Energy & Buildings 324 (2024) 114867

Contents lists available at ScienceDirect

Energy & Buildings

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

An overview on building-integrated photovoltaics: technological solutions, modeling, and control

E. Belloni [a,*], G. Bianchini [b], M. Casini [b], A. Faba [a], M. Intravaia [c], A. Laudani [d], G.M. Lozito [c]

[a] Dipartimento di Ingegneria, Università di Perugia, Via G. Duranti n.93, 06125 Perugia, Italy
[b] Dipartimento di Ingegneria dell'Informazione e Scienze Matematiche, Università di Siena, Via Roma n.56, 53100 Siena, Italy
[c] Dipartimento di Ingegneria dell'Informazione, Università di Firenze, via di Santa Marta n.3, 50139 Firenze, Italy
[d] Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, Università di Catania, Cittadella universitaria, Via Santa Sofia n.64, 95123 Catania, Italy

ARTICLE INFO

Keywords:
Building-integrated photovoltaics
Photovoltaics
Bifacial solar cells
Semi-transparent solar cells
Modeling
Control techniques
Storage

ABSTRACT

The advancement of renewable and sustainable energy generation technologies has been driven by environment-related issues, energy independence, and high costs of fossil fuels. Building-integrated photovoltaic systems have been demonstrated to be a viable technology for the generation of renewable power, with the potential to assist buildings in meeting their energy demands. This work reviews the current status of novel PV technologies, including bifacial solar cells and semi-transparent solar cells. This review discusses the various constructions of PV technologies, recent advances in these products, the influence of key design factors on electrical and thermal performance, and their potential in the design of energy-efficient smart buildings. The attention is focused on bifacial and semi-transparent PV systems, given the high level of interest of the scientific community in their current and potential applications.

Focus is also devoted to the analysis of the electrical, optical, and thermal modeling procedures developed for sizing, designing, and integrating photovoltaics into larger building simulations. The development of these models has a positive impact on the implementation of next-generation smart buildings. The latest innovative developments and key issues in the application of bifacial PV solutions in buildings are also summarized and analyzed. Special attention is paid to rear side electrical performance, which can be evaluated by means of illuminance/optical backside modeling. Finally, energy management and control of PV-equipped buildings via both model-based and data-driven approaches are discussed, as well as the integration of electric storage systems in a multi-building context.

1. Introduction

Renewable energies (RES) are increasingly penetrating urban power grids, leading to increased distributed generation, mainly due to the progressive reduction in the cost of PV modules over the last decades. The installation of PV devices in urban and suburban environments requires specific techniques aimed at integrating the photovoltaic components into the building envelope and structure (such as the roof or facade), possibly replacing conventional building materials. This integration is commonly referred to as Building-Integrated Photovoltaics (BIPV). BIPV systems have been gaining in popularity over the past two decades. In this scenario, the BIPV technology reduces the total building cost and mounting cost, as BIPV panels serve as a building component. In order to achieve a cost-effective BIPV system, it is necessary to consider a number of factors, including the temperature of the PV module, partial shadowing, the angle of installation, the direction of the building, and the orientation of the system [1,2]: all these aspects have a significant impact on the ability to achieve high power output and efficiency in building applications. BIPV devices should also be useful to enhance the comfort and aesthetics of the building. Moreover, the implementation of BIPVs is fundamental for achieving net-zero building target: in [3] authors conducted a quantitative analysis of the role of BIPVs for obtaining a zero-energy building and the results confirmed the importance of BIPVs role in line with the European 2020 targets. Also, Aelenei et al. [4] applied BIPV in the walls and roofs to improve the load supply and the grid interaction, taking into account the energy flexibility from BIPVs and energy storage, in order to enhance the integration of renewable energy sources. Another interesting study was carried out by Yuekuan Zhou [5] where authors analyzed a combined strategy for improving

---

* Corresponding author.
E-mail address: elisa.belloni@unipg.it (E. Belloni).

https://doi.org/10.1016/j.enbuild.2024.114867
Received 30 May 2024; Received in revised form 10 September 2024; Accepted 30 September 2024

Nomenclature

Symbols

i_{PV}	Current produced by the PV cell (A)
I_o	Diode reverse current (A)
I_{irr}	Light-generated current (A)
I_{SC}	Short Circuit Current (A)
n	Ideal number of cells
P_{max}	Maximum Power (W)
R_s	Series resistance
R_{sh}	Shunt resistance
v_{PV}	Voltage across the PV cell (V)
V_{OC}	Open-Circuit Voltage (V)
V_T	Thermal Voltage (V)

Subscripts

f	Front side
PV	Photovoltaic cell
r	Rear side
s	series
sh	shunt
T	Thermal
1	Single diode
2	Two-diode

Acronyms

AVT	Average Visible light Transmittance
BIPV	Building-Integrated Photovoltaic
BIPV/T	Building-Integrated Photovoltaic-Thermal
BSC	Bifacial Solar Cells
DC	Direct Current
DPP	Discounted Payback Period
DS-SC	Dye-Sensitized Solar Cells
ESS	Electric Storage Systems
ITO	Indium-Thin-Oxide
HIT	Hetero-junction with Intrinsic Thin layer
HVAC	Heating, Ventilation, And Air Conditioning
MPC	Model Predictive Control
NIR	Near-infrared
NPV	Net Present Value
OP-SC	Opaque Solar Cells
OSC	Organic Solar Cells
PCE	Power Conversion Efficiency
PERC	Passivized Emitter Rear Cell
PERT	Passivated Emitter, Rear Totally-Diffused
PSC	Perovskite Solar Cells
PV	Photovoltaic
RES	Renewable Energies
SRI	Scaled Rear Irradiance
ST-PV	Semi-Transparent BIPV
ST-SC	Semi-Transparent Solar Cells
TOPCon	Tunnel Oxide Passivated Contact
UHI	Urban heat islands
WWR	Window-to-Wall Ratio

energy efficiency of buildings through BIPVs and passive PCM walls.

BIPVs can also replace the transparent envelope: semi-transparent PV glazed systems and large PV glazed façades are generally integrated in commercial/educational/public buildings that present high window-to-wall ratio percentages (WWR). The semi-transparent BIPV glazing limits the entry of solar heat gain, daylight and generates electricity. Currently, several different BIPV glazing systems have been investigated, including double-paned airflow semi-transparent PV glazing, double-paned thermally insulated PV glazing, and single-pane PV glazing [6]. In the early years, research focused on opaque BIPV systems, as opaque PV (monocrystalline and multi-crystalline silicon cells) was the first PV technology to gain significant market traction. However, thin-film PV cells were rapidly identified as being of interest for BIPV systems since their semi-transparency in the visible spectrum allowed for a wide range of building integration possibilities [7]. Currently, several emerging PV technologies are evolving and some of them can be produced at a very low cost [8]. Moreover, thin-film PV cells and the majority of emerging PV technologies are flexible due to their extremely small thickness of just a few microns, which enables their integration into curved surfaces.

In order to achieve a cost-effective BIPV system, the selected PV technology has a significant influence on the final performance of the PV plant, particularly in the case of novel applications and solutions. For example, bifacial PV cells represent an interesting solution; thanks to their potential to produce additional energy due to rear-side irradiance absorption. The use of a bifacial photovoltaic module instead of a monofacial module can result in an additional 25 %–30 % power output assuming optimal installation and design of the system [9]. In general, the economic feasibility of a BIPV system installation can be assessed in terms of Net Present Value (NPV) and Discounted Payback Period (DPP): the values depend on many factors, such as the countries in which the BIPV solution is installed. In fact, both the electricity tariff and the initial cost of the BIPV system per watt peak vary in different countries, and the BIPV installation is more convenient when the electricity tariff is high, and the PV technologies are not so expensive [10–12]. Moreover, BIPV systems can be installed in an urban environment, where they must be integrated architecturally, oriented to maximize solar gain, and shaded from obstructions to perform at optimal levels.

In general, the use of PV modules as a building envelope and/or architectural material is becoming increasingly prevalent, as BIPV systems are demonstrating the ability to perform well even when not optimally positioned and partially shaded. This is due to the fact that the electrical system design allows for flexibility in architectural decisions [13]. An interesting review paper directed attention toward the impact of BIPV system installation on urban heat islands (UHI) [14]. It was posited that rationalized planning of BIPV and cool roofs in urban environments can assist in mitigating the UHI effect. The deployment of BIPV with high conversion efficiency has been demonstrated to be beneficial for urban cooling due to the reduced quantities of BIPVs [15]. Therefore, BIPV efficiency is crucial to the mitigation of the BIPV-aggravated UHI effect.

Finally, the integration of hidden colored PV modules in architecturally sensitive areas represents the optimal solution for achieving a balance between conservation and energy issues as discussed in [16].

2. Motivation and approach

This review paper presents a comprehensive review of current developments in the BIPV area, with a focus on two key technologies: bifacial solar systems (BSC) and semi-transparent BIPV (ST-PV). These two categories have been selected due to the high level of interest shown by the scientific community in their applications. BSCs have been widely adopted by the market, whereas ST-PV and, in particular, solutions with semi-transparent solar cells (ST-SC) are currently undergoing improvement. However, their future adoption will be a turning point for BIPV applications in windows and glazing facades. Section 3.1 of the present study outlines the main features of ST-PV (constituted by ST-SC or opaque cells OP-SC), while section 3.2 is related to bifacial solar cells that are particularly interesting in the current scenario. In both categories, the key factors that contribute to the maximum building efficiency are identified. This is followed by an overview of the available solutions on the market that meet a wide range of requirements. Subsequently, the authors analyze the efficiency and the electric, optic, and thermal modeling of these PV technologies, with a specific focus on the interaction among these three aspects (Section 4). Authors also study the bifacial rear-side conditions modeling with focus on the illuminance modeling procedures. It has been found that many boundary conditions should be taken into account, including the albedo characteristics of the reflective backside surfaces [9]. Section 5 addresses the management and control of these BIPVs through both model-based and data-driven control techniques. Moreover, the electric storage systems (ESS) role and the BIPV-ESS integration in a multi-building context are also discussed. The final section presents the main findings and conclusions derived from the study, as well as an overview of the challenges and future trends in this field.

The novelty of this paper lies in the detailed analysis of two specific types of BIPV systems, namely semi-transparent PV solutions and bifacial solar cells. The first ones are suitable for buildings with highly glazed facades, typical of European non-residential buildings, while BSCs have demonstrated high efficiencies and strong potential. Special focus is given to the modeling aspects of the considered PV typologies, which are especially important due to the strong interconnection among electrical, optical and thermal characteristics, whose interaction is analyzed in detail. Based on the bibliographic search, few review studies focus on this approach. An additional novelty concerns the review of control techniques used to manage buildings equipped with both BIPVs and ESSs.

