text{ m/s}$	R	[51] ⁴
	$eCHTC = 7.1V_w^{0.78}, V_w \geq 5 \text{ m/s}$	R	[26] [52] ⁵
M5 ⁶	$eCHTC = \frac{k}{H} \left(0.825 + \frac{0.387Ra_H^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}} \right)$	F	[53]

¹According to [43], Model M1 is originally based on the average of six eCHTC models for leeward facades and uses the free stream velocity at 10 m above the building as V_w .

²No information for $V_w > 7 \text{ m/s}$.

³No detailed information about V_w .

⁴Wind velocity and direction measured close to the test bench at about 4.7 m above the ground.

⁵Uses V_w from IWECC/TMY (hourly) data.

⁶ $Ra_H = \rho\beta\Delta TH^3/(\eta\alpha)$ is the Raleigh number based on the BIPV height (H) and the temperature difference between cavity surface and the air inside the cavity (ΔT). $Pr = \nu/\alpha$ is the Prandtl number. Air properties are: density (ρ), thermal expansion coefficient (β), thermal diffusivity (α), dynamic viscosity (η), and kinematic viscosity (ν).

Another important feature of CFD is that it allows forced and natural

convection to be assessed individually. This is particularly appropriate for energy balance models, where heat transfer components are treated individually. In the same way that radiative losses to the sky and to the ground are often treated separately, forced and natural convection can be treated separately. The advantage of assessing forced convection individually in CFD simulations is that forced convection is independent of the BIPV operating temperature. Forced convective heat transfer coefficients can be defined as a function of the wind speed and direction, building geometry, and building surroundings [40, 41]. In contrast, natural convection depends on the BIPV surface temperature, which in turn depends on cavity ventilation and building indoor conditions, and therefore needs to be solved iteratively.

To the best knowledge of the authors, a detailed analysis on the impact of exterior convective heat transfer on the performance of BIPV facades has not yet been presented, in particular considering local eCHTC variations across the building facade. Therefore, the present paper proposes a simulation framework to investigate the impact of the local eCHTCs on the performance of BIPV facades (power and temperature). The framework consists of:

- (1) a multi-physics BIPV model that simulates the energy balance of a BIPV module, including convective, radiative and conductive heat transfer components, and treats forced and natural convection separately; and,
- (2) high-resolution CFD simulations to obtain the local forced CHTC distribution across the building facade (which is implemented in the multi-physics BIPV model as input data).

This simulation framework is based on extensive validation with experimental data [39, 40, 54, 55]. The performance of the BIPV facades is evaluated based on simulated operating temperature and power output. The analysis is performed for different building geometries (high-rise, medium-rise, and slab/low-rise buildings) and under different meteorological conditions (i.e. wind speed, wind direction, irradiance and ambient temperature). A detailed analysis is also performed to investigate the impact of different commonly used eCHTC models on BIPV performance (the models presented in Table 1).

The paper is structured as follows. Section 2 describes the simulation framework including the multi-physics BIPV model and the CFD simulations. Section 3 presents the results. Section 4 discusses the limitations of this work and opportunities for future work. Finally, Section 5 summarises and concludes the paper.

2. Methodology

Figure 2 illustrates the methodology workflow. The framework consists of two main parts:

(1) A multi-physics BIPV model that provides the power output from each BIPV module as well as the temperature of each PV cell in the module. The BIPV model follows an energy balance approach, taking into account convective, radiative and conductive heat transfer components. The BIPV model treats forced (CHTC_f) and natural (CHTC_n) convective heat transfer coefficients individually. The CHTC_f values are obtained from CFD simulations and are inputs to the BIPV model. CHTC_n values depend on the BIPV surface temperature and are iteratively calculated using empirical correlations from literature. The BIPV model was developed originally for transient simulations within the openIDEAS/Modelica environment [56], but it is used in this paper in combination with steady state CFD simulations. Detailed information about this model is given in Section 2.1.

(2) CFD simulations are performed to obtain the forced convective heat transfer coefficients (CHTC_f) data on the building facade. An intermediate step calculates the surface-averaged CHTC_f values for each BIPV module at the facade (module-averaged CHTC_f). Further information about the CFD simulations is provided in Section 2.2.

The simulation inputs and the performance indicators are described in Sections 2.3 and 2.4, respectively.

Figure 2: Methodology workflow.

2.1. Multi-physics BIPV model

The multi-physics BIPV model combines a high-resolution electrical model with physics-based thermal and airflow models. The electrical model calculates the power output, while the thermal and airflow models determine the BIPV temperature. The multi-physics BIPV model follows a control volume approach, as illustrated in Figure 3a. Figure 3b depicts the main variables and the heat fluxes encapsulated in one BIPV control volume. Part of the solar irradiance reaching the BIPV module (I) is converted into power (P), while the rest is dissipated as heat to the exterior environment, to the BIPV cavity and to the building interior. The airflow through the cavity ($\dot{m}$) connects the control volumes (see Figure 3), enabling the simulation of temperature stratification over the BIPV height due to stack effects. Each control volume corresponds to one PV cell.

As illustrated in Figure 3b, the BIPV modules are composed of two glass layers and a PV layer. The PV layer is modelled explicitly to enable the coupling between electrical and thermal models. The power output (P) is imposed on the PV layer as a heat sink. In turn, the temperature of the PV layer is used in the one-diode model to determine the power output. Temperature and power are coupled and solved simultaneously, until convergence is achieved. All material layers are treated as opaque layers. Note that, although BIPV modules also usually present ethylene vinyl acetate (EVA) layers, EVA layers are not modelled explicitly in this study, because their thermal resistance is negligible compared to that of the glass layers.

To estimate the power output, the multi-physics BIPV model uses a temperature-dependent one-diode modelling approach. In this approach, the temperature dependency is expressed in terms of temperature coefficients, which values depend on PV technology. In this paper, the focus is on c-Si technology. Table 2 presents the parameters used in the one-diode model. An increasing temperature affects both the current and voltage of the BIPV module (α_T and β_T in Table 2). Since the decrease in voltage is relatively higher compared to the increase in current, increasing temperatures result in a power reduction (γ_T). Note that the short-circuit current and open circuit voltage values correspond to the BIPV module, i.e. including the glass layer, rather than a naked cell. Therefore, they account for the effect of the glass layer and the encapsulant on the power output.

The heat fluxes are calculated as follows. At the exterior surface of the BIPV module, the heat transfer composed of radiative heat transfer with the sky dome (see $Q_{r,sky}$ in Equations 1-2), radiative heat transfer with the

Figure 3: Schematic of (a) the control volume approach used in the multi-physics BIPV model, (b) a detailed representation of a control volume used in the multi-physics BIPV model (adapted from [54]).

Table 2: Electrical parameters used in the multi-physics BIPV model [55].

Current temperature coefficient (α_T)	0.05 %/K
Voltage temperature coefficient (β_T)	-0.33 %/K
Power temperature coefficient (γ_T)	-0.42 %/K
Short-circuit current (I_{sc})	8.6 A
Open-circuit voltage (V_{oc})	0.63 V

ground (see $Q_{r,gr}$ in Equations 3-4), and convective heat transfer ($Q_{c,ext}$ is explained in detail later on). In Equations 1-4, $T_{s,ext}$ is the exterior surface temperature of the BIPV module, T_{amb} is the ambient temperature, T_{sky} is the sky temperature, and T_{gr} is the ground temperature. ϵ_{ext} is the long-wave emissivity of the glass, σ is the Stefan-Boltzmann constant ($= 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$).

