Energy & Buildings 369 (2026) 117981

Contents lists available at ScienceDirect

Energy & Buildings

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

Building integrated performance simulation of an innovative dynamic BIPV shading device

Alessandro Dama [a,*], Cahyo Adisaputro [a], Emanuele Piccoli [b]

[a] Department of Energy, Politecnico di Milano, Milan, Italy
[b] EMPA, Dübendorf, Switzerland

ARTICLE INFO

Keywords:
Adaptive façades
Building co-simulation
Daylighting
Solar control
Photovoltaics
Renewables integration

ABSTRACT

This study presents a method for the assessment of the building integrated performances of a novel BIPV shading system, which consists of dynamic and extensible blinds integrating PV. A typical office module, located in Milan (Italy), with a South oriented façade, was chosen as case study. Different Window to Wall Ratios (WWR) and different type of controls – fix shading or lamellas tilted and extended on the basis of indoor temperature and/or solar irradiance - of the BIPV system were considered. The shading control strategy was implemented in Building Controls Virtual Test Bed software (BCVTB). In fact, BCVTB enables to dynamically combine EnergyPlus for the thermal calculation and Radiance for daylighting evaluation. The overall energy performance was assessed taking into account heating, cooling and lighting needs as well as PV generation. The results show that the innovative dynamic system, even without PV, reduces the overall energy needs, and with PV generation allows to achieve the *nearly zero energy* target.

1. Introduction

Towards the target of Nearly Zero Energy Buildings (NZEB), the exploitation of Renewable Energy Systems (RES) becomes a key issue and opportunity, both for the design of new buildings and for renovations. According to EU Guidelines (No 244/2012) supplementing Directive 2010/31/EU a Nearly Zero Energy Building is a "very high energy performant building with a very low amount of energy required covered to a very significant extent by energy from on-site or nearby renewable sources" [1].

In this regard, the integration of photovoltaic components in the building envelope (BIPV) can play a significant role, provided that it does not compromise its effectiveness and efficiency.

Although roofs are generally the most favourable place for PV integration, many tall office and residential buildings lack sufficient surface area on the roof to install the PV power required to achieve the nearly zero energy target. They may, however, have a wide façade well exposed to the sun. Therefore, the potential extension of BIPV applications on façade systems assumes decisive importance, expanding the capacity to achieve net zero energy targets at wider scale. Among different options of BIPV window and façade applications, this study focuses on the PV integration of an innovative external shading device, specifically developed for large transparent facades. Indeed, in such cases, PV integration on shading devices offers an intrinsic synergy between the need for solar control and the photovoltaic exploitation of the sun rays intercepted. Towards this end, the dynamic features of the external shading device have been developed to increase capability to balance effective solar control with daylighting needs.

Nowadays the BIPV products mounted on façade cover only 20% of the BIPV market [2]. This limitation reflects many reasons, among them the complex architectonic multifunctionality of the façades and the risk of external or mutual partial shading of the PV components. This turns out in the need of new affordable technical solutions and suitable PV materials for the integration on shading devices and new developments in simulation tools to assess their overall performances in the design phase.

Reviewing the state of art of BIPV systems, we will first refer to papers presenting the available technologies and the main applications on façade, and then mention the ones related to PV on shading devices. For the latter the attention will be further posed on the issues of simulating moveable devices and the effects on both building energy efficiency (i.e. daylighting availabilities, heating and cooling needs) and PV generation under partial shading conditions.

Starting from the state of art of BIPV technologies a first survey of commercially available products can be found in [3], where Jelle and

* Corresponding author.
E-mail address: alessandro.dama@polimi.it (A. Dama).

https://doi.org/10.1016/j.enbuild.2026.117981
Received 8 April 2026; Received in revised form 8 July 2026; Accepted 20 July 2026
Available online 21 July 2026

Nomenclature

BCVTB	Building Controls Virtual Test Bed
BSDF	Bi-Directional Scattering Distribution Function
CFS	Complex Fenestration State
EMS	Energy Management System
E_{net}	Net Annual Electric Energy indicator
E_C	Sensible and latent cooling demand
Q_{cs}	Sensible cooling demand (power)
E_H	Sensible and latent heating demand
E_L	Electrical lighting demand
E_{PV}	PV generation (annual energy per floor unit area)
Tvis	Visual transmittance
SHGC	Solar Heat Gain Coefficient (i.e. solar factor)
U	Thermal transmittance
G_V	Vertical solar irradiance
T_{op}	Indoor operative temperature
T_{amb}	Outdoor air temperature

Breivik presented the achievements in products for rooftops, façades and windows. Another relevant review was given by Ceron et al., whose study analysed current BIPV-Modules and PV- Constructions Elements provided with architectural features specifically manufactured for photovoltaic integration [4]. A more recent review was given by Biyik, whose study surveyed the state of art of technologies both for BIPV and for BIPVT applications. It highlights the improvements on system efficiency by ventilation - obtaining higher yields with lowering the panel temperature - and on new thin film technologies that are suited for building integration [5].

A large industrial and market interest deals with of PV integration in semi-transparent façade elements, as window and glazing systems. In this field Wang evaluated the overall energy performance of an a-Si semi-transparent PV insulating glass unit [6] and Romani presented a more recent review on models for transparent and semi-transparent PV [7].

A more specific sector of application deals with ventilated double skin façades (DSF). Agathokleous and Kalogirou reviewed theoretical and experimental studies on the optimum air gap between the PVs and the building façade, considering both mechanically and naturally ventilated DSF, remarking that only few studies are available for the latter case [8].

Goncalves et al. developed a multi-physics BIPV model for the simulation of BIPV facades within the open IDEAS framework for building and district energy simulations. It couples an high resolution electrical model to a physics based thermal and airflow model. Its experimental validation was carried out for a static vertical PV system mounted on façade with back natural ventilation [9].

Moving to PV applications on shading devices two modelling issues may arise: modelling their dynamic features, if present, and the occurrence of partial shading effects on the PV cells.

Concerning the issue of simulating dynamic facades components Clarke and Hensen first overviewed the achievements with the means to appraise, accurately and rapidly, the multi-variate performance of built environments of arbitrary complexity [10]. Most recently, in its PhD dissertation De Vries has provided a very comprehensive simulation workflow regarding dynamic simulation of automated shading devices without PV integration [11].

Concerning the issue of modelling BIPV under partial shading conditions Drift developed a method for evaluating energy losses of a grid-connected building integrated photovoltaic system [12]. In this regard Nieto and Lopez presented a methodology to calculate the maximum losses permitted in BIPV, whose procedure can be applied in differ countries [13]. Shao investigated partial shading effect due to surrounding buildings for different PV configurations on roof and facades [14]. McCarty et al. extended a framework from literature for modelling parametric BIPV arrays on the opaque surface of the façades using a power model that characterizes IV-curves at the PV cell [15].

Looking hence at BIPV applications on shading devices (PVSD), most of the studies have investigated the performances of static elements. Yoo and Manz studied a fix PV shading device applied as second skin of a building façade and used SOLCEL and computational fluid dynamics methods to model its performances [16]. Sun analysed the performances of PV systems on cladding for optimizing the geometrical parameters of the overhang and of the window under variable conditions, by means of a simplified building simulation model [17]. Skandalos compared energy and daylighting performances of different BIPV applications: on windows glasses, such as semi-transparent photovoltaic (STPV), and on static shading devices (PVSD), such as horizontal louvres [18]. Marzouk modelled the performances of PVSD at four different tilt angles ($-15°$, $-20°$, $-25°$ and $-30°$) for each orientation, with the aim to achieve the optimal balance between daylight availability, energy consumption and PV generation [19]. Akbari investigated movable - month by month - PV overhangs installed over the windows, to optimize their size and tilt angles [20]. Shi carried out a comprehensive energy simulation of photovoltaic-integrated shading devices, including heating, cooling and lighting needs in single-story and multi-story office buildings [21]. The PV slat inclination was limited to horizontal or vertical and partial shading effects were not considered.