To better describe the approach adopted for carrying out this review analysis, a flowchart reporting the main structure is shown in Fig. 1.

3. Analysis of BIPVs solutions

3.1. Semi-transparent PV for windows

Transparent or semi-transparent PV (ST-PV) are suitable to be used as windows or façades. A ST-PV glazing system is designed to absorb a portion of the solar radiation incident upon the window surface, thereby generating electrical power. Consequently, this has an impact on the overall solar energy and natural daylight that penetrates the indoor space. The energy performance and indoor comfort level of a building are influenced by many factors, including the adoption of such windows [17]. The impact of integrating photovoltaic glazing systems needs to be analyzed from three main perspectives: optical and thermal performance, as well as electricity production. With the general term ST-PV, authors consider several kinds of PV glazing or windows that are composed by different technologies (generally standard solutions i.e. crystalline-silicon (c-Si) −based solar cells) that are incorporated in two transparent layers: the distance between the cells determines a certain transparency of the element. Very often the module uses a two-layer glazing construction to safeguard the cells from mechanical stress and enhance energy output: double glass layers are designed to provide higher durability and better performance in adverse environmental conditions (Fig. 2). Transparent solar cells are designed to permit some light to pass through the cell while also absorbing a portion of the light to generate electricity. To achieve both transparency and efficiency, it is necessary for them to be able to reflect certain specific wavelengths of light while allowing others to pass through and be absorbed by the cell.

Fig. 3 identifies the critical elements to be considered when semi-transparent PV (ST-PV) are applied to buildings and the main features that influence the indoor comfort conditions and the final consumptions [18,19]. As visible from the flow-chart in Fig. 3, both transparent PV solutions could potentially contribute to a range of benefits, including the generation of indoor lighting, the control of heat dispersion, the provision of a comfortable environment, and the reduction of additional energy consumption. In addition to the principal indicator that is the power conversion efficiency (PCE), other key performance features such as thermal insulation, average visible light transmittance (AVT), color properties, and integrability are all important for meeting the practical application requirements of BIPVs [20]. ST-PV technology can regulate the spread of heat and create a comfortable natural living environment (temperature comfort and visual comfort) [21–23]. It is interesting to note that the indoor lighting conditions achieved by the natural contribution passing through the PV transparent surfaces influence the on-time of the lamps and consequently the building's electricity consumption for artificial lighting. Furthermore, the lamps contribute to the overall heat gain within the indoor environment, which must be accounted for in any thermal balance calculations. Finally, the color diversity of emerging photovoltaic devices permits the combination of performance with aesthetics, thereby providing visual beauty for architecture and art.

Concerning technologies and materials, an at-a-glance comparison of the different possibilities is given in Table 1.

Perovskite represents the most promising emerging photovoltaic material used in the field of transparent or semi-transparent SC. This emerging photovoltaic technology is safe and environmentally sustainable; perovskite solar cells (PSC) are able to combine the effects of visible light transparency and photoelectric conversion. A ST-SC should allow the utilization of ultraviolet and/or near infrared photons and simultaneously maintain a good photon transmittance in the visible wavelength to achieve a balance between solar spectral absorption and

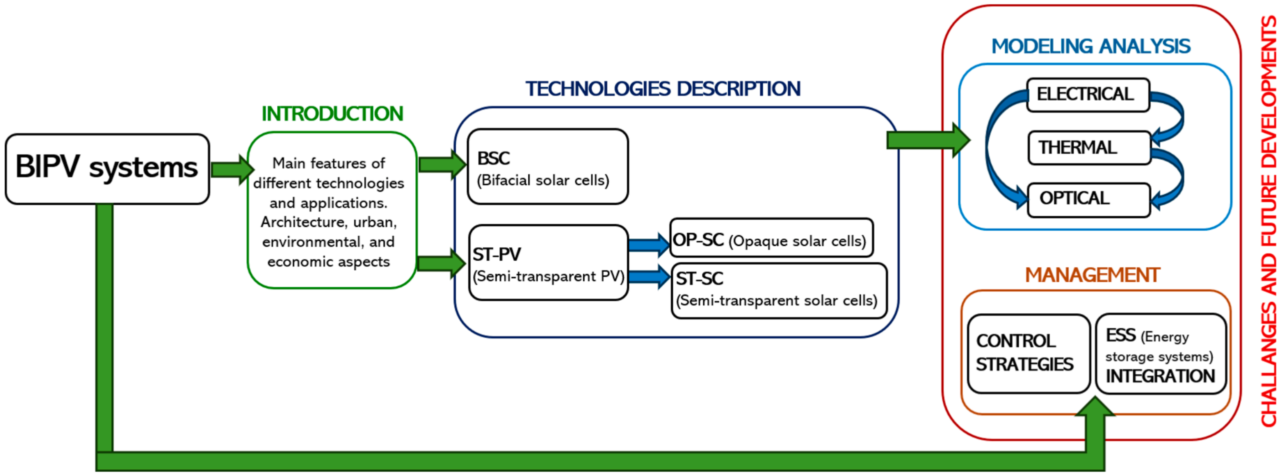

Fig. 1. Flowchart with the main structure and steps of the present literature review.

Fig. 2. Schematic representations of ST-PV glazing systems with opaque solar cells (OP-SC)(on the left) and semi-transparent solar cells (ST-SC) (on the right).

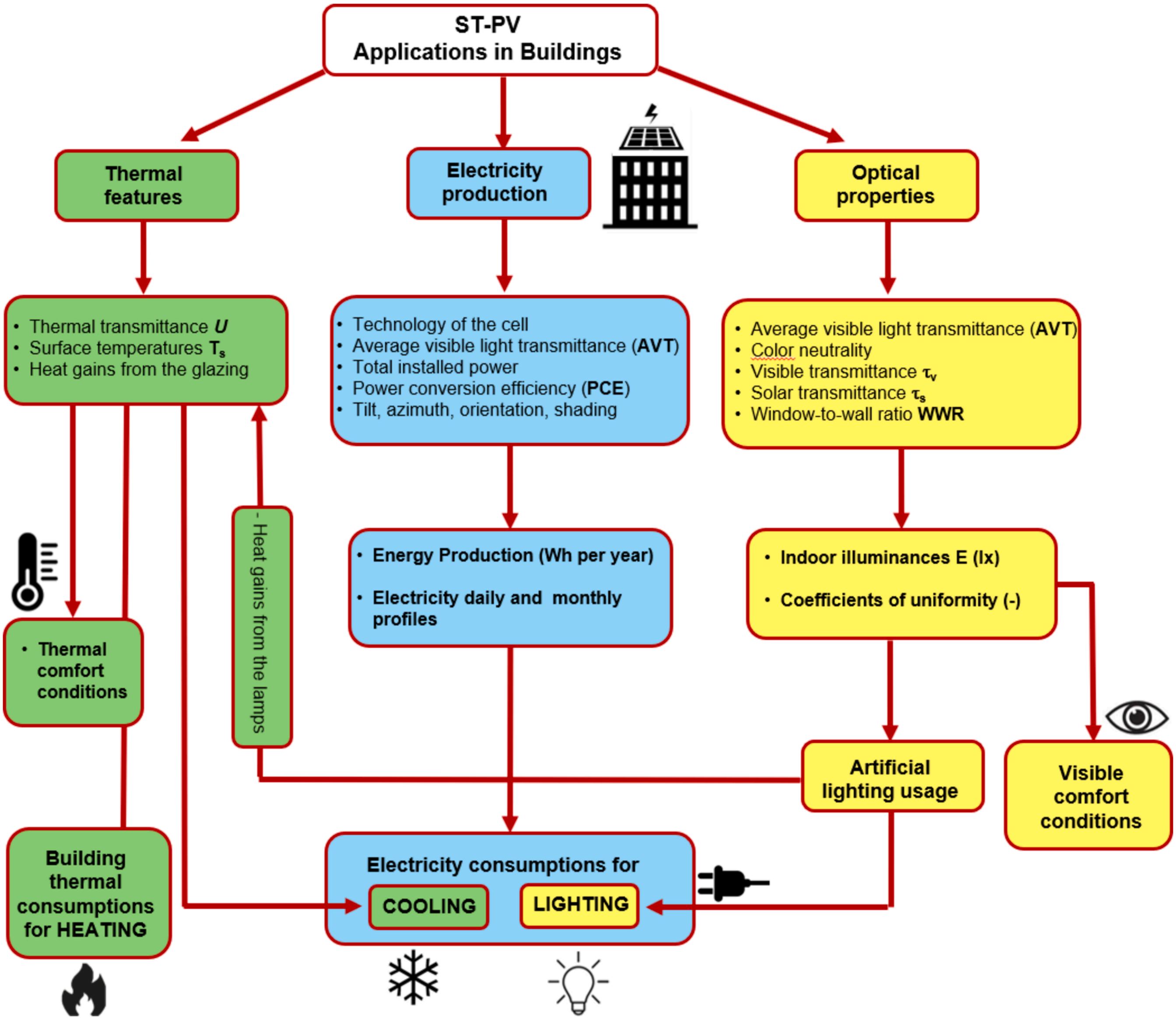

Fig. 3. Effects of semi-transparent PV applications on buildings energy consumptions and global comfort conditions [19].

transmission. Indeed, perovskite materials can achieve color control by adjusting different absorption ranges. Furthermore, they can easily meet the expected features in terms of transparency, resistance, and flexibility.

Inorganic solar cells, such as the ones based on silicon (Si)-PV and perovskite, often necessitate the use of extremely thin or partially

Table 1
At-a-glance comparison of the main technologies and materials for PV cell construction.