$10^{-8} \text{ W/m}^2\text{K}^4$), and A is the surface area of a BIPV control volume. F_{sky} and F_{gr} are view factors, and β is the inclination of the BIPV module ($= 90^\circ$, for vertical facades).

$$Q_{\text{r,sky}} = F_{\text{sky}} \varepsilon_{\text{ext}} \sigma (T_{\text{s,ext}}^4 - T_{\text{sky}}^4) A \quad (1)$$

$$F_{\text{sky}} = \frac{1 + \cos\beta}{2}, \quad \beta = 90^\circ \quad (2)$$

$$Q_{\text{r,gr}} = F_{\text{gr}} \varepsilon_{\text{ext}} \sigma (T_{\text{s,ext}}^4 - T_{\text{gr}}^4) A \quad (3)$$

$$F_{\text{gr}} = \frac{1 - \cos\beta}{2}, \quad \beta = 90^\circ \quad (4)$$

Inside the cavity, the heat transfer consists of radiative heat transfer between the cavity walls (see $Q_{\text{r},12}$ in Equation 5), and convective heat transfer between the air and the cavity walls (see $Q_{\text{c,cav1}}$ and $Q_{\text{c,cav2}}$ in Equations 6-8). In Equations 5-8, $T_{\text{cav},1}$ and $T_{\text{cav},2}$ are the surface temperatures of the cavity walls, $T_{\text{cav,air}}$ is the temperature of the air inside the cavity. ε_1 is the glass emissivity ($= \varepsilon_{\text{ext}}$), ε_2 is the building wall emissivity, and Ra_H is the Rayleigh number. To compute the Rayleigh number ($\text{Ra}_H = \rho \beta \Delta T H^3 / (\eta \alpha)$), the length characteristic (H) is the height of the BIPV element, ΔT is the temperature difference between cavity surface and the air inside the cavity. The air properties thermal conductivity (k), density (ρ), thermal expansion coefficient (β), thermal diffusivity (α) are estimated at the film temperature.

$$Q_{\text{r},12} = \frac{\sigma (T_{\text{cav},1}^4 - T_{\text{cav},2}^4) A}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}. \quad (5)$$

$$Q_{\text{c,cav1}} = \text{CHTC}_n (T_{\text{cav},1} - T_{\text{cav,air}}) A \quad (6)$$

$$Q_{\text{c,cav2}} = \text{CHTC}_n (T_{\text{cav},2} - T_{\text{cav,air}}) A \quad (7)$$

$$\text{CHTC}_n = \frac{k}{H} \left(0.825 + 0.325 \text{Ra}_H^{1/6} \right)^2 \quad (8)$$

The heat transfer with the building interior also takes into account both convective and radiative heat transfer ($Q_{c,int}$ and $Q_{r,int}$, respectively). These two heat fluxes are based on the models already available in the IDEAS library, as described in Ref. [56].

Conduction through the material layers is treated as a one-dimensional heat transfer problem, computed as [56]:

$$Q_{i,j} = G_{i,j} (T_{i,j} - T_{i,j+1}) A, \quad (9)$$

with the time-derivative:

$$C_{i,j} \frac{dT_{i,j}}{dt} = (Q_{i,j-1} - Q_{i,j}) A, \quad (10)$$

where each material layer i consists of n_i time-dependent temperature states $T_{ij}(t)$ [K] with heat capacity $C_{i,j}$ and n_i-1 thermal conductors with thermal conductance $G_{i,j}$. $C_{i,j}$ and $G_{i,j}$ are computed assuming homogeneous material thermal properties over each element layer.

This paper focuses on the exterior convective heat transfer, $Q_{c,ext}$, computed as:

$$Q_{c,ext} = eCHTC(T_{s,ext} - T_{amb})A \quad (11)$$

where $T_{s,ext}$ is the surface temperature of the exterior BIPV layer, and A is the surface area of one BIPV control volume (see Figure 3).

The total exterior convective heat transfer coefficient, $eCHTC$, is computed based on the natural and forced convective heat transfer coefficients using Eq. 12, as recommended in Ref. [57, 58]:

$$eCHTC = (CHTC_f^n + CHTC_n^n)^{1/n} \quad (12)$$

In this work, $n = 3$ is used, as recommended in Ref. [57]. This value is also within the range of 1.9-3.8 obtained for building surfaces in a recent numerical study [59]. It is important to note that the interaction of natural and forced convection is a topic that still deserves further investigation [60].

The natural convective heat transfer coefficient, $CHTC_n$, is modelled using the correlation by Churchill and Chiu [61] developed for natural convection over vertical plates (Equation 8). In this case, the Rayleigh number is computed based on the exterior surface temperature and the ambient temperature.

The forced convective heat transfer coefficient (CHTC_f) is obtained from the CFD simulations presented in Section 2.2. The combination of the local temperature-dependent CHTC_n and CHTC_f values results in different eCHTC values for each BIPV module, leading to temperature variations over the BIPV facade. Note that forced convection dominates the exterior convective heat transfer when wind effects are strong. When wind effects are less strong, natural convection is dominant.

2.1.1. Experimental validation

Because the validation study has been published as separate papers [54, 55], only the headlines are briefly repeated here. The multi-physics BIPV model is validated using field data from two different BIPV modules: a well-ventilated experimental module and a curtain wall prototype (Figure 4b). Both modules are part of the southwest facade of the Vliet test building in the city of Leuven, Belgium (Figure 4). The integration of the modules into a real building guarantees realistic operating conditions in terms of indoor and outdoor conditions (Figure 4). Table 3 provides detailed characteristics of the modules.

The measured data consist of: (1) the weather conditions, and (2) power output and back-of-module temperature. The weather conditions consist of ambient temperature, wind speed and direction, and solar irradiance on the building facade. The ambient temperature is recorded by a weather station located on the roof of the building (Figure 4a). The wind characteristics are recorded using an ultrasonic anemometer situated in the open field in front of the building (Figure 4a). The solar irradiance on the facade is measured by a pyranometer located on the building facade next to the modules (Figure 4b). The power output is recorded using electronic loads with variable resistances and a controller from National Instruments (NI) in [54] and using commercial equipment from Femtogrid Energy Solutions in [55]. The back-of-module temperature is measured using thermocouples Type T Class 1. The validation dataset contains 90 days for the well-ventilated experimental module [54] and 127 days for the curtain wall prototype [55]. In both cases, sunny and overcast days are included.

The weather dataset and the characteristics of the modules are input data for the multi-physics BIPV model. The module characteristics consists of material properties, dimensions, ventilation parameters, number of cells, and electrical parameters. To validate the multi-physics data, the predicted power output and back-of-module temperature are compared with the measured

Figure 4: (a) Test building with a southwest BIPV facade, in which the BIPV modules were installed [54, 55], (b) BIPV facade with the two BIPV modules used for the validation of the multi-physics BIPV module: (1) curtain wall prototype and (2) well-ventilated experimental module [54, 55].

Table 3: Characteristics of the BIPV modules used for the experimental validation of the multi-physics BIPV model.

	Well-ventilated experimental module	Curtain wall prototype
Nominal power [Wp]	70.6	244
Configuration/packing	Glass/EVA/c-Si cells/EVA/Glass/Cavity/Insulation	
Number of cells [-]	18	60
Cavity width [m]	0.14	0.07
Ventilation	Two openings at bottom/top (0.58 x 0.05 m ² each)	16 lateral openings (1 cm diameter each)

data. It should be noted that the power output is integrated over time to obtain the daily energy yield, which is the main energy indicator used for the model validation. A good agreement is observed between the model predictions and the experimental data. The daily energy yield is predicted with an average deviation of 5% and the back-of-module temperature within an average absolute deviation of 2 °C. Further detailed information about the BIPV modules, on-site measurements, and experimental uncertainties, is provided in Ref. [54, 55].

2.2. CFD simulations

High-resolution steady Reynolds-averaged Navier-Stokes (RANS) CFD simulations are performed for three buildings with different geometries: a slab/low-rise building (building height (H) = 15 m, building width (W) = 65 m), a building with square windward facade ($H = W = 30$ m), and a high-rise building ($H = 60$ m, $W = 10$ m). The building depth is the same for all buildings ($D = 20$ m). Different approaching wind directions in relation to the windward facade are considered ranging from $\vartheta = 0^\circ$ to 78.75° with 11.25° intervals.