Ye et al. proposed a multi-objective optimization framework for maximizing the potential of inclined PV slat potential, minimizing PV area, and enabling proper sunshade duration in complex urban surfaces [22]. A GIS-based spatiotemporal analysis and optimization approach was applied to three PVSD planning scenarios: (i) parallel to the horizontal land surface, (ii) inclined at an angle equal to the local latitude, and (iii) rotated in real-time to keep the PV surface perpendicular to the solar radiation.

Nielsen quantified the potential of a dynamic solar shading façade components by using integrated simulations and taking into account: energy demand, indoor air quality, available daylight, and visual comfort. According to their study, the use of dynamic solar devices dramatically improves the amount of available daylight compared to fixed solar shading [23]. This emphasises the need for integrated dynamic simulation tools to assess the performances of innovative BIPV solutions in the design phase of the facade.

Jayathissa confronts the issue of simulating the overall performances of dynamic BIPV systems [24]. In their simulation framework a high resolution radiance model calculates the irradiance on the glazing elements of the façade and on the photovoltaic elements, and the photovoltaic electricity yield is calculated taking into account partial shading between modules. The remaining solar irradiation that penetrates the window is used in a resistance-capacitance building thermal model and the interior illuminance with the simplification of the total flux method.

Despite the existing literature on PV shading devices (PVSD), most of researches are limited to fixed static systems or with intermittent adjustment (e.g. seasonal). Researches and methods on dynamic PV shading solutions are still quite limited. For instance, the methodology implemented by Jayathissa for a dynamic BIPV shading devices provides a complete simulation approach for the performance assessment, nevertheless the building description is limited by a lumped parameters approach and the indoor illuminance evaluation is simplified with the total flux method [24]. Indeed, the additional complexities posed by simulating adaptive transparent facades requires methods for the integration of multiple tools of dynamic simulation in order to properly evaluate the impacts on daylight availability and building thermal balance, as well as PV generation.

Therefore, the aim and novelty of this study are twofold: (1) to investigate the potential of an innovative dynamic BIPV shading device in contributing to meet the nearly zero energy target, at least for the case study of an office module in Milan; (2) to develop a comprehensive methodology to properly simulate all the effects of its dynamic features, potentially applicable to different climates and building typologies. Whitin this, the goal is to assess the adaptive control strategy for the dynamic mechanism, that combines solar control, daylighting and PV generation.

The novel mechanism of the BIPV shading device is based on an extensible and rotating overhang, where each wing is composed of two sliding lamellas. Thin PV cells/modules are integrated on the top of the upper lamella. Thanks to the extensible wings the vertical distance between them can be much wider (almost twice) than in a traditional louvre system of façade, therefore, when the lamellas are retracted, the system allows a larger exploitation of daylight, while, when they are extended, it provides effective solar control as needed.

For the assessment of the overall building energy performances of the BIPV system, a typical office module- located in Milan (Italy) with a south-facing transparent façade - was chosen as the case study. Different window-to-wall ratios (WWR) were considered for the transparent façade, and the different degrees of adaptability of the BIPV shading were investigated.

The complex fenestration system (CFS) combines PV shading and glazing systems. The bidirectional scattering distribution function (BSDF) of the CFS was derived in *pre-process* using an in-house optical model specially developed for this kind of system [25]. The tool was validated against Window 6.3 Software [26] documented in [27].

Heat gains and thermal balance in the office module were simulated by using EnergyPlus software [28]. In order to properly evaluate the interior daylighting illuminance, we decided to use the well-established Radiance software [29], instead of the simplified daylight calculation tool embedded in EnergyPlus, whose accuracy was investigated by [30]. Indeed, Radiance software is based on raytracing and its "three phase method" was validated in [31].

Therefore, the methodology adopted in this study was based on the co-simulation features offered by the free available Building Controls Virtual Test Bed (BCVTB) software [32], which dynamically combines EnergyPlus for the thermal calculation and Radiance for the illuminance evaluation. In particular, the control strategy for the BIPV shading system, which governs the lamella extension and inclination, was implemented in BCVTB.

The electric production was calculated in *post-process* employing a simplified model validated in [33], which takes into account mutual partial shading effects on the PV modules embedded on the lamellas.

Finally, a *Net Electric Energy indicator* was adopted in order to assess the overall energy performance of the BIPV façade, which might behave as a smart energy system. Similar to the *energy balance index* introduced by [34], it considers heating, cooling and lighting needs as well as the PV generation.

2. Case study

The BIPV shading device under study is an innovative dynamic louvre system with integrated thin PV modules. A simulation case study was designed to virtually assess its potential performances. For this purpose a typical office module with a single south oriented transparent façade was chosen. Its façade was equipped with the new dynamic BIPV shading device and a thermally insulated double glazed unit, with low emissive coating. For comparison, a window employing solar control glazing (with spectrally selective coating), without shading devices, was chosen as reference façade system.

2.1. Innovative BIPV shading device

The peculiarity of this novel louvre system is that the distance between the wings is much wider than usual, since their extension (and inclination) can be varied by means of an innovative mechanism. In fact, the extension of the wings is given by a pair of lamellas sliding on an horizontal pin, while the inclination is set by the rotation of the pin. Thanks to the extension of the lamellas the beam radiation is blocked at will, while the permeability to the sunlight remains higher than a traditional overhang system when the lamellas are retracted. Such mechanism was developed and patented by architect Pietro Franchi and engineer Stefano Rui [ITMI20092250 (A1) — 2011-06-22].

On top of each upper lamella a thin flexible PV module is integrated as showed in Fig. 1. The risk of mutual partial shading is reduced by the ability within the system to increase the distance between the PV wings.

The technology considered for the PV integration in this preliminary study was thin silicon based flexible modules, but other PV technologies available in thin foils can also be suitable on such a shading device.

2.2. Adaptive control strategy

The dynamic features of the novel BIPV shading device permit the adaptation of the wings' tilt and extension to meet changing needs of daylighting and solar control, maximizing PV generation. The lamellas can be oriented towards the sun to optimize PV production (Solar Tracking mode), avoiding, as much as possible, mutual shading effects on the PV cells. Additionally, they can be extended to block direct solar radiation and provide effective solar protection (Solar Control mode).

The implemented adaptive control strategy is based on the following priority-rules:

- Daylighting is the priority. If the system is unable to provide sufficient daylighting, the lamellas stay in horizontal position and are retracted (Daylighting mode).
- Solar tracking tilting is activated as long as the daylighting exploitation is not jeopardized.
- Solar control extension is activated when there is a risk of overheating and as long as the daylighting exploitation is not jeopardized.

The illuminance threshold for sufficient daylighting was set to 800 lx. This value is a bit higher than the standard request of 500 lx for artificial lighting on working desk (EN 12464–1). It is motivated by the evidence of a review study that reports occupant strong preferences for daylight in workplaces and high preferred illuminance levels, about 570–700 lx in the automatic mode, and around 680 lx in the semi-automatic mode, with value over 800 lx in the manual mode of operation [35]. The choice of 800 lx is, therefore, meant to be conservative – on the safe side – with the intention of taking into account user preferences with different potential mode of controls as well as not uniform daylight distribution.