Technology	Efficiency	Costs	Durability	Flexibility
Monocrystalline Silicon	✓✓✓	×	✓✓✓	×
Polycrystalline Silicon	✓✓	✓	✓✓	×
CdTe Thin-Film	✓	✓✓	✓	✓✓
CIGS Thin-Film	✓✓	✓	✓	✓✓
a-Si Thin-Film	×	✓✓	×	✓✓
Perovskite	✓✓✓	✓✓	×	✓✓✓
Organic PV	×	✓✓✓	×	✓✓✓
Multi-Junction	✓✓✓✓	×	✓✓	×

ablated absorbing layers in order to provide transparency; this significantly reduces their capability of producing energy [24]. In general, conventional silicon photovoltaic (Si-PV) technology is unable to select wavelengths, is rigid and breakable, and has low power-per-weight. On the contrary, for organic solar technology the absorption does not occur in the visible regions, thus enabling transparency without compromising the energy yield. Organic solar cells (OSC) work with discrete energy levels and employ a clever approach to tailor molecules in the photovoltaic active layer, which ensures light absorption only in the near-infrared (NIR) regions. Moreover, the high absorption coefficient and the good ductility of organic semi-conductors permit the fabrication of solar panels with an ultra-thin profile and excellent mechanical flexibility: an active layer with a thickness of only 100 nm can fully capture the photons. Nevertheless, the primary challenge in the development of semi-transparent OSCs is the achievement of a balance between high transparency in the visible region and high photoelectric conversion efficiency in the near-infrared region.

The high reflectivity of commonly used ultrathin metal electrodes, in silver or aluminum, can result in significant energy losses, which may lead to reduced transparency and efficiency of PV devices. Researchers developed transparent back electrodes to enhance the transparency of the device while maintaining high efficiency: conductive polymers, transparent indium-thin-oxide (ITO) electrodes, dielectric/metal/dielectric photonic structures, and graphene are the most recent and popular technologies.

The present state of the art in the field shows that both ST-PSC and ST-OSC can be considered for practical applications: it has been observed from laboratory tests that semi-transparent perovskite solar cells reach a power conversion efficiency of 14 % with an average visible transmittance of 20–25 %. In the case of semi-transparent organic solar cells, the PCE has reached 13 % with an AVT of about 40 %, in the same conditions.

A performance improvement of ST-PSC can be obtained by reducing the thickness of the active layer and constructing discontinuous perovskite films; moreover, the usage of transparent conductors modulates the optical properties of the device, thereby allowing high values of AVT without decreasing PCE. On the other hand, high costs of transparent conductive oxides limit the applications of these solutions.

It is of paramount importance to give special consideration to the design and optimization of the interface between these devices and the surrounding environment because both OCS and PCS are highly susceptible to environmental factors, particularly oxygen and moisture that can lead to irreversible performance degradation and equipment failure. Another limit is related to the area of conversion of these technologies that is very small considering the expectation for BIPV (up today in the order of cm^2).

Another technology for semi-transparent PV applications is the so-called dye-sensitized solar cells (DS-SC). DS-SC presents a sandwich sealed structure composed by five layers, namely substrate, semi-conductor, dye, electrolyte, and counter electrode substrates.

Synthetic metal complex-based dyes (inorganic) are frequently employed in the production of dyes, including ruthenium, rhodium, and porphyrin dyes. If organic, DS solar cells are synthesized from a variety of plant materials, including leaves, fruit, and flowers. Currently, the highest efficiency recorded for ruthenium-based dyes is of about 14 % while natural dye-based solar cells exhibited a maximum efficiency lower than 10 % [25–28]. The quality of the layers sealing, the types and origin of dye pigments present in different weights, the nature of the extracting solvents and their pH contribute to the final performance of DS-SC. The semi-conductor plays a pivotal role in accelerating electrons from the excited state of the dye to counter electrode via an external load. In DS-SC, wide bandgap semi-conductors have been extensively employed: the most common are TiO_2 and ZnO. It is essential to allow a uniform coating distribution of semi-conductors on the substrate: they can be synthesized in a variety of ways and in a range of sizes, shapes, and morphologies.

Dye-sensitized solar cells are of particular interest for BIPV applications due to their partial transparency, color tunability based on the chosen dyes, light weight and possible flexibility [29,30]. The cells achieved an average power density of 8.0 μW/cm^2 and an efficiency of about 12 % when irradiated by 200 lx compact fluorescent lamps [31]. Nevertheless, chemical degradation, leakage issues when liquid electrolytes are used, and photochemical deterioration of dyes and sealants continue to represent an obstacle to a large-scale diffusion. Fig. 4 presents a selection of images related to semi-transparent and transparent BIPV applications.

3.2. *Bifacial cells for panels*

Bifacial cells are suitable for many BIPV applications and can be integrated into transparent and opaque envelopes. They have attracted great interest in recent years thanks to the potential of an innovative technology able to increase energy output while reducing the surface area requirement and overall costs compared to the conventional PV solution [36,37]. UV-resistant materials are provided on both sides of bifacial solar cells. These materials protect the structures against degradation caused by exposure to sunlight, rain, and other environmental factors. Their spread began in the early eighties with rather high production costs, but now their economic viability is increasing [38–40].

Today a number of manufacturers are engaged in the development and commercialization of different types of bifacial PV modules. Among the current bifacial PV technologies are:

- Passivized Emitter Rear Cell (PERC) technology;
- Hetero-junction with Intrinsic Thin layer (HIT);
- Back contact technology.

The PERC bifacial PV module is able to achieve high energy output by capturing sunlight from both the front and rear sides of the panel. PERC technology employs a rear passivation layer to reduce surface recombination and increase solar cell efficiency with respect to traditional solutions. The configuration of PERC bifacial PV cells typically include an N-type silicon substrate, front contacts, passivation layer, and rear contacts. The rear contact of a PERC cell collects negative charge carriers generated by the solar cell. It can be constructed from various materials, such as silver or aluminum. To achieve bifaciality in the cell, light is allowed to pass through the rear side. Different materials can be used for the passivation layer, such as silicon nitride (SiNx) or aluminum oxide (Al_2O_3).

An interesting evolution of the PERC cells is represented by tunnel oxide passivated contact (TOPCon) solar cell technology, which has the potential to replace passivated emitter and rear contact (PERC) and high-efficiency passivated emitter, rear totally-diffused (PERT) solar panels. One of the key benefits of TOPCon solar cells is that their structure is largely similar to that of PERC/PERT cells. This allows manufacturers to leverage existing production lines with minimal modifications to produce TOPCon cells. TOPCon solar cells present the same base structure of PERT solar cells but they include an ultra-thin

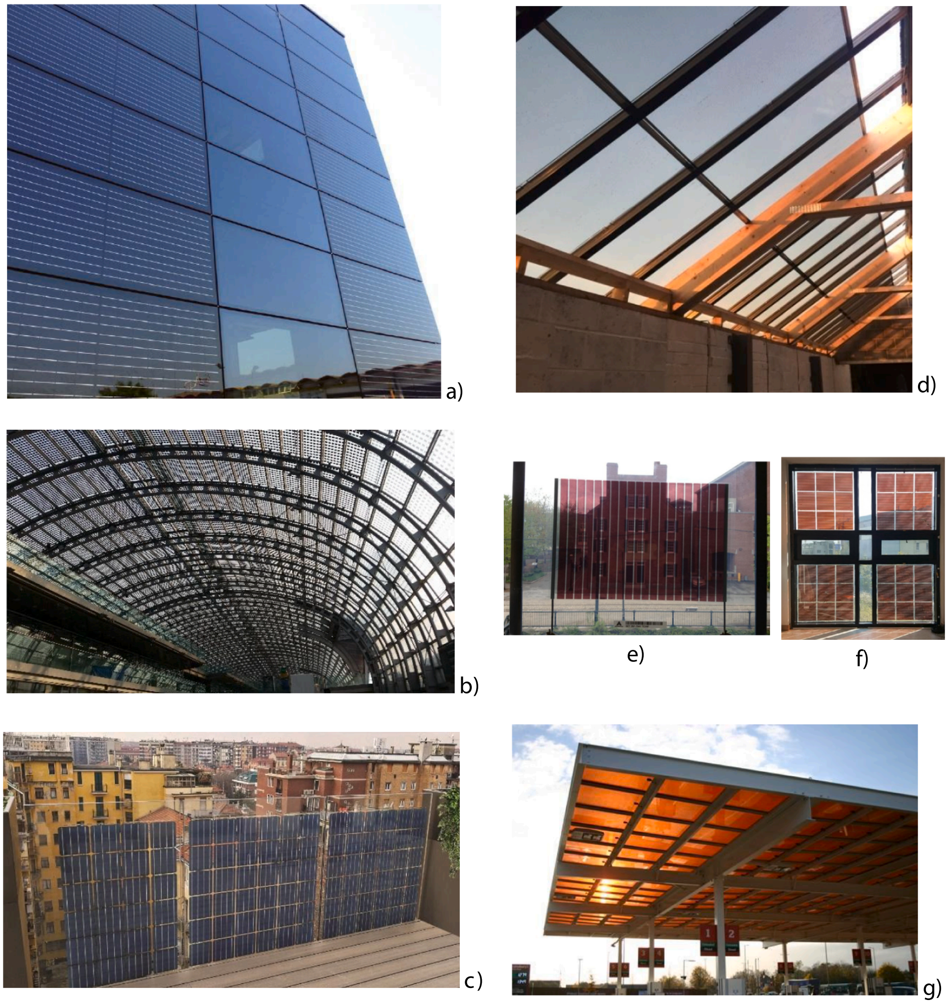

Fig. 4. Semi-transparent and transparent PVs applications: a) ST-PV applied as ventilated curtain wall [32]; b) ST-PV: Turin train station roof [32]; ST-PV applied as balcony with OP-SC [32]; d) transparent see-through Cadmium Telluride (CdTe) thin-film PV technology [33]; e) Organic solar cells (OSC) [34]; f) DS-SC glazing application [35]; g) Sainsbury's Forecourt Canopies [33].

silicon dioxide (SiO_2) layer, which serves as the tunnel oxide layer. Additionally, the back surface field layer is replaced with a phosphorous-doped polycrystalline silicon (n + Poly-Si) layer, further enhancing the structure's efficiency also by curbing recombination through the addition of passivation layers.

HIT PV panels use a thin layer of amorphous silicon (Si) on top of a Carbon-Silicon (C-Si) wafer to enhance the energy conversion efficiency of the module.

The back-contact technology is very useful for avoiding the losses due to shading: modules with the contacts located on the rear side of the cells allow a more efficient light capture. For bifacial solar cells it is important to specify the type of substrate, the light trapping method, and the contacts layout [39]. Among substrate materials, monocrystalline and multicrystalline silicon are commonly used for bifacial PV technologies. The thickness of this substrate is important: the impact of different substrate thicknesses on bifacial solar cell conversion efficiency has been investigated through direct testing [41] and modeling simulation [42]. Experimental results with a substrate thickness of 140 μm compared to 240 μm demonstrated a high efficiency due to a good light trapping. The simulations also demonstrate that minimal decreases in conversion efficiency are observed passing from 200 μm to about 60 μm with a good percentage of cost reduction (despite increasing handling difficulties). One of the most common strategies for enhancing the conversion efficiency of solar cells is to texturize the surface, thereby increasing the absorption of light. Bifacial technology necessitates only front or front-rear texturing, contingent on the configuration of the solar cell. Bifacial solar cells with textured front and planar rear sides are typically sufficient for improvements in light trapping properties, unless a rear side reflector is applied: in this case added back texturization can be useful. Furthermore, a novel research area that deserves attention for enhancing light trapping in bifacial solar cells is the application of photonic grating interfaces: this solution can achieve high reflectivity within the same spectral window, depending on the direction of the incident light [43].