The simulations are based on a detailed validation study against the wind-tunnel measurements presented in Ref. [62, 63], in which the exterior surface temperature was measured to assess the convective heat transfer at the surfaces of a wall-mounted cube in a developing turbulent channel flow. A good agreement between the CFD results and the wind-tunnel results is observed. The average deviations between the surface temperatures obtained by CFD and wind tunnel along vertical and horizontal centrelines on the windward surface of the cube are about 1.7% and 2.4%, respectively. Further information on the wind-tunnel measurements, and computational settings and parameters, but also possible reasons for the deviations between the CFD results and wind-tunnel results are given in Ref. [39, 41].

For the present study, a computational domain is made based on the best practice guidelines for CFD simulations of wind flows in the urban areas [64, 65]. The computational grid consists of prismatic and hexahedral cells and is constructed using the extrusion technique as presented in Ref. [66]. The total number of cells is 1,911,316. In all simulations, the distance from the wall to the center point of the wall-adjacent cell (y_p) is about 400 μm , leading to a maximum dimensionless wall distance (y^*) below 5.

A logarithmic mean wind speed profile U (m/s) representative of a neutral atmospheric boundary layer (ABL) is imposed at the inlet of the domain,

with an aerodynamic roughness length z_0 of 0.03 m and reference wind speeds U_{10} (at 10 m height) of 1 m/s, 5 m/s and 10 m/s (Equation 13). In addition, corresponding profiles of turbulent kinetic energy k (m^2/s^2) and turbulence dissipation rate ε (m^2/s^3) are imposed (Equations 14 and 15):

$$U(z) = \frac{U_{\text{ABL}}^*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \quad (13)$$

$$k(z) = 1.5(I_U(z)U(z))^2 \quad (14)$$

$$\varepsilon(z) = \frac{U_{\text{ABL}}^{*3}}{\kappa(z + z_0)} \quad (15)$$

The resulting building Reynolds number ($\text{Re} = U_{10}H/\nu$) based on the building height H and reference wind speed U_{10} ranges from 1×10^6 to 4×10^7 (with ν the kinematic viscosity of air equal to 1.42×10^{-5}). The imposed longitudinal turbulence intensity (I_u) at the inlet ranges from 20% at ground level to 5% at gradient height (exponential decay). The profile of turbulent kinetic energy is calculated from U and I_u using Equation 14, under the assumption that turbulence levels are similar in three directions ($\sigma_u = \sigma_v = \sigma_w$). Smooth no-slip walls are used for the building and ground surfaces. Zero static gauge pressure is imposed at the outlet plane. Zero normal velocity and zero gradients (symmetry condition) are applied at the top and lateral sides of the domain.

The inlet air temperature is equal to 10 °C and a fixed surface temperature of 30 °C is imposed on the building surfaces. Only forced convection is considered and the buoyancy effect is assumed to be negligible. As a result, the CHTC_f is independent of the given temperature difference between the building surfaces and the air. All CHTC_f values are determined based on the upstream (approach-flow) uniform temperature (reference temperature), at a location where it is not influenced by the building. The ground surface is assumed to be adiabatic. Radiation is not taken into account in the simulations.

The 3D steady RANS equations are solved in combination with the realisable k - ε turbulence model [67] to provide closure to the governing equations. The low-Re number Wolfshtein model [68] is used for near-wall treatment. The SIMPLE algorithm is used for pressure-velocity coupling. Pressure interpolation is second order, and second-order discretisation schemes are used

for both the convection terms and the viscous terms of the governing equations. Convergence is assumed when all the scaled residuals level off and reach the values 10^{-7} for x, y, z momentum and energy, 10^{-5} for continuity and 10^{-6} for k and ϵ .

2.3. Simulation inputs

In this study, the BIPV modules are considered on the windward facade of three isolated (free standing) buildings with different geometries: slab/low rise building ($H = 15$ m, $W = 65$ m), square windward facade building ($H = W = 30$ m), and high-rise building ($H = 60$ m, $W = 10$ m). Each facade is composed of several BIPV modules. Each BIPV module has a surface area of 1×1.5 m² (length $\times$ height) and is composed of 60 c-Si cells (Figure 5a). The output power of the BIPV modules is 244 W_P at standard test conditions (STC), i.e. irradiance of 1000 W/m² and operating cell temperature of 25 °C. Each BIPV module is connected to a maximum power point tracker. This means that the BIPV modules operate independently of one another.

The characteristics of the BIPV module used in the present study correspond to the BIPV curtain wall element used in the validation of the multi-physics BIPV model [55]. The BIPV curtain wall design is based on guidelines for building elements (with respect to materials, size, air/water tightness, thermal insulation, etc.). As depicted in Figure 3, the BIPV curtain wall includes a glass-glass PV module, a ventilated air cavity with a depth of 0.07 m, and a building wall with a thickness of 0.15 m. The building wall corresponds to a single layer of insulation material. Table 4 summarises the material properties of the BIPV module used in the simulations. With a relatively thick layer of insulating material, the BIPV curtain wall can be considered as a well-insulated building component. For this reason, a constant interior temperature of $T_{\text{int}} = 21$ °C is used in the simulations.

The simulations are performed for the approaching wind directions ranging from $\vartheta = 0^\circ$ to 78.75° with 11.25° intervals (ϑ is indicated in Figure 5), three reference wind speeds $U_{10} = 1, 5$ and 10 m/s, four levels of solar irradiance $I = 400, 800, 1000$ and 1200 W/m², and seven ambient temperatures $T_{\text{amb}} = -5, 0, 5, 10, 15, 25$, and 35 °C. In this work, $T_{\text{gr}} = T_{\text{amb}}$ and $T_{\text{sky}} = T_{\text{amb}} - 20$ [K]. Table 5 summarises the parameters and respective values used in this work. In total, 2016 simulations are performed. Note that, although the multi-physics BIPV model was developed for transient simulations, in this paper, it is used in combination with steady-state CFD simulations.

Figure 5: Schematic of (a) BIPV facade and BIPV module and (b) building geometries: slab/low-rise (building height (H) = 15 m, building width (W) = 65 m), square windward facade ($H = W = 30$ m), and high-rise ($H = 60$ m, $W = 10$ m). Building depth is $D = 20$ m for all building geometries.

Table 4: Main material properties used in simulations.

Property	Glass	PV	Insulation
Thickness [m]	0.003	0.0001	0.15
Thermal conductivity [W/mK]	0.96	710	0.036
Heat capacity [J/kgK]	750	710	840
Density [kg/m ³]	2500	2330	110
Solar absorption* [-]	0.95	-	-
Long-wave emissivity [-]	0.90	-	0.80

*Solar absorption is relevant only for the exterior glass layer because material layers are treated as opaque layers in the thermal part of the BIPV model (as explained in Section 2.1).

Table 5: Summary of parameters and respective values used in the simulations (in total, 2016 simulations are performed).

Parameter	Value
Building geometry	H = 15 m, W = 65 m, D = 20 m (Slab/low-rise building)
	H = 30 m, W = 30 m, D = 20 m (Building with square windward facade)
	H = 60 m, W = 10 m, D = 20 m (High-rise building)
Building surface	Windward facade
Surroundings	Isolated building (free standing)
Wind direction, ϑ [°]	0, 11.25, 22.5, 33.75, 45, 56.25, 67.5, 78.75
Wind speed at 10 m, U_{10} [m/s]	1, 5, 10
Irradiance, I [W/m ²]	400, 800, 1000, 1200
Ambient temperature, T_{amb} [°C]	-5, 0, 5, 15, 25, 30, 35
Building interior temperature, T_{int} [°C]	21

2.4. Performance indicators

In this study, both electrical and thermal performance of the BIPV modules are evaluated where the following indicators are considered:

(1) *Normalised power output* (P/P_{STC}): It is defined as the total produced power by a BIPV module in relation to its nominal power (P/P_{STC}). The normalised power output describes how well the BIPV modules perform (electrically) compared to its power output at STC.