At any timestep the indoor illuminance is evaluated for different tilt angles and extensions of the lamellas; only configurations which guarantee sufficient illuminance are considered. The ultimate choice of the lamella tilt maximizes the irradiance on the PV surface; if daylighting is sufficient, the lamella are extended for solar control when the indoor temperature exceeds a certain value (i.e. 25 or 26 °C).

2.3. Office module and reference façade system

In order to simulate the energy performances of the new BIPV façade system, a typical office building module, with a transparent façade oriented to the South, was chosen. The simulation case study was located in Milan (Latitude 45-degree North, ITA_Milano-Linate.160800_IGDG.epw). Different window to wall ratio were considered: WWR equal 50%, 67% and 100%. Electrical lighting control was activated in two steps mode, based on the daylight illuminance on the working plane with a minimum threshold of 800 lx. The positionings of the window and control points are shown in blue dots in Fig. 2. The main parameters used for the building simulation of the office module are reported in Table 1. The assumed air infiltration rate can be representative of an intermediate condition between conventional building stock and the standard for new buildings.

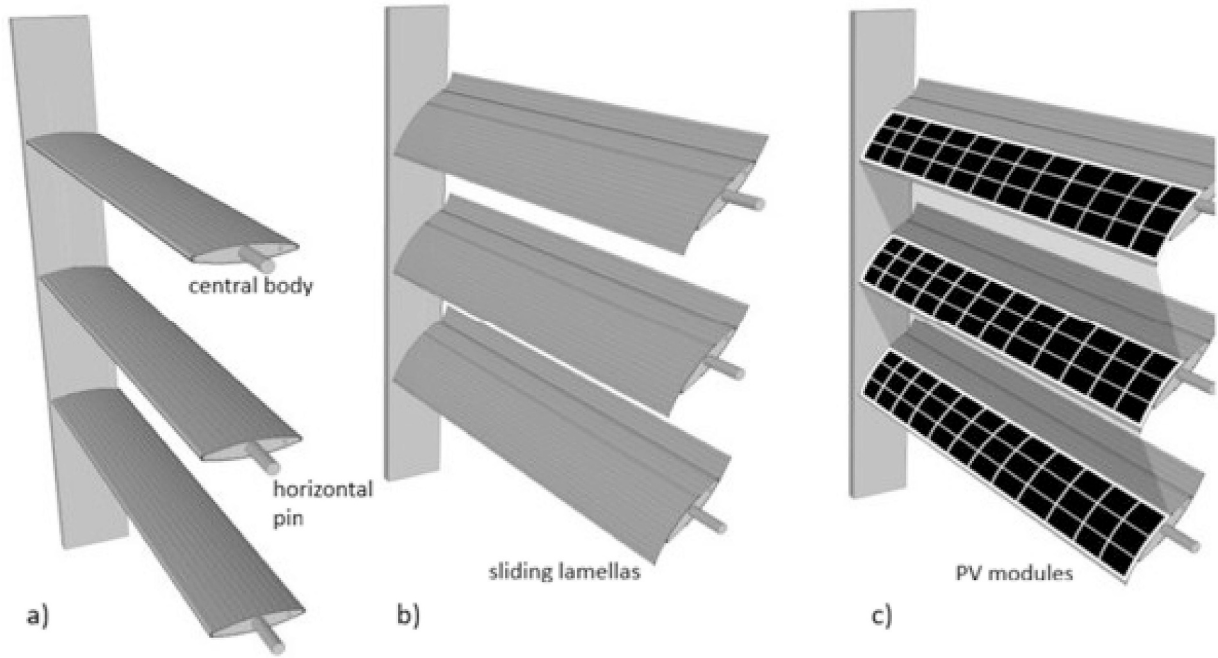

Fig. 1. Drawings of the innovative BIPV shading device: a) lamellas compacted on the central body; b) central body tilted and lamella extended, front and back; c) the new shading system with the integration of PV modules on the frontal lamellas.

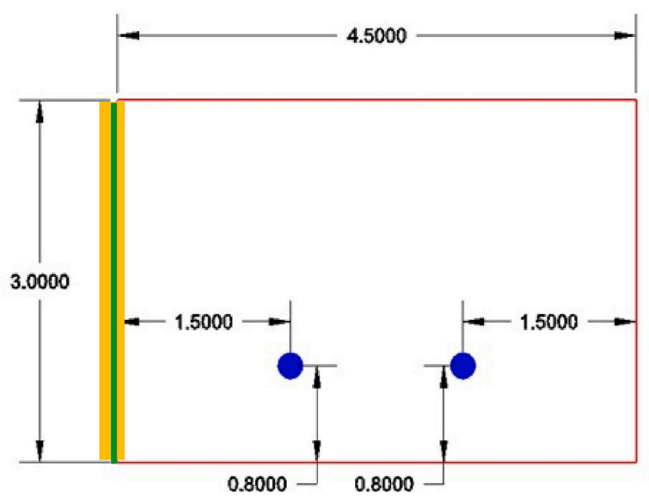

Fig. 2. Plan view of the office module with the position of the reference points for lighting control (at the level of working desks). The window width covers the external wall (on the left of the drawing). The other borders are interior opaque walls.

Table 1
Main parameters of the building module simulation.

Floor area	Window area	Heat/Cool setpoints	HVAC System	Daylighting threshold
13.5 m^2	4.5 m^2, 6 m^2, 9 m^2	20/26 °C	Ideal unit with economizer	800 lx
Lighting Power	**Equipment Power**	**Lighting activation**	**N. of people & PC**	**Max air infiltration**
11 W/ m^2	11 W/ m^2	Two steps	2	0.15 Vol./h

In the adaptive façade the BIPV shading device was combined with a LowE double glazing, while for the reference window system a Solar Control double glazing, with spectrally selective coating, was chosen as schematically showed in Fig. 3. This choice provide to both systems the same thermal insulation performance (U value), suitable for the type of building and climate, and a solar control performance, compliant with the regional standard (solar factor below 0.35). The main glazing performance indicators are reported in Table 2.

3. Methods

To simulate the dynamic and integrated performances of the BIPV façade multiple simulation tools are required. In this study EnergyPlus was used to simulate the building thermal environment and Radiance was used to perform daylighting simulation. The choice of Energy plus was motivated by the fact that it is open, widely used and validated for the thermal balance simulation, and compatible with window outputs of complex fenestration systems. Nevertheless is accuracy in indoor daylighting calculation was found questionable, especially dealing with shading and scattering window systems, therefore Radiance, as open and well established ray tracing software, was entrusted for this task. The connections between EnergyPlus and Radiance and the adaptive control strategy have been implemented in Building Controls Virtual Test Bed (BCVTB), an open software precisely developed for co-simulation purposes.

Moreover, two in house tools, developed in Matlab for the specific curved geometry and bi-coloured PV shading surface, were used to provide the angular optical characterization of the shading and glazing system and to calculate the power produced by the integrated PV modules, respectively in pre-processing and post-processing.

3.1. Building co-simulation process

Fig. 4 show the dataflow implemented in BCVTB with all the software components involved in the dynamic simulation. BCVTB communicates with EnergyPlus through an object called EnergyManagementSystem (EMS), which is used to run dynamic simulation.