Furthermore, research activities in this area for bifacial solar cells are focused on replacing conventional screen-printed silver (Ag) front contacts with either Cu-plated contacts, TCO, or aluminum (Al), reducing the silver amount per bifacial cell that represents a substantial cost for the fabrication process. Cu-plated contacts can also help to reduce the high temperature firing silver pastes (curing temperature is at 160 °C) and the high recombination velocity of Al-coated rear surfaces, which reduces the conversion efficiency with decreasing wafer thickness. Efficiencies higher than 23 % for bifacial solar cells have been recently obtained using copper electrochemical plating to form the electrodes [44]. An advantage of bifacial PV cells is that they reduce recombination at the rear surface by restricting the metal contact area to a grid. Bifacial PV cells capture photons on both cell faces and, in particular, up-converters placed on the cells capture photons with energy lower than the band gap of the semi-conductor substrate and, simultaneously, they re-emit the photons with energy higher than the bandgap to the active region of the solar cell, thereby increasing the efficiency of the solar cell [45].

Specific bifacial solar cells are developed for flexible and low-weight applications, including semi-transparent solutions. They are mainly based on dye-sensitized technology, as well as thin film technologies based on CdTe, CIGS and GaAs. These cells are inserted in glass or plastic, with TCO thin films used for the electric contacts. To increase the efficiency of these particular bifacial PV modules that are generally quite low and to improve the device longevity, alternative materials can be used. As previously stated, the use of a bifacial PV module instead of a monofacial system can result in increased power. However, many factors including the adopted configuration, the temperature of the module, and the uniformity of irradiance, can affect the performance of a bifacial PV module in the field [46–48]. In general, it can be said that the non-uniformity of back irradiance represents a significant limitation on the back contribution, which is particularly sensitive to the height of the lower edge of the module from the ground and to the non-uniform irradiance (when diffused radiation is dominant). In general, the larger the surface area of the ground reflective surface, the greater the energy yield of the PV module. This effect is more pronounced when the module elevation is increased, but it reaches a saturation point above a certain value [49]. It is recommended to maintain the optimum tilt angles low in installations with a high albedo coefficient. This reduces the inhomogeneity of the rear irradiation and increases the energy yield. Fig. 5 resumes the most important aspects that influence the final electric/thermal behavior and the efficiency of bifacial PV applications.

4. Optical, thermal, and electrical models

Modeling an operative PV device is a complex task since its behavior must be studied in three different physical domains: the electrical domain, the optical domain and the thermal domain. The models implemented for each domain are not autonomous, but instead, interact with the models in the other domains. A schematic representation is given in Fig. 6. Models interact as follows. The optical model is used to understand the illumination profile on the PV device. This information is used by the electrical model as useful solar radiation (in terms of spectrum) on front and backside of the PV panel, also taking into consideration diffused radiation and shading effects. The same information is also used by the thermal model to estimate the thermal power flow due to the solar illumination. The electrical model estimates the electrical power produced by the PV device, which is strongly dependent on the normal irradiance (provided by the optical model) and the device temperature (provided by the thermal model). The thermal model estimates the state representation from which the PV device temperature is estimated. For this estimation, information on the heating coming from solar insolation (provided by the optical model), and the net solar radiation converted in electrical power (provided by the electrical model) are required.

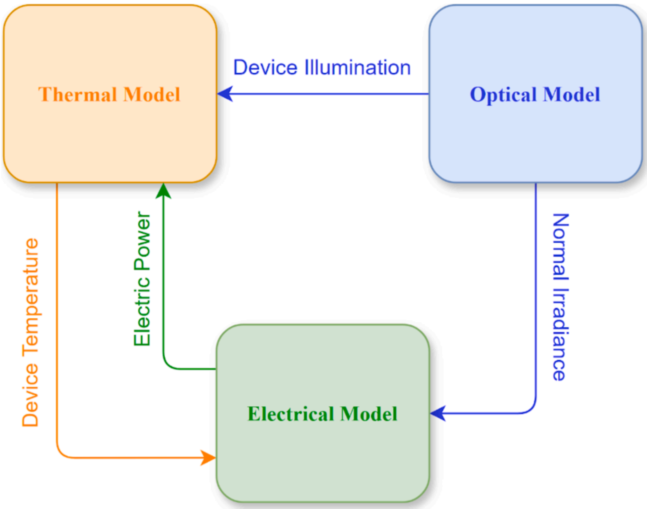

Fig. 6. Interaction between the three modeling aspects involved in bifacial solar cells.

Concerning the efficiency of the PV system, which is probably the most important figure of merit in design and operations, it is influenced by all the three domains at the same time. The electrical domain affects efficiency in terms of optimal operating point (which is acted upon by maximum power point tracking algorithms). Optical domain affects the performance in terms of useful radiation reaching the semi-conductor and being transformed into electrical carriers (this is especially true for bifacial devices). Thermal domain affects the efficiency through alteration of the electrical model as a function of the junction's temperature. Thus, efficiency modeling requires a suitable representation of the device in all the domains at the same time. It should be noted that the strong interaction and coupling between these models makes the

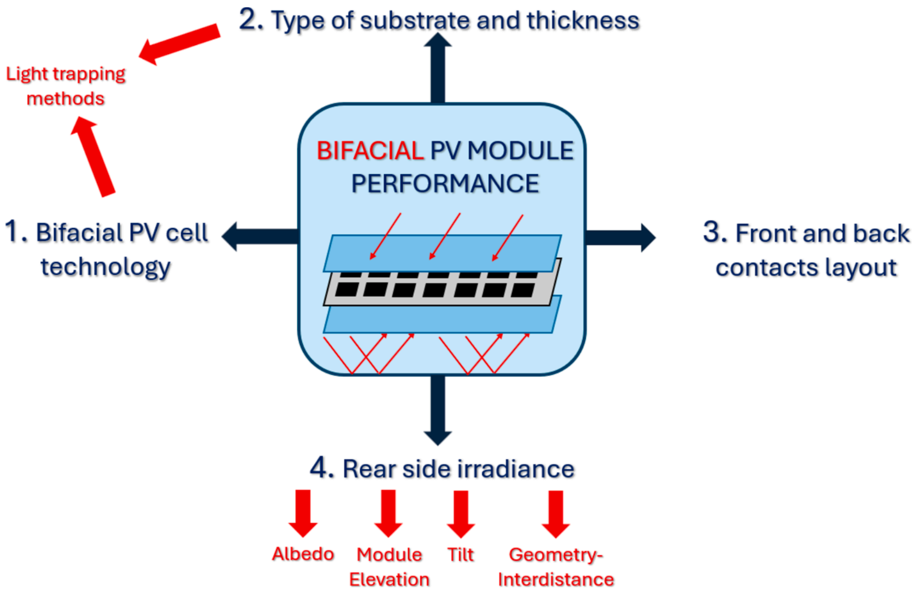

Fig. 5. Key factors for the efficiency of Bifacial PV modules determination.

simulation of the complete PV system a challenging task, especially considering that the three domains operate on different timescales. For this reason, the importance of studies featuring the contextual simulation of the three domains turns out to be a very important task.

4.1. Models for semi-transparent solar cells

Modeling approaches for semi-transparent solar cells can in general be traced back to models used for non-transparent solar cells [34,35,50,51]. This is because the illumination for the cell is mono-directional. Given this nature, approaching the model using classic PV device models such as the single-diode or the double diode model, shown respectively in the top and bottom of Fig. 7, has the advantage of exploiting a well-established methodology both in terms of model adaptation and identification for different specific construction technologies.

For the circuits shown in Fig. 7, the current–voltage relationships are given by (1) and (2), respectively:

$$i_{pv} - I_{irr} \; - I_o\left(\exp\left(\frac{v_{pv} - R_s i_{pv}}{nV_T}\right)\right) \; - \frac{v_{pv} - R_s i_{pv}}{R_{sh}} = 0 \tag{1}$$

$$i_{pv} - I_{irr} \; - I_{o,1}\left(exp\left(\frac{v_{pv} - R_s i_{pv}}{n_1 V_T}\right)\right) - I_{o,2}\left(exp\left(\frac{v_{pv} - R_s i_{pv}}{n_2 V_T}\right)\right) - \frac{v_{pv} - R_s i_{pv}}{R_{sh}} = 0 \tag{2}$$

where the terms $\{R_s, \; R_{sh}, I_{irr} \; n, \; I_o\}$ re the circuit parameters for the single diode model, $\{R_s, \; R_{sh}, I_{irr} \; n_1, n_2, \; I_{o,1}, \; I_{o,2}\}$ re the circuit parameters for the double diode model, and V_T is the thermal voltage.

A modern and up to date review on the modeling for semi-transparent SC applied in BIPV can be found in [7]. Concerning the identification of the single diode model for PV devices several methodologies are present in the literature. Up to date reviews are presented in [52] and [53]. A notable methodology for parameter identification featuring solution space reduction is proposed in [54] and applied to sealed PV modules in [55]. Concerning the numerical simulation of the model, implementations in time-domain simulations for circuit conversion is fairly common [56–58].

4.2. Models for bifacial solar cells

Electrical modeling approaches fall, in general, in two categories. The first category is relative to approaches where an equivalent circuit model is either derived ex novo or adapted from simpler configurations (e.g. monofacial solar cells). This category in general exploits the same models that are adapted for semi-transparent SC shown in Fig. 7**.** The second category is relative to approaches where bifaciality factors are estimated. Bifaciality factors express the ratio of key electrical quantities (open circuit voltage, short circuit current, maximum power) when illumination is applied on the back side with respect to when illumination is applied on the front side. In particular,three bifaciality coefficients are defined:

$$\varphi_{V_{OC}} = \frac{V_{OC,r}}{V_{OC,f}} \tag{3}$$

$$\varphi_{I_{SC}} = \frac{I_{SC,r}}{I_{SC,f}} \tag{4}$$

$$\varphi_{P_{max}} = \frac{P_{max,r}}{P_{max,f}} \tag{5}$$

The procedure to determine the bifaciality factors is reported in the technical standard TS IEC 60904–1-2 [59] where the parameters V_{OC}, I_{SC} and P_{max}, reported in eq. (3), (4), and (5), are, respectively, the open circuit voltage, the short circuit current, and the maximum power related to the front or the rear sides. The subscript *f,r* denotes if the illumination is provided on the front (*f*) or the rear (*r*) side, as shown in Fig. 8. In general, the front and rear side efficiencies of bifacial solar cells are given separately, and this precludes the provision of information regarding the actual bifacial operation of the cells.