(2) *Temperature of PV cells at the top of BIPV modules* (T_{BIPV}): As mentioned previously, each BIPV module is composed of 60 cells. The multi-physics BIPV model provides the temperature of each PV cell. Due to natural convection, the BIPV temperature varies over the height of the module, increasing from the bottom to the top. In this paper, the BIPV temperature corresponds to the temperature of the PV cells at the top of the module, i.e. the highest temperature of the BIPV module. Temperature is considered as a performance indicator not only because temperature is coupled with power output, but also because it influences degradation.

Furthermore, the analysis is performed based on (1) the local and facade-averaged T_{BIPV} and P/P_{STC} , and (2) the difference between the minimum and maximum local values of both parameters, i.e. $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{min-max}}$, given by Eqs. 16 and 17:

$$\Delta T_{\text{BIPV,max-min}} = T_{\text{BIPV,max}} - T_{\text{BIPV,min}} \quad (16)$$

$$\Delta P_{\text{min-max}} = (P_{\text{max}} - P_{\text{min}})/P_{\text{max}} \quad (17)$$

Note that, for convenience, $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{min-max}}$ values will be referred to as *local differences* in the remaining of the paper.

3. Results

A reference case is defined as starting point to present the results. This reference case corresponds to the building with a square windward facade in Figure 11 ($H = 30$ m, $W = 30$ m, $D = 20$ m), wind direction perpendicular to the windward facade ($\vartheta = 0^\circ$), wind speed of $U_{10} = 5$ m/s, irradiance of $I = 800$ W/m², and ambient temperature of $T_{\text{amb}} = 25$ °C. From this reference case, the sensitivity of the results to various parameters is presented in the following order:

(1) Impact of local eCHTC variations across the facade on the BIPV performance (Section 3.1): A detailed analysis is performed for the reference case (i.e. building with square windward facade, $\vartheta = 0^\circ$, $U_{10} = 5$ m/s, $I = 800$ W/m², $T_{\text{amb}} = 25$ °C).

(2) Impact of wind speed and wind direction on the BIPV performance (Sections 3.2 and 3.3): These analyses are performed for the geometry, irradiance and ambient temperature from the reference case (i.e. building with square windward facade, $I = 800$ W/m², $T_{\text{amb}} = 25$ °C).

(3) Impact of building geometry on the BIPV performance (Section 3.4): This analysis is performed for the three geometries presented in Figure 5, i.e. slab/low-rise building, building with the square windward facade, and high-rise building ($\vartheta = 0^\circ$, $U_{10} = 5$ m/s, $I = 800$ W/m², $T_{\text{amb}} = 25$ °C).

(4) Impact of irradiance and ambient temperature on the BIPV performance (Section 3.5): This analysis is performed for the geometry and wind direction from the reference case (i.e. square windward facade, $\vartheta = 0^\circ$).

(5) Impact of different eCHTC models (Section 3.6): This analysis is performed for the three geometries presented in Figure 5 ($\vartheta = 0^\circ$, $I = 800$ W/m², $T_{\text{amb}} = 25$ °C).

3.1. Impact of local eCHTC variations over the facade

Figure 6 presents the distributions of the BIPV temperature (T_{BIPV}) and the normalised power (P/P_{STC}) on the windward facade for the reference case ($\vartheta = 0^\circ$, $U_{10} = 5$ m/s, $I = 800$ W/m², and $T_{\text{amb}} = 25$ °C). The temperature and power distributions are inversely proportional to each other (see Figure 6). This is because the PV efficiency decreases with increasing temperatures. A closer look at Figure 6 reveals that the BIPV modules near

the top and side edges of the windward facade experience relatively lower temperatures, while the highest temperatures are observed for the modules situated at the bottom middle of the facade (Figure 6a). In addition, relatively uniform T_{BIPV} and P/P_{STC} distributions are observed over the central area of the windward facade.

Table 6 presents the facade-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$, and the local differences across the facade $\Delta T_{\text{BIPV},\text{max-min}}$ and $\Delta P_{\text{min-max}}$. The table also shows the surface-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$, and the local differences for three specific rows of modules installed at the bottom ($h/H = 0.05$), middle ($h/H = 0.5$), and top of the facade ($h/H = 1$). The surface-averaged temperature of the row of modules positioned at the top of the facade is about 40 °C, while this goes up to about 49 °C and 62 °C for the rows of modules in the middle and at the bottom of the facade, respectively. Consequently, the top modules produce the highest power. The surface-averaged power production for these modules is about 4% and 11% higher than those in the middle and at the bottom of the facade, respectively. These results are a consequence of differences in $e\text{CHTC}$ across the facade. The surface-averaged $e\text{CHTC}$ at the top row of the facade is 31.5 W/(m²K), compared to 18.0 and 9.3 W/(m²K) at the middle and bottom rows, respectively.

For the entire facade, the $\Delta T_{\text{BIPV},\text{max-min}}$ is about 30 °C resulting in about 14% difference between the minimum and maximum power output (Table 6). For the rows of modules at the top, middle and bottom of the facade, the $\Delta T_{\text{BIPV},\text{max-min}}$ are about 4.5 °C, 9.3 °C and 16.1 °C, respectively. In this case, the $\Delta P_{\text{min-max}}$ are 2.2%, 4.5% and 7.5%, respectively (Table 6). It should be noted that the results at row level might have implications concerning the electrical connection of BIPV facades (discussed later in Section 4).

Table 6: Reference case: Facade-averaged and surface-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$, and local differences $\Delta T_{\text{BIPV},\text{max-min}}$ and $\Delta P_{\text{min-max}}$ ($\vartheta = 0^\circ$, $U_{10} = 5$ m/s, $I = 800$ W/m², $T_{\text{amb}} = 25$ °C).

	Facade-averaged	Surface-averaged for top row ($h/H = 1$)	Surface-averaged for middle row ($h/H = 0.5$)	Surface-averaged for bottom row ($h/H = 0.05$)
T_{BIPV} [°C]	49.6	40.3	49.1	62
P/P_{STC} [W/W _P]	0.74	0.77	0.74	0.69
$e\text{CHTC}$ [W/(m ² K)]	18.3	31.5	18	9.3
$\Delta T_{\text{BIPV},\text{max-min}}$ [°C]	30.1	4.5	9.3	16.1
$\Delta P_{\text{max-min}}$ [%]	13.6	2.2	4.5	7.5

Figure 6: Reference case: Contour plots of (a) BIPV temperature and (b) normalised power ($\vartheta = 0^\circ$, U_{10} , $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25^\circ\text{C}$).

3.2. Impact of wind speed

Figure 7 presents the distributions of the BIPV temperature (T_{BIPV}) and normalised power (P/P_{STC}) at the windward facade of the reference building ($\vartheta = 0^\circ$, $I = 800 \text{ W/m}^2$, and $T_{\text{amb}} = 25^\circ\text{C}$). Three reference wind speeds are presented: $U_{10} = 1$, 5 , and 10 m/s . Figure 7 shows that the wind speed can significantly affect both T_{BIPV} and P/P_{STC} . By increasing the wind speed, the local temperature decreases over the entire facade, while the normalised power increases. Similar to the reference case ($U_{10} = 5 \text{ m/s}$), for $U_{10} = 1 \text{ m/s}$ and $U_{10} = 10 \text{ m/s}$, modules in the lower part of the facade also experience the maximum local temperatures and produce the lowest power outputs, while the minimum local temperatures, and consequently highest power, occur near the top and lateral edges of the facade.

Table 7 presents the facade-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$ for the three reference wind speeds. As wind speed increases, the facade-averaged T_{BIPV} monotonically decreases, while the facade-averaged P/P_{STC} increases. For $U_{10} = 1$, 5 and 10 m/s , the facade-averaged T_{BIPV} is 70.4 , 49.6 , and 40.7°C , respectively. For the facade-averaged P/P_{STC} , this is 0.67 , 0.74 ,

and 0.77, respectively. The relatively important impact of the wind speed on the facade-averaged T_{BIPV} and P/P_{STC} is a consequence of its impact on the facade-averaged eCHTC. When the wind speed increases from $U_{10} = 1$ to 5 m/s, the facade-averaged eCHTC increases by three times. When the wind speed increases from $U_{10} = 1$ to 10 m/s, the facade-averaged eCHTC increases by about five times.