The control logic was distributed into three boxes, each performing a different calculation, that select the optimal BIPV shading mode and regulate the state of the lamellas (tilt and extension). A discrete number geometrical configuration was defined varying lamella tilt and

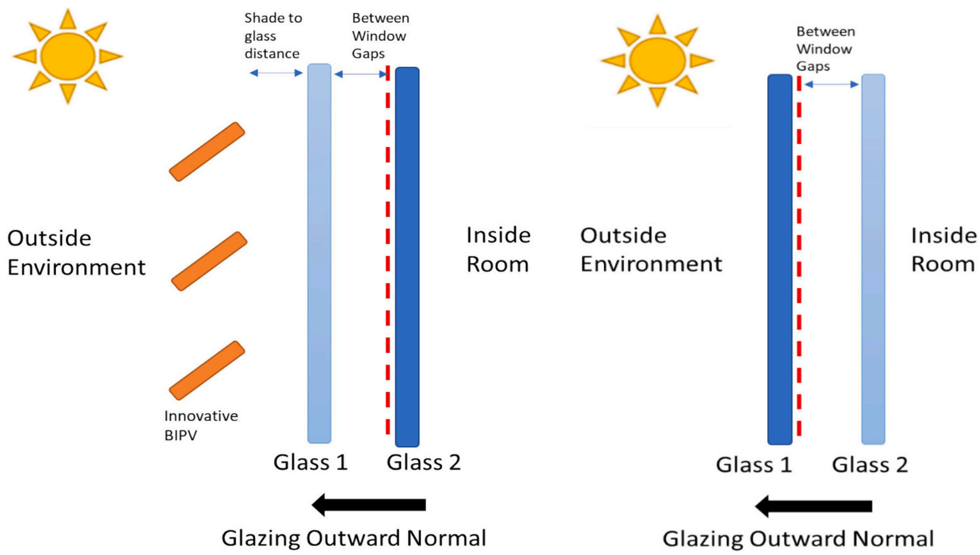

Fig. 3. Schematic representation of the components for the BIPV system (left) and the reference transparent façade (right). In dark blue with dashed red line the coated glass panes of the Low Emissive (left) and Solar Control (right) glazing systems. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Glazing properties.

(Glazing system)	Reference (Solar control)	BIPV (LowE)
U-value W/m2/K	1.353	1.390
SHGC	0.359	0.486
Tvis	0.699	0.754

extension. For each of them an optical bidirectional characterization (BSDF) was derived and a ComplexFenestrationState (CFS), which includes the glazing, was associated.

The illuminance was evaluated by Radiance for every timestep having as input the BSDF.

Via EMS in EnergyPlus the same BDSF input was used for the CFS to perform the building thermal calculation at each timestep. Daylighting, indoor temperatures, heating and cooling needs were hence evaluated. Based on this feedback and the priority rules set in the previous section, the control strategy selects the optimal shading state for the lamellas tilt and extension.

This process was repeated until the optimal shading state was reached for every timestep. Then the shading state was used to simulate the PV production in Matlab.

3.2. Optical model

The optical properties of the novel shading device were investigated in a previous study [25], in which an in-house model was developed in Matlab and validated against Window Software. The model takes into account the peculiar geometry of the lamellas and the reflectance of the integrated PV modules, which differs from the others. Such model was used to derive in pre-processing, for a discrete number of shading states, the BSDF characterization of the CFS, composed by the BIPV shading device and a LowE glazing.

3.3. PV model

For the PV integration a thin film of m-Si technology was employed, with nominal efficiency in Standard Test Conditions 15.9%. Considering the shape of the shading device, the height and width of the South façade 6 PV modules, each with 85 Wp, were assumed to lay on the BIPV façade, independently by the WWR. The PV production was hence evaluated in post-processing employing a dedicated PV model, which was developed in Matlab and validated against experimental data [33] for a pre-prototype of the BIPV system configurations. Indeed, in [33] a detailed and a simplified PV model were presented and discussed, taking into account mutual shadows of the lamellas on the PV cells, solar incidence and slat temperature by means of an integrated thermal model. In the detailed model each PV cell is individually simulated. Such model describes the effects of mismatching considering the PV cells reverse characteristic and power losses. The simplified model was hence developed to reduce the computational time. Since both models proved to predict the electric power production with good accuracies, with daily averaged relative errors between 2% and 10% and main deviations occurring during severe mismatching conditions, the latter was employed in this study.

4. Results

4.1. Façade configurations

Four BIPV façades configuration were simulated for the building case study, assuming different possibility to adjust the state of the shading device and three window to wall ratios (WWR): 50%, 67% and 100%. The complete set of configurations simulated is reported in Table 3.

In configuration 1 and 2, the tilt angle is fixed at 40 degrees, whereas in cases 3 and 4 the lamella tilt angle can be adjusted to maximize the PV production (Solar Tracking mode). Lamella extension for Solar Control mode is possible in configuration 2, 3 and 4. Two activation methods were investigated, one based on room temperature, when it exceeds 25 °C, and the other based on a pre-simulated cooling load (with setpoint at 26 °C). As comparison the reference façade system, without shading and with solar control glazing, was also simulated for each WWR (named A, B and C).

4.2. Performance indicator

In order to evaluate the energy potential of the new BIPV façade an overall energy performances indicator was introduced, the *Net Annual Electric Energy*, E_{net}:

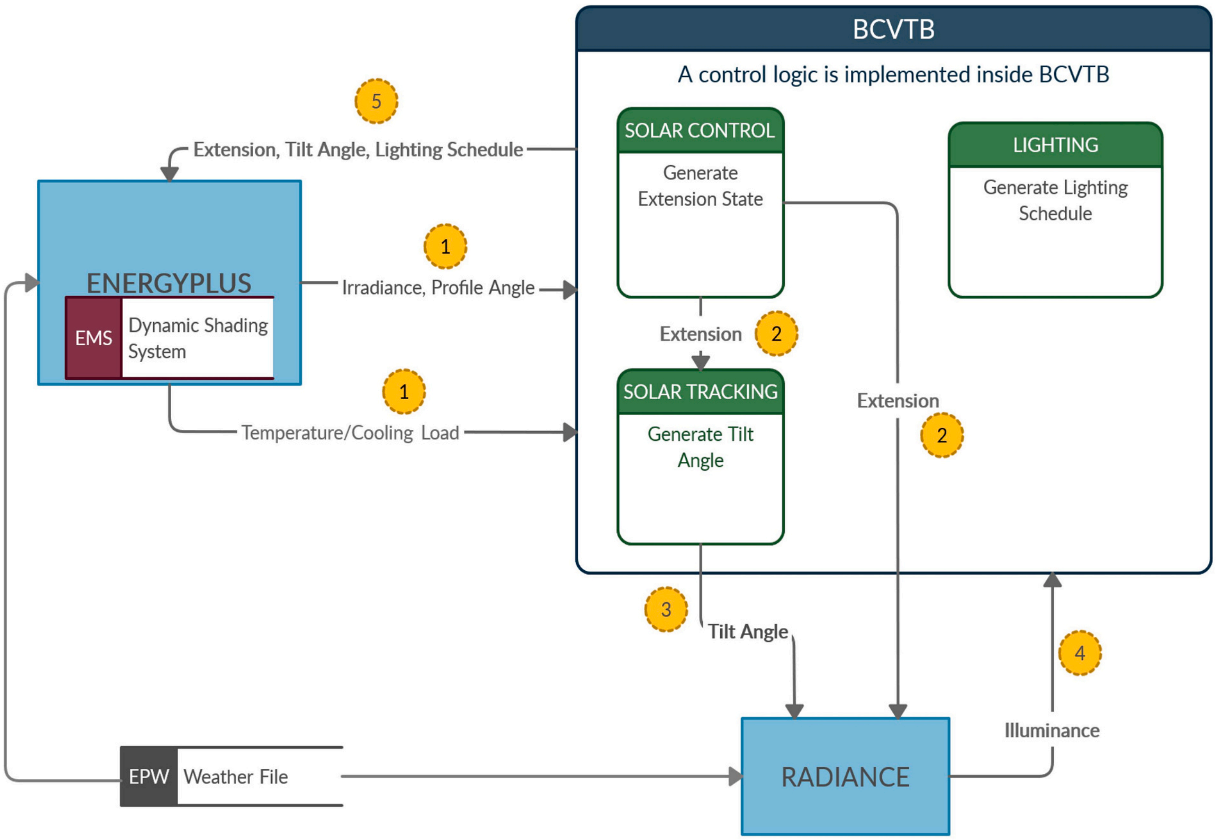

Fig. 4. Flow chart of BIPV shading control implemented in BCVTB. 1) thermal calculation of loads and temperatures, 2) evaluation of solar control necessity, 3) potential PV optimization, 4) assessment of illuminance requirements, 5) action based on the defined priorities.