Thermal models aim at estimating the cell temperatures in real operating conditions. Knowledge of the temperature is critical since higher operating temperatures reduce the efficiency of solar cells due to

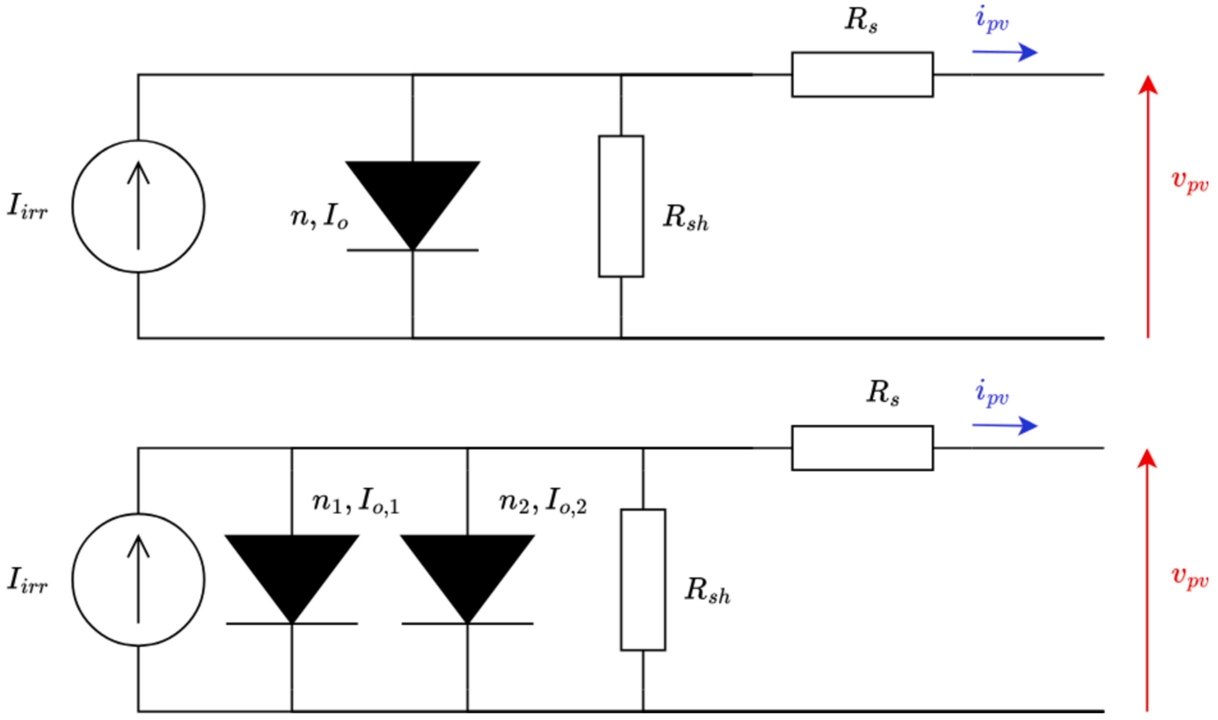

Fig. 7. Single diode (top) and double diode (bottom) models for the equivalent circuit modeling of a photovoltaic device.

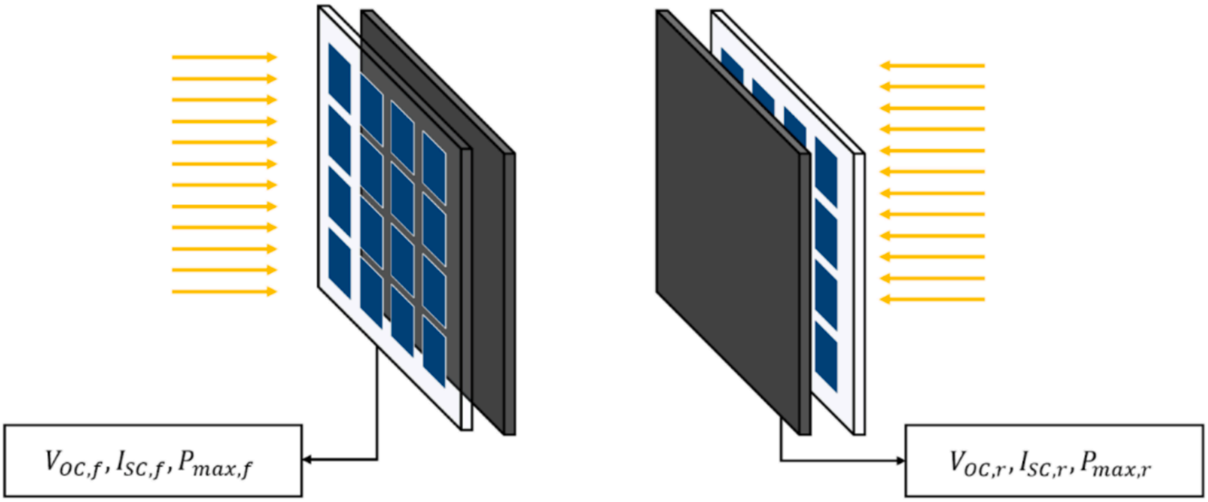

Fig. 8. Characterization methodology for bifacial devices. Illumination is provided to the front and the back separately by placing a non-reflective screen on the non-illuminated side.

the increase in intrinsic carrier concentration, which affects the open-circuit voltage and, consequently, the fill factor (FF). For bifacial solar cells, thermal modeling becomes even more critical due to their exposure to additional light and thermal loads from both sides. This increased exposure can lead to higher operational temperatures, further impacting their performance and reliability. Thermal modeling is in general a difficult task due to the complexity of the structure surrounding the cell. In this case, several solutions are found in literature, ranging from simple 1D lumped parameters models up to computational fluid dynamics approaches taking into account the full geometry surrounding the active cell.

Optical models are probably the most complex aspect in BSC modeling approaches. This is due to the heterogeneous panorama of operating conditions that are present, especially considering the application of BSC to BIPV scenarios. In general, the goal of an optical model is the complete characterization of the illumination on the device. This characterization is used to estimate the power-converted radiation from the cell, and the insolation on the structure for thermal purposes. As for thermal models, optical models found in literature vastly differ in terms of complexity. The simplest approach involves the formulation of a view factor, which is a computationally light approach able to give a coarse estimation of the backscattered radiation. A more complex approach involves ray-tracing techniques, which however requires a detailed characterization of the geometry and the materials involved in the photovoltaic system structure. Regardless of the complexity of the backscattering model, the ground characterization still needs to be performed, which is in general approached through albedo (or equivalent albedo) estimation. Lastly, the modeling for reflection and absorption, both by the PV cell itself and by coating materials, is also an aspect studied in the field of optical models.

Concerning electrical modeling, it is important to note that the proposed models are suitable for describing the behavior not only of silicon-based cells, but also of cells with different technologies. In fact, once the parameters of the equivalent circuit model have been identified, it is possible to use it independently of the cell/panel construction technology. However, it must be underlined that currently the dominant technology for bifacial cells remains the silicon-based one. Indeed, CdTe or CIGS cells do not find an equivalent diffusion in the field of bifacial cells for BIPV due to their lower performance in terms not only of efficiency, but also of reliability [60]. In the case of CdTe, the limiting issue is related to the realization of the rear and contact region and its efficiency, so CdTe cells are built employing nanoparticles and nanotubes [61] or exploiting specific manufacturing solutions [62,63]. Even if the results are promising, the adoption in BIPV cannot take place in a short time [60]. A similar discussion applies to CIGS cells [64]. For this particular technology is worth noticing the proposal of a digital twin model in [65], which enhances the simulation performance.

In Table 2, a summary of the models for BSC is reported. The models are classified according to their coverage on the thermal, electrical, and optical domains, along with the type of validation (experimental and/or simulation) performed by the authors.

5. Control techniques for integrated energy management in BIPV-enabled buildings

To fully exploit the benefits of BIPVs in optimal building energy management, suitable control techniques must be designed to satisfy several requirements. As pointed out in the review paper [115], a three-layer control architecture is generally adopted. Controllers at the lowest level are related to current and voltage regulation, maximum power point tracking (MPPT), and synchronization. Second-level controllers are designed to guarantee power quality requirements, offer grid support, and provide safety mechanisms, like, e.g., anti-islanding protections. Finally, the purpose of upper-level controllers is to perform integrated energy management of several different devices, such as storage systems, heating, ventilation, and air conditioning (HVAC) apparatuses, radiant floor heating systems, etc., and to detect and mitigate faults. This section focuses on the latter control level, with special emphasis on the smart integration of BIPVs. Indeed, optimized operation of BIPVs in synergy with other devices allows for improved overall performance and flexibility of the system.

Among the methodologies recently employed in this context, Model Predictive Control (MPC) has gained remarkable importance [116,117]. The main reason for its wide adoption lies in its flexibility and ability to take several different requirements and constraints into account, while optimizing performance indices which are relevant to the application. In its most general formulation, MPC involves a sequence of optimization steps based on the plant model, the cost function to be optimized, and design constraints enforced on the system variables and actuation commands. At every time instant k, the current plant state is measured or estimated, and the optimal control strategy is computed via numerical optimization. Such a task is performed over a limited time horizon of p steps in the future by predicting system state evolutions that stem from the present state using the plant model (see Fig. 9) [120]. Then, only the first step of the control strategy is actuated, and the process is repeated at the following time step $k + 1$, starting from the new plant state and shifting the prediction horizon one step forward. In this respect, MPC is regarded as a *receding horizon* strategy. The result is a sub-optimal

Table 2
Summary of the modeling approaches for bifacial solar cells.