Figure 7: Impact of wind speed: Contour plots of BIPV temperature for the square windward facade building at (a) $U_{10} = 1$ m/s, (b) $U_{10} = 5$ m/s, and (c) $U_{10} = 10$ m/s. (d-f) Same for normalised power. ($\vartheta = 0^\circ$, $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25^\circ\text{C}$).

Table 7 also shows the local differences $\Delta T_{\text{BIPV}, \text{max-min}}$ and $\Delta P_{\text{min-max}}$. Interestingly, the largest local differences across the facade are observed for $U_{10} = 5$ m/s, with $\Delta T_{\text{BIPV}, \text{max-min}} = 30.1^\circ\text{C}$ and $\Delta P_{\text{min-max}} = 13.6\%$. For $U_{10} = 1$ m/s, $\Delta T_{\text{BIPV}, \text{max-min}} = 16.8^\circ\text{C}$ and $\Delta P_{\text{min-max}} = 7.8\%$. For $U_{10} = 10$ m/s, $\Delta T_{\text{BIPV}, \text{max-min}} = 24.8^\circ\text{C}$ and $\Delta P_{\text{min-max}} = 11.4\%$. There are two reasons for the non-monotonic increase in the local differences.

The first reason is the combination of forced and natural convection. Variations across the facade are associated with forced convection caused by the wind flow. In the absence of wind effects, the BIPV modules in the facade would operate under the same thermal conditions (as Eq. 11 would include only natural convection). When wind effects are introduced, this behaviour changes, but the change is not uniform across the facade. This can be observed in Figure 8, where the ratio $\text{CHTC}_n/\text{eCHTC}$ is presented. For $U_{10} = 1$ m/s, the ratio $\text{CHTC}_n/\text{eCHTC}$ is mostly above 0.7, which indicates that natural convection is dominant over most of the facade (except at the corners where the ratio can be as low as 0.36). For both $U_{10} = 5$ and 10 m/s (Figure 8b and c), wind effects dominate over most of the facade (ratio mostly below 0.3 and 0.15, respectively), with small areas in the lower part of the facade where higher values of the ratio $\text{CHTC}_n/\text{eCHTC}$ are observed (about 0.6 and 0.3, respectively). High $\text{CHTC}_n/\text{eCHTC}$ values mean that the resulting eCHTC is higher than it would be if only wind effects were present. This leads to smaller differences in surface-averaged eCHTC between top, middle and bottom row. Indeed, for $U_{10} = 1$ m/s, the surface-averaged eCHTC at the top of the facade is about 1.7 times higher than the bottom row. This is about 1.2 for the middle row compared to the bottom row. For comparison, for $U_{10} = 5$ and 10 m/s, the surface-averaged eCHTC at the top row is 3.4 and 3.5 times higher compared to the bottom row, respectively. Smaller differences in eCHTC between top, middle and bottom lead to more uniform temperature and power distributions over the facade, resulting in smaller local differences.

The second reason is related to the BIPV response to variations in eCHTC, presented in Figure 9. Increasing the wind speed leads to an increase in eCHTC across the entire facade. However, the effect of eCHTC on T_{BIPV} and P/P_{STC} decreases with increasing eCHTC for $U_{10} = 5$ and 10 m/s (non-linear relation as shown in Figure 9b and c). In particular for $U_{10} = 10$ m/s, with increasing eCHTC, smaller reductions in temperature (and increases in power) are observed. This can be explained by the fact that a decrease in BIPV surface temperature leads to a decrease in the temperature differential that drives the exterior convective heat transfer (i.e. temperature difference between BIPV surface and exterior environment). Therefore, additional reductions in BIPV temperature associated with increasing eCHTC are actually limited by the temperature differential. For this reason, the local differences for $U_{10} = 10$ m/s are smaller than for $U_{10} = 5$ m/s.

Table 7: Impact of wind speed: Facade-averaged and surface-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$, and local differences $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{max-min}}$ ($\vartheta = 0^\circ$, $U_{10} = 5 \text{ m/s}$, $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25^\circ\text{C}$).

	U_{10}	Facade-averaged	Surface-averaged for top row ($h/H = 1$)	Surface-averaged for middle row ($h/H = 0.5$)	Surface-averaged for bottom row ($h/H = 0.05$)
T_{BIPV} [$^\circ\text{C}$]	1 m/s	70.4	63.3	70.7	73.9
	5 m/s	49.6	40.3	49.1	62
	10 m/s	40.7	34.1	40.2	51.6
P/P_{STC} [W/W_P]	1 m/s	0.67	0.65	0.66	0.69
	5 m/s	0.74	0.77	0.74	0.69
	10 m/s	0.77	0.79	0.77	0.73
$e\text{CHTC}$ [$\text{W}/(\text{m}^2\text{K})$]	1 m/s	6	8.5	5.8	4.9
	5 m/s	18.3	31.5	18	9.3
	10 m/s	32.6	56.3	32.1	16.1
$\Delta T_{\text{BIPV,max-min}}$ [$^\circ\text{C}$]	1 m/s	16.8	6.8	6.6	2.8
	5 m/s	30.1	4.5	9.3	16.1
	10 m/s	24.8	2.9	6.7	15.2
$\Delta P_{\text{max-min}}$ [%]	1 m/s	7.8	3.2	3.1	1.4
	5 m/s	13.6	2.2	4.5	7.5
	10 m/s	11.4	1.4	3.2	7.2

Figure 8: Impact of wind speed: Ratio $\text{CHTC}_n/e\text{CHTC}$ for (a) $U_{10} = 1 \text{ m/s}$, (b) $U_{10} = 5 \text{ m/s}$, and (c) $U_{10} = 10 \text{ m/s}$ ($\vartheta = 0^\circ$, $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25^\circ\text{C}$).

Figure 9: (a) T_{BIPV} of each module as a function of $eCHTC$ for the three wind speeds. (b) Same for P/P_{STC} .

3.3. Impact of wind direction

Figure 10 shows the distributions of the BIPV temperature (T_{BIPV}) and normalised power (P/P_{STC}) for the reference building for three wind directions $\vartheta = 0^{\circ}$, 45° and 78.75° . As the wind direction increases from 0° to 78.75° , the T_{BIPV} and P/P_{STC} distributions become asymmetric. In this case, the maximum temperature and, hence, the minimum power production is observed for the modules at the bottom of the facade, but also in the middle part near the most upstream corner of the facade. The complex distributions observed for the most oblique wind direction of 78.75° are a result of multiple areas of wind flow separation, recirculation and reattachment on the building facade (Figure 10c and f).

Table 8 presents the facade-averaged T_{BIPV} , P/P_{STC} and $eCHTC$ for the three wind directions. Although the wind direction clearly changes the temperature and power distributions across the facade, the impact of the wind direction on facade-averaged indicators is less pronounced. For $\vartheta = 0^{\circ}$, 45° and 78.75° , the facade-averaged T_{BIPV} is $49.6^{\circ}C$, $49.9^{\circ}C$ and $52.3^{\circ}C$,

respectively. The corresponding facade-averaged P/P_{STC} is 0.737, 0.735 and 0.727, respectively. This is because the facade-averaged eCHTC does not change significantly with the wind direction: 18.3, 17.5 and 15.3 W/(m²K) for $\vartheta = 0^\circ$, 45° and 78.75° .