Table 3
Façade configurations and dynamic control simulated.

Case	Configuration	WWR	PV shading tilting	shading extension
Aref	Reference	0.5	–	–
A1	1	0.5	Fix	–
A2	2	0.5	Fix	Indoor temperature
A3	3	0.5	Solar Tracking	Indoor temperature
A4	4	0.5	Solar Tracking	Cooling load
Bref	Reference	0.67	–	–
B1	1	0.67	Fix	–
B3	3	0.67	Solar Tracking	Indoor temperature
Cref	Reference	1	–	–
C1	1	1	Fix	–
C3	3	1	Solar Tracking	Indoor temperature

$$E_{net} = \frac{E_C}{\eta_C} + \frac{E_H}{\eta_H} + \frac{E_L}{\eta_L} - \eta_E E_{PV} \quad (1)$$

The E_{net} indicator, defined in Eq. (1), is similar to the *energy balance index* introduced in [34]. Here E_C, E_H, E_L, are the specific annual energy needs respectively for cooling, heating, lighting, and E_{PV} is the PV energy generated (specific to the floor area). η_C, η_H, η_L are the average efficiencies associated to each system, assuming an electric energy input, and η_E is the inverter efficiency for the PV current. In this work, energy needs and the PV generation were dynamically simulated, while the system efficiencies were assumed constant. Their values are reported in Table 4.

Table 4
Overall system efficiencies employed for the Net Energy indicator (Eq. (1)).

η_H	η_C	η_L	η_E
3.9	3	1	0.9

4.3. Annual energy needs

A first comparison, among the reference and the four configurations of BIPV façade with WWR equal 50% is given in Fig. 5, in terms of annual heating, cooling and lighting demand. The annual specific energy need simulated were divided by the coefficients in Table 4 to derive an equivalent electric energy demand. The totals in Fig. 5 do not consider yet the PV production.

The results show that the BIPV façades, performs better than the reference in reducing heating and cooling needs. This proves the solar control efficacy of the external shading devices, combined with LowE glazing against the sole adoption of a high-performance selective glazing. Moreover, the external shading device improves the façade thermal insulation, especially in winter by night, and contributes to a reduction of the heating need.

On the other hand, the louvres system increases the lighting demand. Nevertheless, it can be stated that such increase is moderate and fully counterbalanced by the higher efficacy in solar protection when a dynamic control of the tilting and of the extension of the lamellas is implemented. Indeed, for configurations A3 and A4, the total electric energy demand (without considering PV generation) results to be lower than the reference case.

Finally, Fig. 6 shows the annual results for all the configurations, including PV generation and assuming for all the BIPV façades the same number of PV modules. It can be observed that a *nearly zero energy* target is always achieved with the proposed BIPV façades. However, only the configurations implementing the dynamic shading features - A3, A4, B3 and C3 – achieve a *net zero energy* performance with E_{net} negative and/or below 0.5 kWh/(m^{2}y). Looking at the window to wall ratio variants, the optimal overall energy performance, for this case study, can be achieved

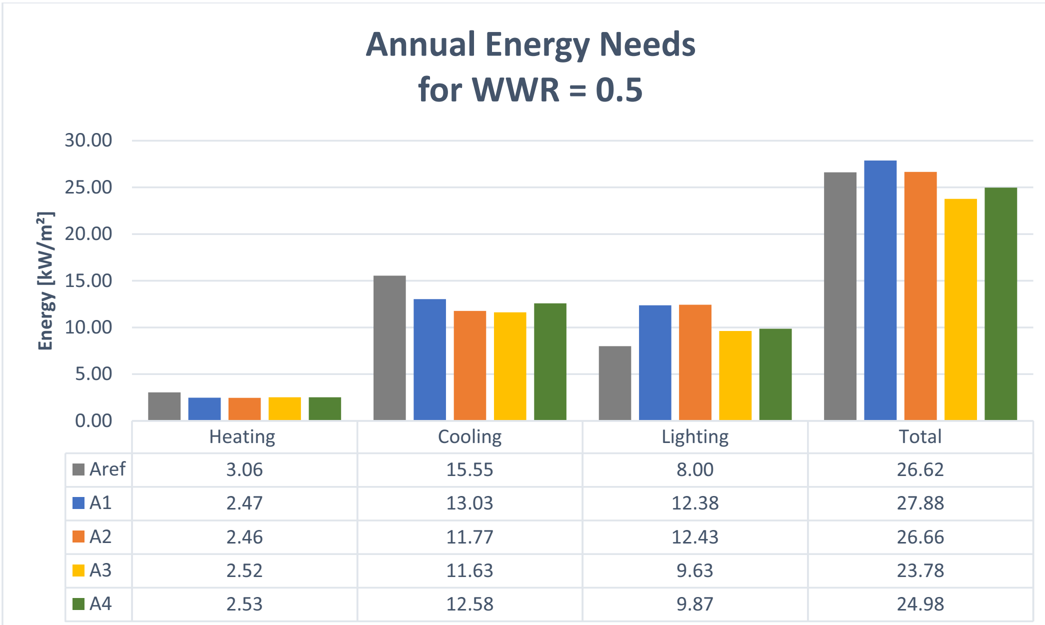

Fig. 5. Specific annual energy needs (in equivalent electric demand per floor area) for WWR =50%.

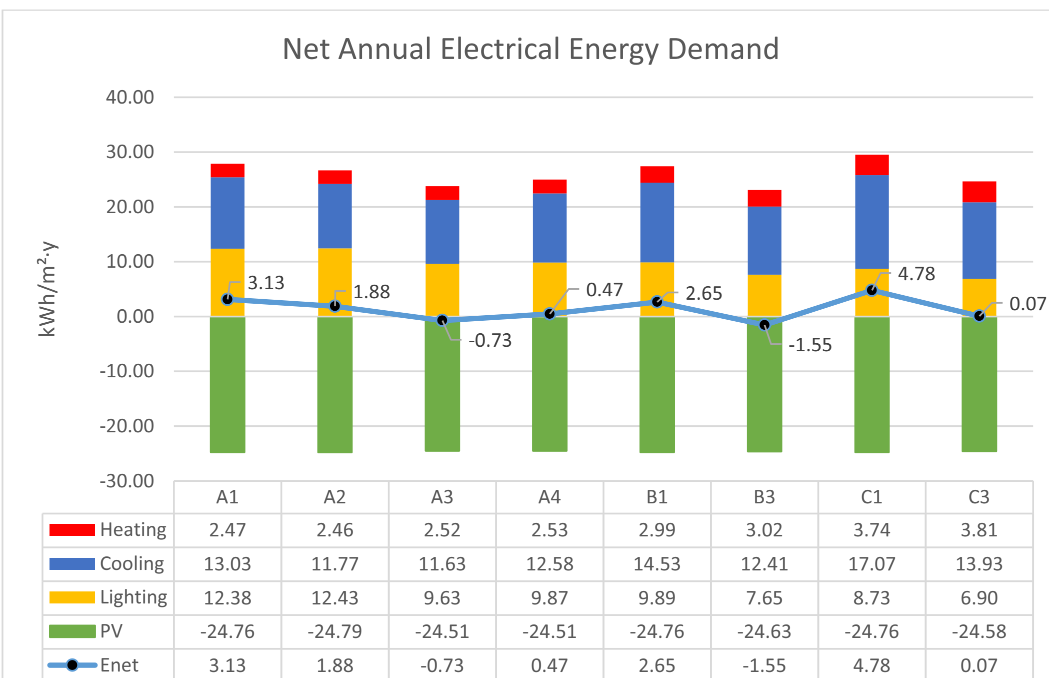

Fig. 6. Net annual energy (in equivalent electric demand) for all the BIPV configurations.

with WWR between 50% and 67%.