Reference	Electrical	Thermal	Optical	Validation	Notes
[66]	Yes	No	No	Experimental	Reference to Standard IEC TS 60904–1-2. BF varies with irradiance
[67]	No	No	Yes	Simulation	Study the effects of tilt and rear irradiance
[68]	Yes	No	No	Simulation	Spice model
[69]	Yes	No	Yes	Experimental	Front and rear side irradiance based on the isotropic sky model
[70]	Yes	No	Yes	Simulation	Optimization of the tilt angle
[71]	Yes	No	Yes	Simulation and experimental on samples	Micro-scale coupled electrical and optical models for contact shading characterization
[72]	Yes	No	No	Experimental on samples	Study of the impact of some physical factors on the solar cell's open-circuit voltage, maximum power point, and fill factor.
[73]	Yes	No	No	Experimental	Study the effects of front and rear irradiance
[74]	Yes	Yes	Yes	Simulation	Deep discussion on the modeling and further consideration about the effects of various installation and weather parameters on the PV generation
[75]	No	Yes	No	Experimental	Verification of the FEM simulation of thermal model implemented in COMSOL
[76]	Yes	No	No	Experimental	Circuital model taking into account the effect of rear illumination.
[77]	Yes	No	No	Simulation	Circuital model implemented in simulink taking into account rear illumination and temperature.
[78]	Yes	No	Yes	Simulation and Experimental	Power performance verification with estimation of improvements production with respect to monofacial, by using rear irradiance model. Simulation and experimental validation
[79]	No	No	Yes	Experimental	Optical model for the evaluation of Bifaciality Factor
[80,81]	No	No	Yes	Experimental	Optical model for the evaluation of the effects of rear illumination and integration in SANDIA model
[82]	Yes	Yes	Yes	Simulation	It is a review and reports the several models available for optical-thermal-electrical analysis of Bifacial PV
[83]	No	No	Yes	Experimental and simulation	Models for back irradiance. comparison of ray-tracing model and view factor models. Practical rules for effective installations are achieved.
[84]	No	No	Yes	Simulation	Comparison among different models (and commercial software) for the evaluation of rear irradiance in order to predict Bifacial Factor and energy production
[85]	No	No	Yes	Experimental	Verification of two different models for rear irradiance evaluation and Bifacial Factor study
[86]	No	Yes	No	Experimental	Transient thermal analysis with 1D finite difference method
[87]	No	No	Yes	Simulation	Propose a scaled rear irradiance (SRI) to correct prediction of IEC standard and discuss several installations of interest
[88]	No	Yes	No	Experimental	Discussion on the temperature of the module and its influence on energy evaluation, taking into account the temperature at both sides of the module
[89]	No	Yes	Yes	Simulation	Discussion about solar load model, aimed to calculate energy flux from solar radiation for thermal analysis. Several models are tested in order to compare performance. A well-written introduction about the optical-thermal-electrical modeling is also reported
[90,91]	Yes	Yes	No	Experimental and simulation	Validation of thermal model with Computational Fluid Dynamic (CFD) for façade with Bifacial PV. Bifacial Factor estimation for electrical model
[92]	No	Yes	No	Experimental	CFD and thermal camera measurements comparison for a bifacial agrivoltaics system
[93]	Yes	No	No	Simulation	Authors discuss the circuital model with one-diode and double diode and the identification of electrical parameters with a stochastic approach.
[94]	Yes	Yes	Yes	Simulation	optical-thermal-electrical models are discussed together with synthetic and empirical formulae and commercial simulators suitable for Bifacial PV system performance evaluation
[95]	No	Yes	No	Simulation	It is of interest for its use of equivalent resistive-capacitive network for the simulation of the thermal behavior. Even if it is a general theory, it can be easily applied to semi-transparent PV and to Bifacial PV.
[96]	No	Yes	No	Simulation	Modeling double glass (GG) and glass-transparent material (GT) in the realization of Bifacial PV
[97]	No	Yes	No	Simulation	Apart to the thermal modeling, it is of interest for its review of BIPV technologies comparison
[98]	No	No	Yes	Simulation	Optical model at structure level with TCAD
[99]	Yes	Yes	No	Experimental	Electric-thermal model coupled with building model for study of interaction of the two systems in BIPV
[100]	No	No	Yes	Simulation	Optical model aimed to taking into account ground illumination in terms of both direct and diffuse components
[101,23]	Yes	Yes	Yes	Experimental	Study of thermal model (temperature) for BIPV (facade, windows, etc). In [16] a review of model and applications is widely reported
[102]	No	No	Yes	Experimental	Geometric optical model for blinds in BIPV of Bifacial PV
[103]	Yes	No	No	Experimental	Comparison among models in terms of Bifacial Factor to predict power production. Specifically, for BIPV
[104]	Yes	Yes	Yes	Experimental	A complete optical-thermal-electrical model aiming at simulation of I-V characteristic in BIPV
[37]	Yes	No	Yes	Experimental	Electrical performance assessment with variable tilt angles.
[105]	No	No	Yes	Simulation	improvement of performance with infrared reflective coating and white reflective coating
[106]	Yes	No	Yes	Simulation	Variable albedo effects investigation
[107]	No	No	Yes	Experimental	Estimation of albedo on complex landscapes
[108]	No	No	Yes	Simulation	Geometrical model and performance comparison
[109]	No	No	Yes	Simulation	Irradiation calculation for large power plants and effects of reflectors
[110]	Yes	No	Yes	Simulation	Power production estimation with different albedo profiles
[111]	No	No	Yes	Experimental	Albedo statistical analysis on satellite data
[112]	No	No	Yes	Experimental	Front and back soling rates with variable tilt angle
[113]	Yes	Yes	Yes	Experimental	Application of thermochromic materials to bifacial systems
[114]	No	No	Yes	Experimental	Indoor lighting effects

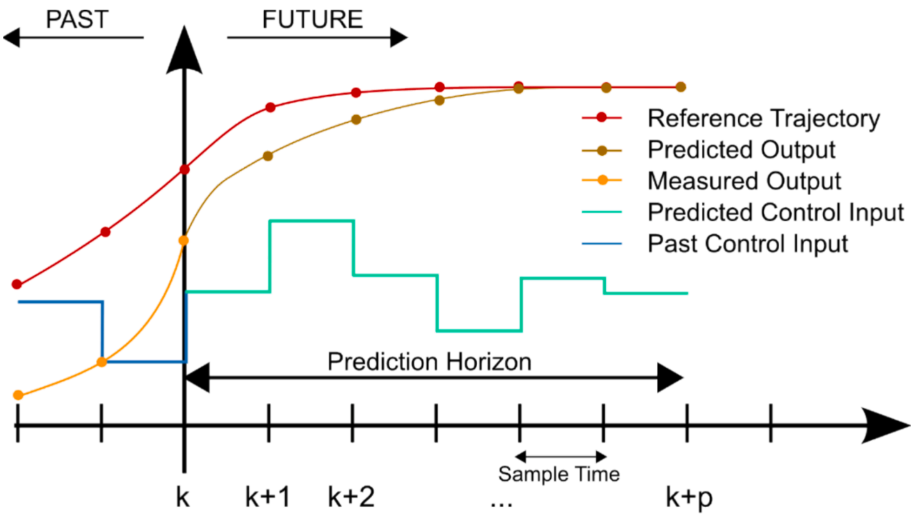

Fig. 9. General predictive framework used in MPC [120].

control action over the whole evolution (possibly over an infinite time horizon) of the closed-loop system. Under suitable conditions, MPC guarantees global asymptotic stability [118]. In the recent literature, robust variants of MPC schemes have been proposed [119]. Such techniques can account for set-bounded uncertainties and disturbances by preserving constraint satisfaction and feasibility of the optimization problem at every time step despite the presence of the uncertainty sources.

Beside MPC and more traditional model-based approaches, *data-driven* control techniques have recently gained attention. The main advantage of these techniques is that the control action is computed without relying on a specific model. A recent survey on data-driven control applied to smart BIPVs can be found in [121]. In this paper, the four fundamental components of the control system are analyzed: data sensing, data analysis, data-driven prediction, and data-driven optimization.

In the following, a review of works focusing on high-level operation of BIPVs interconnected with other devices is presented. Special attention is devoted to the interplay between BIPVs and energy storage systems, which plays a key role in promoting energy efficiency and reducing costs. Some of these works concentrate on solutions involving a single building, while others address applications involving coordinated control across a district-wide group of buildings.

5.1. Integration with electrical energy storage systems

In [122], some issues related to combining BIPVs and Electrical Storage Systems (ES S) systems in a building are addressed. This work is focused on the optimal dispatch of energy produced by a BIPV. More specifically, the aim is to minimize the daily cost of building operation, by considering facility costs, electricity price, and CO_2 price. To this purpose, a nonlinear optimization problem is formulated and solved through a general-purpose solver. Three clear-sky scenarios are simulated, showing that the convenience of BIPV-ES S integration strongly depends on the building consumption patterns and storage costs. A study involving a real office building located in Portugal has been developed in [123]. In the experimental results, batteries with four different capacities have been integrated with BIPV panels, in order to promote self-consumption and therefore reduce economic costs. Differently from other works, real generation and consumption profiles are used, while the storage behavior is simulated. Results show that the use of suitably dimensioned storage systems can increase load matching and provide remarkable economic benefits.

A special class of BIPVs is represented by Building-Integrated Photovoltaic-Thermal (BIPV/T) devices, which are designed to produce both electricity and heat. Heat is usually employed for ventilation preheating through a transpired collector [124]. As reported in [125], the integration of thermal storage may improve the efficiency of the overall system compared with the direct use of heat, thus providing reduced energy consumption and peak loads as well as increased thermal comfort. In [126] a gray-box and a subspace state-space system identification are adopted to estimate the parameters of a model to be used in an MPC algorithm devoted to optimally managing the interaction between BIPV/T, radiant floor heating, HVAC, and thermal storage devices. The work in [127] investigates the use of simplified linear models obtained from system identification for the development of control strategies in solar buildings with passive and active thermal storage capabilities. In [128], MPC techniques are employed to regulate the airflow rate of BIPV/T systems connected to multiple appliances, such as energy recovery ventilators and HVAC systems. Three scenarios based on a real building in Canada are considered. Results obtained in some scenarios by using MPC show a reduction of energy consumption up to 36 % with respect to the simple rule-based control currently employed. Moreover, the heated air excess can be conveyed to the closest buildings, thus providing additional benefit. Along the same line, J.A. Candanedo et al. [129] investigate a method to account for weather forecasts, namely solar radiation availability, in the control system of a solar-optimized building equipped with building-integrated photovoltaic thermal devices. Findings show the effectiveness of MPC combined with such forecasts in the management of stored thermal energy and in overall performance optimization, with special attention to cutting down the utilization of backup heat sources and the reduction of the total electric energy consumption of auxiliary heat pumps. Simulations indicate that a BIPV/T roof can supply 70 % of the auxiliary heating needed by a house in cold climates.