Table 8 also presents the local differences $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{min-max}}$. The difference between the maximum and minimum temperature across the facade decreases from about 30 °C for $\vartheta = 0^\circ$ to about 24 °C for $\vartheta = 78.75^\circ$. In this case, the $\Delta P_{\text{min-max}}$ is about 14% and 11%, respectively. For the row of modules at the top and middle of the facade, the local differences in temperature and power between modules slightly increase as the wind direction increases from $\vartheta = 0^\circ$ to 78.75° (from 4.5 °C to 5.0 °C and from 2.2% to 2.4% at the top; from 9.3 °C to 11.2 °C and from 4.5% to 5.3% at the middle). For the modules at the bottom of the facade, as the wind direction increases from $\vartheta = 0^\circ$ to 78.75° , the $\Delta T_{\text{BIPV,max-min}}$ decreases from 16.1 °C to 9.1 °C, while the $\Delta P_{\text{min-max}}$ decreases from 7.5% to 4.2%.

Figure 10: Impact of wind direction: Contour plots of BIPV temperature for the reference case at (a) $\vartheta = 0^\circ$, (b) $\vartheta = 45^\circ$, and (c) $\vartheta = 78.75^\circ$. (d-f) Same for normalised power. ($U_{10} = 5$ m/s, $I = 800$ W/m², $T_{\text{amb}} = 25$ °C).

Table 8: Impact of wind direction: Facade-averaged and surface-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$, and local differences $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{max-min}}$ for the reference building with windward square facade ($U_{10} = 5 \text{ m/s}$, $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25 \text{ }^\circ\text{C}$).

	ϑ	Facade-averaged	Surface-averaged for top row ($h/H = 1$)	Surface-averaged for middle row ($h/H = 0.5$)	Surface-averaged for bottom row ($h/H = 0.05$)
T_{BIPV} [$^\circ\text{C}$]	0°	49.6	40.3	49.1	62
	45°	49.9	42	49.6	60.1
	78.75°	52.3	45	52	61.3
P/P_{STC} [W/W_P]	0°	0.74	0.69	0.74	0.77
	45°	0.74	0.76	0.74	0.7
	78.75°	0.73	0.75	0.73	0.7
$e\text{CHTC}$ [$\text{W}/(\text{m}^2\text{K})$]	0°	18.3	31.5	18	9.3
	45°	17.5	27.7	17.4	10
	78.75°	15.3	22.7	15.2	9.5
$\Delta T_{\text{BIPV,max-min}}$ [$^\circ\text{C}$]	0°	30.1	4.5	9.3	16.1
	45°	25	5.6	7.1	9.1
	78.75°	24.4	5	11.2	8.8
$\Delta P_{\text{max-min}}$ [%]	0°	13.6	2.2	4.5	7.5
	45°	11.4	2.7	3.4	4.3
	78.75°	11.2	2.4	5.3	4.2

3.4. Impact of building geometry

Figure 11 shows the T_{BIPV} and P/P_{STC} distributions for the three building geometries presented in Figure 5 ($\vartheta = 0^\circ$, $U_{10} = 5 \text{ m/s}$, $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25 \text{ }^\circ\text{C}$). For the three geometries, the minimum T_{BIPV} and maximum P/P_{STC} values occur at the top and lateral edges of the facade. Relatively uniform T_{BIPV} and P/P_{STC} distributions are observed over the central region of the facade for the three cases. In addition, the maximum T_{BIPV} and minimum P/P_{STC} values are observed for modules near the base of the buildings. For the slab/low-rise building (Figure 11a), the area with higher temperatures is relatively larger compared to the building with square windward facade and the high-rise building (Figure 11b and c).

Table 9 provides the facade-averaged and surface-averaged T_{BIPV} and P/P_{STC} and local differences $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{min-max}}$ for the three building geometries. The slab/low-rise building presents the highest average temperature ($55.4 \text{ }^\circ\text{C}$), followed by the building with square windward facade ($49.5 \text{ }^\circ\text{C}$), and then the high-rise building ($45.5 \text{ }^\circ\text{C}$). For these geometries, the facade-averaged P/P_{STC} are 0.72, 0.74 and 0.75, respectively. The impact of the building geometry on the BIPV performance is related to the different $e\text{CHTC}$ conditions observed for the different geometries. The slab/low-rise building presents the lowest facade-averaged values: $e\text{CHTC} = 13.6 \text{ W/m}^2$, compared to 18.2 W/m^2 and 23.0 W/m^2 for the square windward facade and

high-rise buildings (Table 9).

Figure 11: Impact of building geometry: Contour plots of BIPV temperature for (a) slab/low-rise building, (b) building with square windward facade, and (c) high-rise building. (d-f) Same for normalised power. ($\vartheta = 0^\circ$, $U_{10} = 5$ m/s, $I = 800$ W/m², $T_{amb} = 25$ °C).

The local temperature differences across the facade are more critical for the slab/low-rise building and the building with square windward facade, with $\Delta T_{BIPV, \max - \min} = 32.5$ °C and 30.1 °C, respectively (Table 9). This is only 23.1 °C for the high-rise building. For these geometries, the $\Delta P_{\min - \max}$ is 14.6% , 13.6% and 10.6% , respectively (Table 9). Similar trends are also observed for the local differences at the bottom and top of the facade.

Table 9: Impact of building geometry: Facade-averaged and surface-averaged T_{BIPV} , P/P_{STC} and $e\text{CHTC}$, and local differences $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{max-min}}$ ($\vartheta = 0^\circ$, $U_{10} = 5 \text{ m/s}$, $I = 800 \text{ W/m}^2$, $T_{\text{amb}} = 25^\circ \text{C}$).

	Building geometry	Facade-averaged	Surface-averaged for top row ($h/H = 1$)	Surface-averaged for middle row ($h/H = 0.5$)	Surface-averaged for bottom row ($h/H = 0.05$)
T_{BIPV} [$^\circ\text{C}$]	Slab/low-rise building	55.4	44	54.2	67.4
	Square windward facade	49.6	40.3	49.1	62
	High-rise building	45.5	37.9	45.3	54.3
P/P_{STC} [W/W_P]	Slab/low-rise building	0.72	0.68	0.72	0.76
	Square windward facade	0.74	0.77	0.74	0.69
	High-rise building	0.75	0.78	0.75	0.72
$e\text{CHTC}$ [$\text{W}/(\text{m}^2\text{K})$]	Slab/low-rise building	13.8	24.3	13.8	7.1
	Square windward facade	18.3	31.5	18	9.3
	High-rise building	23	38.5	22.9	13.8
$\Delta T_{\text{BIPV,max-min}}$ [$^\circ\text{C}$]	Slab/low-rise building	32.5	6.8	14.6	18.4
	Square windward facade	30.1	4.5	9.3	16.1
	High-rise building	23.1	3.9	8.7	11.5
$\Delta P_{\text{max-min}}$ [%]	Slab/low-rise building	14.6	3.2	6.9	8.5
	Square windward facade	13.6	2.2	4.5	7.5
	High-rise building	10.6	1.9	4.1	5.5

3.5. Impact of irradiance and ambient temperature

This section discusses how irradiance and ambient temperature affect the BIPV performance. This analysis is presented here because (1) irradiance directly affects both the BIPV temperature and power production, and (2) ambient temperature affects the convective heat transfer, both to the exterior and to the cavity, as it affects the Rayleigh number and the temperature difference ($\Delta T = T_{\text{s,ext}} - T_{\text{amb}}$ in Eq. 11).

The simulations are performed for the three wind speeds $U_{10} = 1, 5$ and 10 m/s . Figure 12 presents the BIPV temperature (T_{BIPV}) and normalised power (P/P_{STC}) for two different irradiance values ($I = 800$ and 1000 W/m^2) and ambient temperature T_{amb} ranging from -5 to 35°C . This paper focuses on these irradiance values because they represent critical operating conditions for BIPV facades, for which high temperatures and high power outputs are expected. Note that, in this figure, the small solid circles (which form lines) represent the local values for each BIPV module over the facade. The larger solid circles represents the facade-averaged values. The following observations can be made:

(1) For a given I and U_{10} , by increasing T_{amb} , T_{BIPV} increases while P/P_{STC} decreases. By increasing T_{amb} from -5°C to 35°C , the facade-averaged T_{BIPV} increases by $33\text{-}40^\circ \text{C}$ (Figure 10a and b) and the facade-averaged P/P_{STC} decreases by $17\text{-}18\%$ (Figure 12c and d).