4.4. Effect of the lamella extension

In order to analyze the sole effect of the lamella extension, Figs. 7 and 8 show the cooling rate in a typical working week of spring, respectively for configuration A1 (tilting fixed, minimum extension) and A2 (extension based on indoor temperature). To facilitate the comparison the cooling load for the reference case is also plotted.

Comparing the two graphs it can be seen, firstly, how the presence of the external shading device reduces the cooling load and, lastly, how the extension of the lamella further reduces the cooling rate, so that in some spring days the cooling demand can be completed avoided blocking the excess of solar gains.

4.5. Effect of the activation control

Similarly, in order to investigate the efficacy of the two solar control activations adopted in A3 and A4, results of configurations A3 and A4 are compared in Figs. 9 and 10. It can be observed that the control based on indoor temperature with activation at 25 °C, anticipating the occurrence of the cooling demand, whose setpoint is at 26 °C, offers a higher prevention from overheating, without jeopardizing the daylight exploitation. This is confirmed by the annual results reported in Fig. 5.

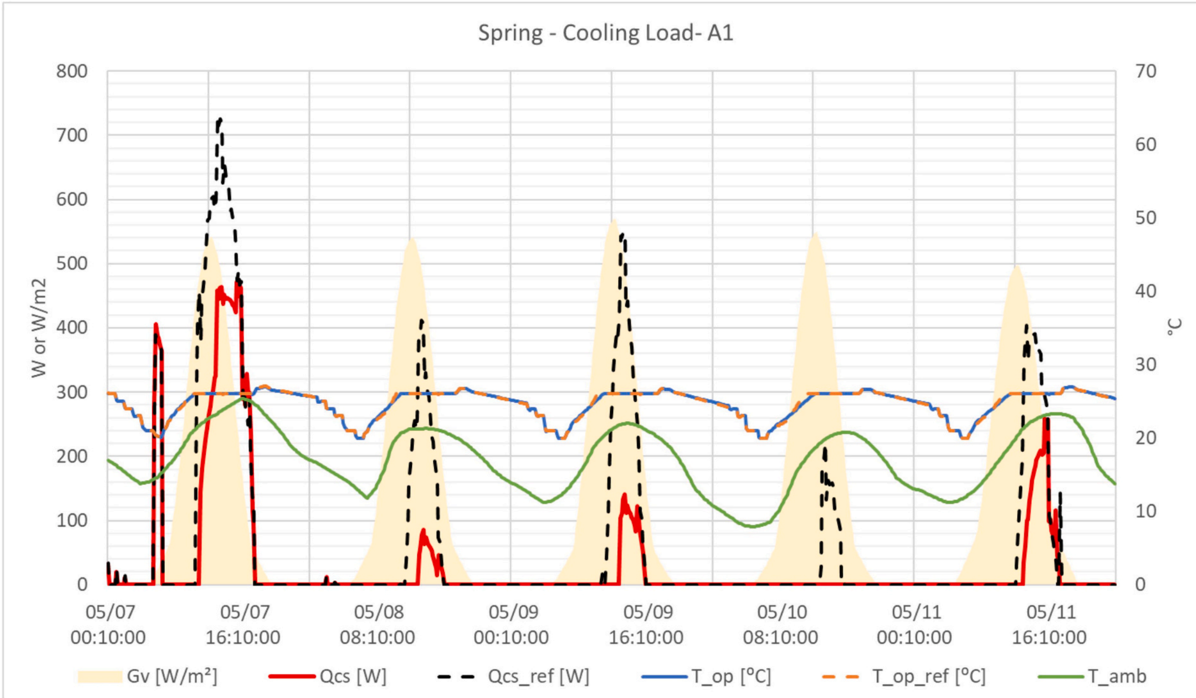

Fig. 7. Profiles of the hourly cooling load in a spring week for the reference case (no shading) and A1 configuration (external shading with tilt fixed and no extension).

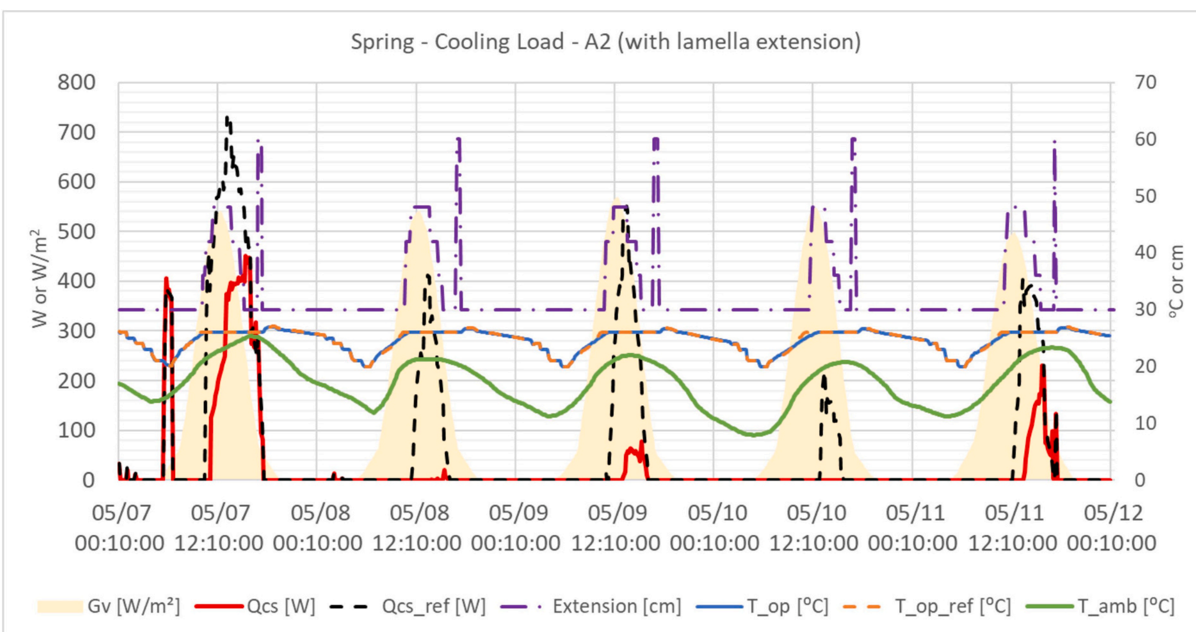

Fig. 8. Profiles of the hourly cooling load in a spring week for the reference case (no shading) and A2 configuration (external shading with tilt fixed and lamella extensible).

5. Conclusions

This study sought to both evaluate the potential of an innovative dynamic BIPV-shading device, and establish a reusable methodology through which to simulate its dynamic features comprising daylighting, thermal and PV performance.