5.2. BIPV-ESS integration in a multi-building context

In addition to controlling BIPV integration inside a single building, some works extend the energy management range to several buildings in a neighborhood. In this case, buildings are assumed to communicate with each other to exchange the relevant information.

In [130], a district of buildings equipped with vertically placed BIPV panels and battery energy storage systems, is considered. The purpose of this work is to maximize the autonomy of the district from the external grid, by exploiting cooperation within the group of buildings. To accomplish this task, an MPC algorithm relying on three components (a forecaster, an optimizer, and the district) is implemented. To assess the performance of this solution, a simulation of four days involving a five-node distribution network located in Greece is performed, as well as a sensitivity analysis under different weather conditions. Energy interaction of buildings equipped with BIPVs has been considered in [131], where the presence in the district of additional sources of renewable generation (wind turbine and solar thermal collectors) as well as Electric Vehicle (EV) charging stations, is assumed. A multi-criteria approach is developed to mitigate storage system degradation. The presence of electric vehicles has been considered also in [132], where a small residential district in Sweden has been analyzed. In this work, cost-optimal capacity and position of BIPVs are optimized, taking into account the interactions between thermal-electrical loads, power sharing among buildings, and electrical storage systems. The analysis is conducted for varying penetration of electric vehicle demand.

The problem of managing a network of several buildings equipped with BIPVs and battery energy storage systems is addressed in [133]. This work aims at minimizing the energy cost of a residential building assuming a dynamic energy price policy. This is obtained by maximizing the overall efficiency of the network while satisfying constraints related to devices like HVAC and other aggregated thermal appliances. The problem is cast as a MILP and solved by using off-the-shelf tools. The approach is validated on a simulation of five apartment towers located in Sydney. Results show that the best solution is to use the energy generated by BIPVs locally or, if a generation surplus occurs, to store it in an ESS. A more involved architecture for high-level control of BIPVs is reported in [134]. To reduce losses due to energy conversion, generation, and storage, buildings are assumed to be connected through a DC network distribution grid. A hierarchical supervisor controller is supposed to interface with both the utility grid and the considered smart buildings, exchanging messages and metadata. Such a controller is composed of four layers: human–machine interface, prediction, cost management, and operation. In this approach, the energy produced by PV panels is mainly self-consumed, while the main grid is used as a backup. Experimental results show the viability of the considered interaction between BIPVs and the utility grid.

6. Conclusions, challenges, and future developments

BIPVs represent a promising technology that offers the functionality of conventional structural elements while providing additional benefits, including the generation of electricity. Recent research has focused on their electrical, thermal, and optical properties. In this scenario, the present review examined more than 130 papers published over the past 25 years on the development, design, modeling and improvement of bifacial and semi-transparent PV technologies. With regard to semi-transparent perovskite and organic solar cells (PSC and OSC), there is room for improvement in the selection of the active layer and device optimization. Furthermore, there are still some outstanding issues to be resolved in order to ensure optimal power conversion efficiency under conditions of satisfactory visible light transmittance. This assessment also indicates that bifacial solar cell and module solutions have reached a rather good level of maturity. However, the implementation of new technologies will have a significant impact on the efficiency, cost-effectiveness, ease of manufacturing, and durability improvement. In relation to BPV, it is of paramount importance to pay close attention to the specific boundary conditions of the installation site and to select the optimal configuration.

Modeling techniques, especially for BSCs, are fairly developed in literature. The review identified that the electrical aspects are investigated in 30 works, thermal aspects are investigated in 16 works and optical aspects are investigated in 31 works. The interaction between the domains, however, has received much less attention. Only 6 articles propose a three-domain model, 8 articles correlate electrical and optical, 1 optical and thermal and 2 electrical and thermal. All remaining studies are exclusively electrical (14), exclusively thermal (7) or exclusively optical (16). It can surely be stated that the optical characterization is the most common for this kind of technology, but interaction with the electrical and especially the thermal domain is still to be developed. The proposed models are validated either by comparison against other models or against experimental data. An interesting opportunity for future research is to define a standard reference (in the form of a dataset) to be used in validating new models under different domains. Such dataset would provide a reference for a quantitative comparative analysis of both well-established models and novel ones. The last part of this review concerns energy management in buildings equipped with BIPV systems. The reported works agree with the fact that interfacing BIPVs with storage systems helps improving the overall building efficiency, thanks to their ability to allow deferral of generated energy consumption. Model-based and data-driven techniques for coordinated control of BIPVs, storage systems, HVAC, and other devices are surveyed, both in a single-building environment and in district-wide scenarios.

The development of a unified model capable of representing the comprehensive behavior of BIPV technologies is a significant future challenge for manufacturers, engineers, researchers, and stakeholders. This model should consider not only the thermal, optical, and electrical behavior of these technologies but also the economic balance, the life cycle assessment and environmental implications associated with their installation. Indeed, economic analysis on some specific case studies already pointed out the feasibility and advantages of using PV as building components, providing a holistic view of the scenario. Integration of such models with the three domains already studied in the literature will provide stakeholders with a complete understanding of the system and with an instrument useful for intelligent design, maintenance scheduling and full lifetime economic analysis of the PV installation.

CRediT authorship contribution statement

E. Belloni: Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **G. Bianchini:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M. Casini:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **A. Faba:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M. Intravaia:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Laudani:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **G.M. Lozito:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors 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.

Acknowledgments

The project has been funded by the EUROPEAN UNION - NEXT GENERATION EU, MISSION 4, COMPONENT 1, CUP B53D23023820001 (Title project: MOST4BIPV - Modeling and Optimization of Smart Technologies for Building Integrated Photovoltaics).

References

[1] M. Tripathy, S. Yadav, P.K. Sadhu, S.K. Panda, Determination of optimum tilt angle and accurate insolation of BIPV panel influenced by adverse effect of shadow, Renew. Energy 104 (2017) 211–223.

[2] A.K. Shukla, K. Sudhakar, P. Baredar, A comprehensive review on design of building integrated photovoltaic system, Energ. Buildings 128 (2016) 99–110.

[3] A. Kylili, P.A. Fokaides, Investigation of building integrated photovoltaics potential in achieving the zero energy building target, Indoor Built Environ. 23 (1) (2013) 92–106.

[4] D. Aelenei, R.A. Lopes, L. Aelenei, H. Gonçalves, Investigating the potential for energy flexibility in an office building with a vertical BIPV and a PV roof system, Renew. Energy 137 (2019) 189–197.

[5] Y. Zhou, Demand response flexibility with synergies on passive PCM walls, BIPVs, and active air-conditioning system in a subtropical climate, Renew. Energy 199 (2022) 204–225.

[6] A. Ghosh, N. Sarmah, S. Sundaram, T.K. Mallick, Numerical studies of thermal comfort for semi-transparent building integrated photovoltaic (BIPV)-vacuum glazing system, Sol. Energy 190 (2019) 608–616.

[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) 3286.

[8] Fraunhofer ISE. Photovoltaics Report; Fraunhofer Institute for Solar Energy Systems: Freiburg, Germany, 2020.

[9] E. Biyik, M. Araz, A. Hepbasli, M. Shahrestani, R. Yao, L. Shao, E. Essah, A. C. Oliveira, T. del Caño, E. Rico, J.L. Lechón, L. Andrade, A. Mendes, Y. Baver Atlı, A key review of building integrated photovoltaic (BIPV) systems, Engineering Science and Technology, Int. J. 20 (3) (2017) 833–858.

[10] H. Gholami, H.N. Røstvik, D. Müller-Eie, Holistic economic analysis of building integrated photovoltaics (BIPV) system: case studies evaluation, Energ. Buildings 203 (2019) 109461.

[11] H. Gholami, H.N. Røstvik, Economic analysis of BIPV systems as a building envelope material for building skins in Europe, Energy 204 (2020) 117931.

[12] Y.W. Wu, M.H.D. Wen, L.M. Young, I. Hsu, LCA-based economic benefit analysis for building integrated photovoltaic (BIPV) façades: a case study in Taiwan, Int. J. Green Energy 15 (1) (2018) 8–12.

[13] C. Zomer, I. Custódio, A. Antoniolli, R. Rüther, Performance assessment of partially shaded building-integrated photovoltaic (BIPV) systems in a positive-energy solar energy laboratory building: architecture perspectives, Sol. Energy 211 (2020) 879–896.

[14] T.S. Elhabodi, S. Yang, J. Parker, S.r Khattak, B-J. He, S. Attia, A review on BIPV-induced temperature effects on urban heat islands, Urban Clim. 50 (2023) 101592.

[15] H.r. Taha, The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas, Sol. Energy 91 (2013) 358–367.

[16] M. Pelle, E. Lucchi, L. Maturi, A. Astigarraga, F. Causone, Coloured BIPV Technologies: Methodological and Experimental Assessment for Architecturally Sensitive Areas, Energies 13(17) (2020), 4506.

[17] Y. Sun, K. Shanks, H. Baig, W. Zhang, et al., Integrated semi-transparent cadmium telluride photovoltaic glazing into windows: energy and daylight performance for different architecture designs, Appl. Energy 231 (2018), 972-984.

[18] L. Xu, J. Ji, C. Yuan, J. Cai, L. Dai, Electrical and thermal performance of multidimensional semi-transparent CdTe PV window on offshore passenger ships in moored and sailing condition, Appl. Energy 349 (2023) 121672.

[19] P.K. Ng, N. Mithraratne, H.W. Kua, Energy analysis of semi-transparent BIPV in Singapore buildings, Energ. Buildings 66 (2013) 274–281.

[20] Z. Zhou, Z. Yuan, Z. Yin, Q. Xue, N. Li, F. Huang, Progress of semitransparent emerging photovoltaics for building integrated applications, Green Energy Environ. 9 (6) (2024) 992–1015.

[21] M.T. Horantner, P.K. Nayak, S. Mukhopadhyay, K. Wojciechowski, C. Beck, D. Mcmeekin, B. Kamino, G.E. Eperon, H.J. Snaith, Shunt-blocking layers for semitransparent perovskite solar cells, Adv. Mater. Interfac. 3 (2016) 1500837.

[22] A. Cannavale, M. Horantner, G.E. Eperon, H.J. Snaith, F. Fiorito, U. Ayr, F. Martellotta, Building integration of semitransparent perovskite-based solar cells: Energy performance and visual comfort assessment, Appl. Energy 194 (2017) 94–107.