(2) For a given T_{amb} and U_{10} , by increasing I , both T_{BIPV} and P/P_{STC} increase. For the range of T_{amb} and U_{10} investigated in this paper, by increasing the irradiance from 800 to 1000 W/m^2 , the facade-averaged T_{BIPV} increases by 3-11 $^{\circ}\text{C}$. The corresponding P/P_{STC} increases by 16-22%.

(3) Larger local differences are observed for $U_{10} = 5$ m/s (i.e. the spread in small dots). For example, at $I = 1000$ W/m^2 and $T_{\text{amb}} = 35$ $^{\circ}\text{C}$, for $U_{10} = 5$ m/s, $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{min-max}}$ are about 36 $^{\circ}\text{C}$ and 16%, respectively. For $U_{10} = 1$ and 10 m/s, $\Delta T_{\text{BIPV,max-min}}$ is about 18 $^{\circ}\text{C}$ and 30 $^{\circ}\text{C}$ and $\Delta P_{\text{min-max}}$ is about 10% and 14%. At $I = 1000$ W/m^2 and $T_{\text{amb}} = -5$ $^{\circ}\text{C}$, for $U_{10} = 5$ m/s, $\Delta T_{\text{BIPV,max-min}}$ and $\Delta P_{\text{min-max}}$ are about 42 $^{\circ}\text{C}$ and 17%, respectively. For $U_{10} = 1$ and 10 m/s, $\Delta T_{\text{BIPV,max-min}}$ is about 22 $^{\circ}\text{C}$ and 37 $^{\circ}\text{C}$ and $\Delta P_{\text{min-max}}$ is about 10% and 14%. The reasons for these differences were previously explained in Section 3.2.

Figure 12: Influence of irradiance and ambient temperature on (a,b) BIPV temperature and (c,d) normalised power output for the reference building ($\vartheta = 0^{\circ}$). Small solid circles represent local T_{BIPV} and P/P_{STC} of all BIPV modules on the facade. Large solid circles represent facade-averaged T_{BIPV} and P/P_{STC} .

3.6. Impact of eCHTC model

This section compares the simulation framework described in this paper to eCHTC models commonly used in BIPV models. The five eCHTC models

listed in Table 1 are considered. In addition, constant eCHTC values equal to 21 and 25 W/(m²K) are included in this analysis as reference values (models M6 and M7, respectively). These values are also typically used to assess the performance of facades (e.g. [69]).

The analysis is based on the implementations of all seven eCHTC models in the multi-physics BIPV model presented in Section 2.1. All the other inputs and parameters of the multi-physics BIPV model remain the same. Note that no adaptation/correction is applied to the eCHTC models from Table 1, and they are implemented in the same way as they are used in the BIPV models. Therefore, it is important to highlight that:

- (1) model M1 is based on the average of six eCHTC models for leeward facades [43] and is used in Ref. [25] to model a BIPV roof;
- (2) the wind speed used in models M2 and M3 is not clearly described in Ref. [29] and [28], respectively. Therefore, the U_{10} value is used as wind speed in these models;
- (3) model M4 is used in Ref. [26, 52] for building performance simulations with the wind speed corresponding to U_{10} ;
- (4) model M5 is based on the difference between the BIPV exterior surface temperature and the ambient temperature, and does not consider wind effects (forced convection);
- (5) none of the models M1-M7 considers the building geometry.

Figure 13 compares the BIPV temperature (T_{BIPV}) and normalised power (P/P_{STC}) for the different eCHTC models. Results for the three building geometries shown in Figure 5 are presented only for the simulation framework proposed in this paper (see item 5 above). For the high-rise building (HR), the reference building with square windward facade (SQ), and the slab/low-rise building (SL), the smaller circles represent the temperature/power of each BIPV module over the facade. The large solid circles indicate the facade-averaged values. Note that models M1-M7 do not consider the building geometry nor wind direction, and do not distinguish between the different BIPV positions across the facade. Therefore, they are represented by a horizontal line.

The spread of local T_{BIPV} and P/P_{STC} values can be clearly observed for the eCHTC values obtained from the high-resolution CFD simulations. Obviously, the highly varying T_{BIPV} and P/P_{STC} distributions cannot be predicted using models M1-M7. Among the models that consider wind speed (M1-M4), local deviations in T_{BIPV} and P/P_{STC} up to 25 °C and 13% are observed (solid lines compared to small black circles). For these models, the

average T_{BIPV} and P/P_{STC} show differences up to 10 °C and 6% (solid lines compared to the large black circles).

Another remark is that model M5 provides significantly higher temperature and lower power output compared to all other models, since it does not consider wind effects (M5 is insensitive to the reference wind speed U_{10}). For $U_{10} = 1$ m/s, M5 shows deviations in average T_{BIPV} and P/P_{STC} up to 17 °C and 10%, respectively (line M5 compared to black large circles in Figure 11a and 11d). For $U_{10} = 10$ m/s, the deviations are significantly higher, up to 47 °C and 22%, respectively (line M5 compared to black large circles in Figure 13c and 13f).

Finally, the results also show that constant eCHTC values (M6 and M7) are not suitable to represent different wind speeds. For $U_{10} = 1$ m/s, M6 and M7 underestimate the average T_{BIPV} up to 23 °C and overestimate the average P/P_{STC} up 12% (Figure 13a and 13d). For $U_{10} = 5$ m/s, the differences are smaller: up to 5 °C for the average T_{BIPV} and up to 3% for the average P/P_{STC} . For $U_{10} = 10$ m/s, the differences increase again: M6 and M7 overestimate the average T_{BIPV} up to 14 °C and underestimate the average P/P_{STC} up to 7% (Figure 13c and 13f).

4. Discussion

The results in this paper show that large differences in temperature and power can occur between BIPV modules that compose a BIPV facade. In general, BIPV modules close to the building edges experience lower temperatures and provide higher power outputs, whereas BIPV modules situated at the bottom and close to the middle of the facade experience higher temperatures and provide less power. These differences in temperature and power are caused by local variations of exterior convective heat transfer conditions across the facade, which are in turn caused by the wind flow around the building. Therefore, understanding how the wind flow affects the exterior convective heat transfer is crucial to understand the results presented in this paper.

For near-perpendicular wind directions, three distinct flow patterns can be identified. At the upper part of the building, the so-called stagnation point occurs. The region close to the stagnation point is characterised by low local wind speeds, resulting in relatively lower eCHTC values. Lower eCHTC values explain the higher temperatures and lower power output observed earlier in this region of the facade. From this stagnation point, the flow

Figure 13: (a, b, c) Impact of the eCHTC model on BIPV temperature and (d, e, f) impact of the eCHTC model on normalised power output ($\vartheta = 0^{\circ}$, $I = 800 \text{ W}/\text{m}^2$, $T_{\text{amb}} = 25^{\circ}\text{C}$). Black solid circles represent the simulation framework proposed in this work: large solid circles represent the facade-averaged values and small circles represent each BIPV module in the facade; results are presented for the slab/low-rise (SL), square windward facade (SQ), and high-rise (HR) buildings. Models from Table 1 (M1-M5) and reference eCHTC values of 21 and 25 $\text{W}/(\text{m}^2\text{K})$ (M6 and M7) are represented by horizontal lines.

separates in different directions. Part of the flow goes sideways and upwards, resulting in high local wind speeds near the top and side edges of the building. High local wind speeds are associated with high eCHTC values. This explains the lower temperatures and higher power outputs at this position, as observed earlier. Another part of the flow goes downwards, generating the so-called standing vortex or horseshoe vortex at the base of the building. In this

region, low local wind speeds are observed. Low wind speeds are associated with relatively lower eCHTC values. This leads to higher temperature and lower power outputs at this position, as observed earlier as well. For oblique wind directions, the wind flow becomes more complex, with multiple areas of flow separation, recirculation and reattachment on the building facade. As a result, the distributions of temperature and power across the facade change, with one side of the facade experiencing higher temperatures (lower power) compared to the other side.