The innovative BIPV shading system achieved its *net zero energy* target under the simulated conditions of an office building located in Milan with south-oriented façade, demonstrating the efficacy of the dynamic system and the potential synergy between renewable generation and solar control offered by the PV integration of the shading device. The geometric and dynamic features of the novel system, combined with its optimization of daylighting exploitation, lead to a global reduction of the energy needs of the building module, with the additional benefit of the exploitation of renewable energy.

Nevertheless, the selected building case for this study determines

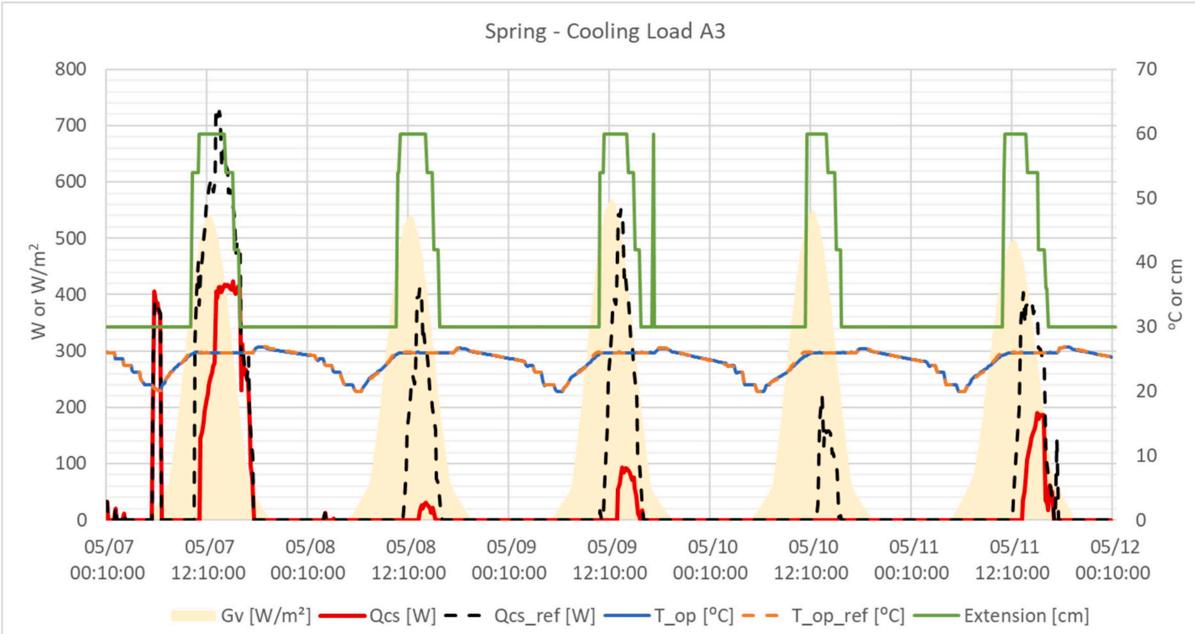

Fig. 9. Hourly cooling load in a spring week for the reference case (no shading) and A3 configuration (dynamic shading with lamella extension based on indoor temperature).

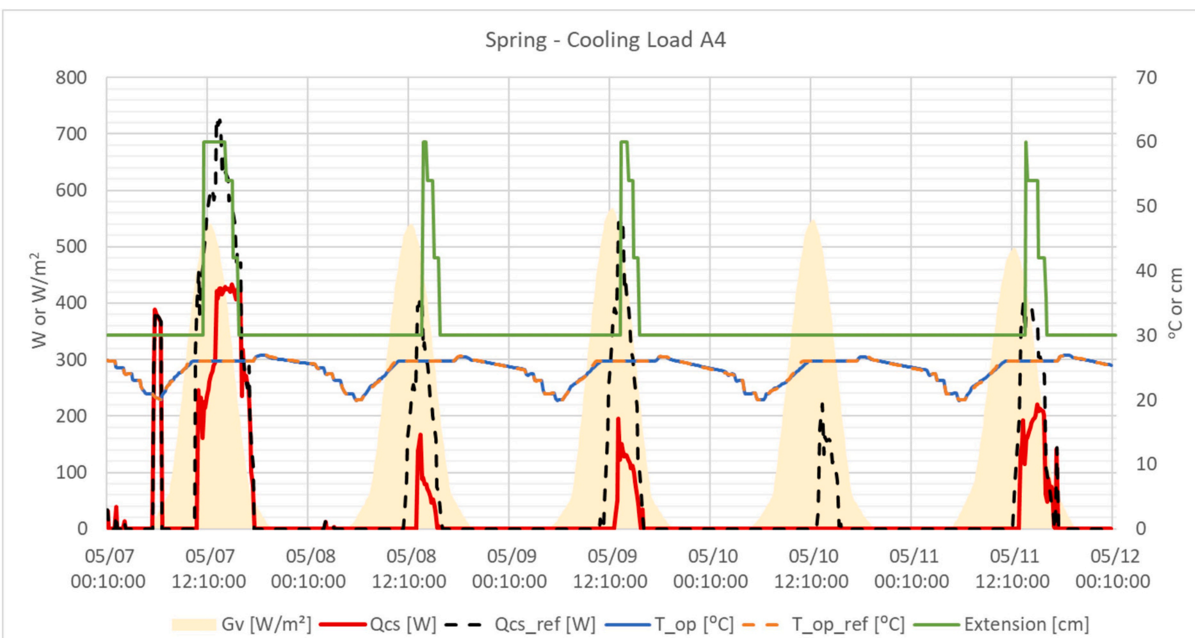

Fig. 10. Hourly cooling load in a spring week for the reference case (no shading) and A3 configuration (dynamic shading with lamella extension based on indoor cooling activation).

some limitations: a single climatic location, only South orientation and a single type of office.

in this work we focus on (1) setting the performance evaluation methodology, which combines different dynamic simulation tools, and (2) giving a first assessment of the potentialities of the new systems with a suitable control strategy.

The investigation of the dynamic performances on the new BIPV system in different climatic contexts, for different façade implementations with different control strategies will be the object of our future work.

Additional studies and simulations are necessary to assess the potential of the novel BIPV system in different climatic contexts, at different latitudes and for different façade orientations and building typologies. Moreover, user's acceptance, preferences and interaction should be included in the adaptive control strategies.

Regarding the second objective, the methodology developed for this analysis successfully permitted the integration of a variety of existing tools and methods of calculation into a single framework. This method could be replicated in future analyses to assess energy performance of this novel BIPV system, as well as that of other dynamic BIPV facades, across different environmental contexts.

In a future perspective, the novel BIPV system might be integrated in the building energy management system, as a smart energy system, including energy conservation and renewable generation. Such integration, maintaining an informed user centred approach in the control of the shading device, might optimize energy dispatch, improve demand response capabilities and/or the grid interaction for net-zero energy communities.