The impact of the building geometry on the BIPV performance is also related to the relationship between the building geometry and the wind flow. The variation in eCHTC with the building geometry is explained by the combination of two effects. The first effect concerns the (natural) increase of wind speed with height in the atmospheric boundary layer. An increasing wind speed leads to higher CHTC_f and, thus, higher eCHTC values [39]. This means that higher building experience higher eCHTC. The second effect concerns the upstream wind deceleration due to the flow blockage by the building, an effect known as wind-blocking effect [70]. The wind-blocking effect refers to the fact that the wind-flow pattern is disturbed by the presence of a building, leading to a slower wind speed upstream of the building [70]. The higher and wider the building, the stronger the wind-blocking effect, the larger the upstream wind deceleration [39]. This wind deceleration leads to lower CHTC_f , as explained in Ref. [39]. In the case of the slab/low-rise building, a relatively small height and relatively large width intensify both effects, leading to lower CHTC_f and, thus, lower eCHTC. For further information on how the building geometry affects CHTC_f distributions, the reader is addressed to [39].

The simulation framework proposed in this paper may be even more important to assess the performance of BIPV facades in dense urban areas, since the local wind fields in urban areas are very complex. The configuration of buildings in urban areas may lead to areas with local acceleration of wind flows due to, for example, channelling effects and shielding by upstream buildings [71–73]. Such highly chaotic wind flows are difficult to predict without advanced CFD simulations or detailed wind tunnel experiments, making it non-trivial to estimate the effect of surrounding buildings on the CHTC_f (and on eCHTC).

4.1. Relevance and practical implications

This research was motivated by the limitations of exterior convective heat transfer (eCHTC) models commonly used for the assessment of BIPV facades. A simulation framework is proposed in which detailed high-resolution computational fluid dynamics (CFD) simulations are combined with a detailed multi-physics BIPV model. Addressing four limitations identified in the BIPV literature, the methodology has the following features: (1) it uses local values of eCHTC rather than facade-averaged values, (2) it considers a detailed treatment of the wind direction, (3) it distinguishes between natural and forced convective effects, and (4) it takes the building geometry into account.

The simulation framework proposed in this paper is particularly relevant for applications in which the knowledge of the local performance of BIPV modules on building facades is important. For example, this is the case for:

(1) The identification of modules operating under critical temperature conditions. At the module level, high operating temperatures accelerate material degradation, causing additional performance losses.

(2) Understanding of the effect of temperature variations on the degradation of the facade. The present study results show that BIPV modules located at the bottom and at the central region of the facade will likely operate under higher temperature conditions compared to modules at the top and edges of the facade. These temperature variations may lead to non-uniform degradation over the facade, jeopardising the aesthetics of the building.

(3) The design of the BIPV electrical architecture. In a large BIPV facade, it is unlikely that all BIPV modules would be connected to the same power converter. A more likely situation is that BIPV modules installed at the same building floor (at the same height/row) are connected to the same power converter. This study shows that a temperature difference of 20-30 °C between modules located on the same floor can occur, which leads to a power difference of 8-13%. From this perspective, the bottom of the facade could be considered as a critical position due to the significant differences between the temperature and power output of modules in a row, while the top of the facade presents more uniform conditions. Low-rise/slab buildings are also more critical in this respect. The implications of temperature and power mismatches on the electrical architecture of the BIPV facade should be considered in a broader context, since shading can lead to situations that are even more critical in terms of local variations. This is, however, out of the scope of this paper as the main objective was to quantify the power and

temperature differences between modules within the facade caused by local variations of eCHTC.

Identifying critical locations across the BIPV facade allows the BIPV designer to mitigate potentially adverse effects. For example, dummy modules could be used in these critical locations across the facade to avoid high temperatures and degradation issues. Alternatively, BIPV modules located in areas where high temperatures are expected could benefit from extra ventilation. In this case, the designer could enlarge the cavity openings to enable higher airflow rates in the cavity. Furthermore, module-level converters could be used to avoid that mismatches between modules affect the overall performance of the BIPV facade, in line with current trends for BIPV electrical design [74, 75].

4.2. Limitations and future work

This paper presents a first step towards the evaluation of the influence of spatial variations of eCHTC on the performance of a BIPV facade. The scope of the current study is limited to windward facades of an isolated (free standing) building. For future research, the following studies are suggested:

- (1) Investigating the side and leeward facades of the building in addition to the windward facade;
- (2) Investigating the influence of the urban surroundings on the BIPV performance. For example, for a dense urban configuration;
- (3) Investigating the influence of shading and wind effects simultaneously. This analysis is interesting because shading affects the irradiance reaching the BIPV modules, while the wind affects the heat transfer conditions of the BIPV modules;
- (4) Evaluating the eCHTC at the cell level (rather than module level). Given the large difference in size between a PV cell and a building, the current paper focused first on module-averaged eCHTC, but the simulation framework is also suitable for cell-level analysis;
- (5) Evaluating the cumulative effects of temperature (and irradiance) over a year, combining the framework proposed in this work with degradation models available in the literature (e.g. [76]). This suggestion comes with the remark that quantifying the degradation in PV modules is not straightforward, since additional factors are associated to degradation mechanisms, such as humidity and UV irradiance [20–22];

- (6) Quantifying the effect of local eCHTC variations on the electrical architecture of the BIPV facade;
- (7) Analysing the influence of eCHTC under different conditions of irradiance. This paper focuses on irradiance values of 800 and 1000 W/m², because they represent critical operating conditions for BIPV facades, for which high temperatures and high power outputs are expected.

5. Conclusion

This paper investigates the impact of exterior convective heat transfer on the performance of building integrated photovoltaic facades. A simulation framework is developed in which high-resolution computational fluid dynamics simulations are combined with a detailed multi-physics model. The computational fluid dynamics simulations are validated in previous publications using wind tunnel experiments from the literature, showing deviations within 2.4% between the measurement results and the numerical results. Similarly, the multi-physics model is also validated in previous publications using field data from two different building integrated photovoltaic modules. A good agreement is observed between the model predictions and the experimental data. The daily energy yield is predicted with an average deviation of 5% and the back-of-module temperature within an average absolute deviation of 2 °C. This framework allows a detailed spatial description of the exterior heat transfer across the buildings integrated photovoltaic facade.

This work evaluates three representative facade geometries, i.e. a high-rise building, a slab/low-rise building and a square building, for different combinations of wind speed, wind direction, irradiance and ambient temperature. The focus of the study is on windward facades. The performance of the buildings integrated photovoltaic facade is analysed in terms of (cell) temperature and power output.

Results show that differences in cell temperature up to 40 °C can occur between the modules that compose a building facade. The differences in temperature lead to differences in power output up to 17%. These differences are caused by local variations of exterior convective heat transfer coefficient across the facade. The simulation framework proposed in the paper is also compared to existing models commonly used for the assessment of building integrated photovoltaic facades. Because the existing models do not distinguish the position of the module within the facade, their use means that spatial variations across the facade are not taken into account. Moreover,

they do not consider the wind direction and do not account for the facade geometry. Not considering these parameters and local variations of exterior convective heat transfer coefficient leads to differences in temperature up to 25 °C and power deviations up to 13%.

Therefore, a detailed description of the exterior convective heat transfer such as proposed in this paper is important for the performance assessment of building integrated photovoltaic facades. The ability to predict local variations of temperature and power across the facade is of interest not only for the identification and mitigation of critical operating conditions across the building facade, but also for the investigation of local phenomena, such as thermal degradation. A detailed assessment of wind effects could be particularly valuable at the final stages of the building integrated photovoltaic facade design in order to verify the final operating conditions of the modules.

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