CRediT authorship contribution statement

Alessandro Dama: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Cahyo Adisaputro:** Software, Methodology, Investigation, Formal analysis, Data curation. **Emanuele Piccoli:** Validation, Software, Methodology, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nothing to declare If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] D.D. Agostino, L. Mazzarella, D. D'Agostino, L. Mazzarella, What is a nearly zero energy building overview, implementation and comparison of definitions, J. Build. Eng. 21 (2019) 200–212, https://doi.org/10.1016/j.jobe.2018.10.019.
[2] A.K. Shukla, K. Sudhakar, P. Baredar, Recent advancement in BIPV product technologies: a review, Energ. Buildings 140 (2017) 188–195, https://doi.org/10.1016/j.enbuild.2017.02.015.
[3] B.P. Jelle, C. Breivik, State-of-the-art building integrated photovoltaics, Energy Procedia 20 (1876) (2012) 68–77, https://doi.org/10.1016/j.egypro.2012.03.009.
[4] I. Cerón, E. Caamaño-Martín, F.J. Neila, 'State-of-the-art' of building integrated photovoltaic products, Renew. Energy 58 (2013) 127–133, https://doi.org/10.1016/j.renene.2013.02.013.
[5] E. Biyik, et al., A key review of building integrated photovoltaic (BIPV) systems, Eng. Sci. Technol. Int. J. 20 (3) (2017) 833–858, https://doi.org/10.1016/j.jestch.2017.01.009.
[6] M. Wang, J. Peng, N. Li, L. Lu, T. Ma, H. Yang, Assessment of energy performance of semi-transparent PV insulating glass units using a validated simulation model, Energy 112 (2016) 538–548, https://doi.org/10.1016/j.energy.2016.06.120.
[7] J. Romaní, A. Ramos, J. Salom, Review of transparent and semi-transparent building-integrated photovoltaics for fenestration application modeling in building simulations, Energies 15 (9) (2022), https://doi.org/10.3390/en15093286.
[8] R.A. Agathokleous, S.A. Kalogirou, Double skin facades (DSF) and building integrated photovoltaics (BIPV): a review of configurations and heat transfer characteristics, Renew. Energy 89 (2016) 743–756, https://doi.org/10.1016/j.renene.2015.12.043.
[9] J.E. Goncalves, T. van Hooff, D. Saelens, A physics-based high-resolution BIPV model for building performance simulations, Sol. Energy 204 (March) (2020) 585–599, https://doi.org/10.1016/j.solener.2020.04.057.
[10] J.A. Clarke, J.L.M. Hensen, Integrated building performance simulation: Progress, prospects and requirements, Build. Environ. 91 (2015) 294–306, https://doi.org/10.1016/j.buildenv.2015.04.002.
[11] S.B. de Vries, A Computational Framework for Analysis and Optimisation of Automated Solar Shading Systems: Within High Performance Building Facades, Eindhoven University of Technology, Eindhoven, 2022.
[12] M. Drif, A. Mellit, J. Aguilera, P.J. Pérez, A comprehensive method for estimating energy losses due to shading of GC-BIPV systems using monitoring data, Sol. Energy 86 (9) (2012) 2397–2404, https://doi.org/10.1016/j.solener.2012.05.008.
[13] L.F. Mulcué-Nieto, L. Mora-López, Methodology to establish the permitted maximum losses due to shading and orientation in photovoltaic applications in buildings, Appl. Energy 137 (2015) (2015) 37–45, https://doi.org/10.1016/j.apenergy.2014.09.088.
[14] C. Shao, A. Migan-Dubois, D. Diallo, Performance of BIPV system under partial shading condition, Sol. Energy 283 (October) (2024) 112969, https://doi.org/10.1016/j.solener.2024.112969.
[15] J. McCarty, C. Waibel, S.W. Leow, A. Schlueter, Towards a high resolution simulation framework for building integrated photovoltaics under partial shading in urban environments, Renew. Energy 236 (September) (2024) 121442, https://doi.org/10.1016/j.renene.2024.121442.
[16] S.H. Yoo, H. Manz, Available remodeling simulation for a BIPV as a shading device, Sol. Energy Mater. Sol. Cells 95 (1) (2011) 394–397, https://doi.org/10.1016/j.solmat.2010.02.015.
[17] L. Sun, W. Hu, Y. Yuan, X. Cao, B. Lei, Dynamic performance of the shading-type building-integrated photovoltaic claddings, Procedia Eng. 121 (2015) 930–937, https://doi.org/10.1016/j.proeng.2015.09.053.
[18] N. Skandalos, D. Karamanis, An optimization approach to photovoltaic building integration towards low energy buildings in different climate zones, Appl. Energy 295 (January) (2021) 117017, https://doi.org/10.1016/j.apenergy.2021.117017.
[19] M.A. Marzouk, M. Atwa, Daylighting and energy performance of PVSDs, Sci. Res. J. 8 (8) (2020) 69–75, https://doi.org/10.31364/scirj/v8.i8.2020.p0820796.
[20] M. Akbari Paydar, Optimum design of building integrated PV module as a movable shading device, Sustain. Cities Soc. 62 (July) (2020) 102368, https://doi.org/10.1016/j.scs.2020.102368.
[21] S. Shi, J. Sun, M. Liu, X. Chen, W. Gao, Y. Song, Energy-saving potential comparison of different photovoltaic integrated shading devices (PVSDs) for single-story and multi-story buildings, Energies 15 (23) (2022) 9196, https://doi.org/10.3390/en15239196.
[22] Y. Ye, et al., Planning the installation of building-integrated photovoltaic shading devices: a GIS-based spatiotemporal analysis and optimization approach, Renew. Energy 216 (July) (2023), https://doi.org/10.1016/j.renene.2023.119084.
[23] M.V. Nielsen, S. Svendsen, L.B. Jensen, Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight, Sol. Energy 85 (5) (2011) 757–768, https://doi.org/10.1016/j.solener.2011.01.010.
[24] P. Jayathissa, M. Luzzatto, J. Schmidli, J. Hofer, Z. Nagy, A. Schlueter, Optimising building net energy demand with dynamic BIPV shading, Appl. Energy 202 (2017) 726–735, https://doi.org/10.1016/j.apenergy.2017.05.083.
[25] E. Piccoli, A. Dama, Modelling the performances of an innovative shading device integrating PV, Build. Simul. Conf. Proc. 7 (2019) 4879–4886, https://doi.org/10.26868/25222708.2019.210564.
[26] Lawrence Berkeley National Laboratory, WINDOW 6.3. https://windowslblgov/software/window/windowhtml, 2010.
[27] D.C. Curcija, L. Zhu, S. Czarnecki, R.D. Mitchell, C. Kohler, S.V. Vidanovic, C. Huizenga, in: Berkeley Lab (Ed.), Window, 2015.
[28] EnergyPlus. https://energyplus.net/.
[29] U.B.T. Division, L.B.N. Laboratory, Radiance. https://www.radiance-online.org/.
[30] G. Ramos, E. Ghisi, Analysis of daylight calculated using the EnergyPlus programme, Renew. Sust. Energ. Rev. 14 (7) (2010) 1948–1958, https://doi.org/10.1016/j.rser.2010.03.040.
[31] A. McNeil, E.S. Lee, A validation of the radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems, J. Build. Perform. Simul. 6 (1) (2013) 24–37, https://doi.org/10.1080/19401493.2012.671852.
[32] U.B.T. Division, L.B.N. Laboratory, Building Controls Virtual Test Bed. https://simulationresearch.lbl.gov/bcvtb/FrontPage.
[33] E. Piccoli, A. Dama, A. Dolara, S. Leva, Experimental validation of a model for PV systems under partial shading for building integrated applications, Sol. Energy 183 (November 2018) (2019) 356–370, https://doi.org/10.1016/j.solener.2019.03.015.
[34] L. Olivieri, E. Caamaño-Martín, F.J. Moralejo-Vázquez, N. Martín-Chivelet, F. Olivieri, F.J. Neila-Gonzalez, Energy saving potential of semi-transparent photovoltaic elements for building integration, Energy 76 (2014) 572–583, https://doi.org/10.1016/j.energy.2014.08.054.
[35] A.D. Galasiu, J.A. Veitch, Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review, Energ. Buildings 38 (7) (2006) 728–742, https://doi.org/10.1016/j.enbuild.2006.03.001.