[23] N. Martín-Chivelet, K. Kapsis, H.R. Wilson, V. Delisle, R. Yang, L. Olivieri, J. Polo, J. Eisenlohr, B. Roy, L. Maturi, G. Otnes, M. Dallapiccola, W.M.P. Upalakshi Wijeratne, Building-Integrated Photovoltaic (BIPV) products and systems: a review of energy-related behavior, Energ. Buildings 262 (2022) 111998.

[24] W. Song, J. Ge, L. Xie, Z. Chen, Q. Ye, D. Sun, J. Shi, X. Tong, X. Zhang, Z. Ge, Semi-transparent organic photovoltaics for agrivoltaic applications, Nano Energy 116 (2023) 108805.

[25] P. Singh Saud, A. Bist, A.A. Kim, A. Yousef, A. Abutaleb, M. Park, S.-J. Park, B. Pant, Dye-sensitized solar cells: fundamentals, recent progress, and optoelectrical properties improvement strategies, Opt. Mater. 150 (2024) 115242.

[26] A. Bist, S. Chatterjee, Review on efficiency enhancement using natural extract mediated dye-sensitized solar cell for sustainable photovoltaics, Energy Technol. 9 (2021) 1–19.

[27] N. Sangiorgi, A. Sangiorgi, A. Sanson, Seawater-based electrolytes facilitate charge transfer mechanisms improving the efficiency of dye-sensitized solar cells, J. Electroanal. Chem. 915 (2022) 116352.

[28] I. Joseph, H. Louis, E.E.D. Okon, T.O. Unimuke, A.D. Udoikono, T.O. Magu, O. Maitera, M.I. Elzagheid, L. Rhyman, E.I. Ekeng-Ita, et al., Experimental and theoretical study of the dye-sensitized solar cells using Hibiscus sabdariffa plant pigment coupled with polyaniline/graphite counter electrode, Pure Appl. Chem. 94 (2022) 901–912.

[29] A. Cannavale, L. Ierardi, M. Hörantner, G.E. Eperon, H.J. Snaith, U. Ayr, F. Martellotta, Improving energy and visual performance in offices using building integrated perovskite-based solar cells: a case study in Southern Italy, Appl. Energy 205 (2017) 834–846.

[30] B. O`Regan, M. Grätzel, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films, Nature 353 (1991) 737–739.

[31] F. De Rossi, T. Pontecorvo, T.M. Brown, Characterization of photovoltaic devices for indoor light harvesting and customization of flexible dye solar cells to deliver superior efficiency under artificial lighting, Appl. Energy 156 (2015) 413.

[32] STG Group - Energy Glass. Available at: https://energyglass.gruppostg.com/it/elementi-fotovoltaici/vetri-fotovoltaici-strutturali.html. [accessed September 2024].

[33] Polysolar, Building integrated transparent photovoltaic glass. Available at: http://www.polysolar.co.uk/. [accessed September 2024].

[34] J.B. Yerima, et al., Modeling, Simulation and extraction of model parameters of dye-sensitized solar cells (DSSCs) using different single-diode models. Computational and experimental research, Mater. Renew. Energy 6 (1) (2023) 33–42.

[35] W. Peng, Y. Zeng, H. Gong, Y.Q. Leng, Y.H. Yan, W. Hu, Evolutionary algorithm and parameters extraction for dye-sensitised solar cells one-diode equivalent circuit model, Micro Nano Lett. 8 (2) (2013) 86–89.

[36] E. Saretta, P. Caputo, F. Frontini, A review study about energy renovation of building facades with BIPV in urban environment, Sustain. Cities Soc. 44 (2019) 343–355.

[37] P.K. Sahu, J.N. Roy, C. Chakraborty, Performance assessment of a bifacial PV system using a new energy estimation model, Sol. Energy 262 (2023) 111818.

[38] J. Carolus, J.A. Tsanakas, A. van der Heide, E. Voroshazi, W. De Ceuninck, M. Daenen, Physics of potential-induced degradation in bifacial p-PERC solar cells, Sol. Energy Mater. Sol. Cells 200 (2019) 109950.

[39] R. Guerrero-Lemus, R. Vega, Taehyeon Kim, Amy Kimm, L.E. Shephard, Bifacial solar photovoltaics – a technology review, Renew. Sustain. Energy Rev. 60 (2016), 1533-1549.

[40] E. Lorenzo, On the historical origins of bifacial PV modelling, Sol. Energy 218 (2021) 587–595.

[41] Pan AC, del Cañizo C, Luque A. Effect of thickness on bifacial silicon solar cells. In: Proceedings of the Spanish conference on electron devices, Madrid, Spain; 2007. pp. 234–7.

[42] N. Dwivedi, S. Kumar, A. Bisht, K. Patel, S. Sudhakar, Simulation approach for optimization of device structure and thickness of HIT solar cells to achieve 27% efficiency, Sol. Energy 88 (2013) 31–41.

[43] J.B. Pang, Y.A. Cai, Q. He, H. Wang, W.L. Jiang, J.J. He, T. Yu, W. Liu, Y. Zhang, Y. Sun, Preparation and Characteristics of MoSe2 Interlayer in Bifacial Cu(In, Ga) Se2 Solar Cells, Phys. Procedia 32 (2012) 372–378.

[44] J.B. Heng J. Fu, B. Kong, Y. Chae, W. Wang, Z. Xie, et al. >23.1% high efficiency tunnel oxide junction bifacial solar cell with electroplated Cu gridlines. In Proceedings of the 29th European photovoltaic solar energy conference, Amsterdam, The Netherlands; 2014, 492–6.

[45] M. Rüdiger, S. Fischer, J. Frank, A. Ivaturi, B.S. Richards, K.W. Krämer, M. Hermle, J.C. Goldschmidt, Bifacial n-type silicon solar cells for up-conversion applications, Sol. Energy Mater. Sol. Cells 128 (2014) 57–68.

[46] G. Raina, S. Sinha, A comprehensive assessment of electrical performance and mismatch losses in bifacial PV module under different front and rear side shading scenarios, Energ. Conver. Manage. 261 (2022) 115668.

[47] M.R. Khan, E. Sakr, X. Sun, P. Bermel, M.A. Alam, Ground sculpting to enhance energy yield of vertical bifacial solar farms, Appl. Energy 241 (2019) 592–598.

[48] J. Lopez-Garcia, A. Casado, T. Sample, Electrical performance of bifacial silicon PV modules under different indoor mounting configurations affecting the rear reflected irradiance, Sol. Energy 177 (2019) 471–482.

[49] U.A. Yusufoglu, T.M. Pletzer, L.J. Koduvelikulathu, C. Comparotto, R. Kopecek, H. Kurz, Analysis of the annual performance of bifacial modules and optimization methods, IEEE J. Photovolt. 5 (2015) 320–328.

[50] S.C. Ezike, J.B. Yerima, D. William, B. Alkali, A.D. Ahmed, Extraction of five photovoltaic parameters of nature-based dye-sensitized solar cells using single diode model, Renew. Energy Res. Appl. 4 (2) (2023) 199–208.

[51] L. Wang, X. Fang, Z. Zhang, Two-step precise determination of the parameters of the single-diode equivalent circuit model for dye-sensitized solar cells, Heat Transfer Eng. 35 (11–12) (2014) 1007–1013.

[52] A.M. Humada, M. Hojabri, S. Mekhilef, H.M. Hamada, Solar cell parameters extraction based on single and double-diode models: a review, Renew. Sustain. Energy Rev. 56 (2016) 494–509.

[53] R. Venkateswari, N. Rajasekar, Review on parameter estimation techniques of solar photovoltaic systems, Int. Trans. Electr. Energy Syst. 31 (11) (2021) e13113.

[54] A. Laudani, F.R. Fulginei, A. Salvini, Identification of the one-diode model for photovoltaic modules from datasheet values, Sol. Energy 108 (2014) 432–446.

[55] J.C. Blakesley, F.A. Castro, G. Koutsourakis, A. Laudani, G.M. Lozito, F. R. Fulginei, Towards non-destructive individual cell IV characteristic curve extraction from photovoltaic module measurements, Sol. Energy 202 (2020) 342–357.

[56] F. Corti, A. Laudani, G.M. Lozito, A. Reatti, Computationally efficient modeling of DC-DC converters for PV applications, Energies 13 (19) (2020) 5100.

[57] S. Shongwe, M. Hanif, Comparative analysis of different single-diode PV modeling methods, IEEE J. Photovoltaics 5 (3) (2015) 938–946.

[58] Y.C. Hsieh, L.R. Yu, T.C. Chang, W.C. Liu, T.H. Wu, C.S. Moo, Parameter identification of one-diode dynamic equivalent circuit model for photovoltaic panel, IEEE J. Photovoltaics 10 (1) (2019) 219–225.

[59] T.S. Iec, 60904-1-2 - Photovoltaic devices - Part 1–2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices, Techn. Specificat. Published 29 (2019) 01.

[60] M.A. Scarpulla, et al., CdTe-based thin film photovoltaics: recent advances, current challenges and future prospects, Sol. Energy Mater. Sol. Cells 255 (2023) 112289.

[61] D. Pokhrel, et al., Copper iodide nanoparticles as a hole transport layer to CdTe photovoltaics: 5.5 % efficient back-illuminated bifacial CdTe solar cells, Sol. Energy Mater. Sol. Cells 235 (2022) 111451.

[62] Ç. Çetinkaya, Efficient and high-bifacial CdTe-based solar cell enabled by functional designed dielectric/metal/dielectric transparent top contact via light management engineering, Opt. Mater. 133 (2022) 113003.

[63] C.P. Muzzillo, M.O. Reese, C. Lee, G. Xiong, Cracked film lithography with CuGaOx buffers for bifacial CdTe photovoltaics, Small 19 (2023) 2301939.

[64] S.C. Yang, T.Y. Lin, M. Ochoa, et al., Efficiency boost of bifacial Cu(In, Ga)Se2 thin-film solar cells for flexible and tandem applications with silver-assisted low-temperature process, Nat. Energy 8 (2023) 40–51.

[65] A.F. Violas, A.J.N. Oliveira, P.A. Fernandes, P.M.P. Salomé, J.P. Teixeira, CIGS bifacial solar cells with novel rear architectures: simulation point of view and the creation of a digital twin, Sol. Energy Mater. Sol. Cells 272 (2024) 112899.

[66] P.K. Sahu, E.I. Batzelis, J.N. Roy, C. Chakraborty, Irradiance Effect on the Bifaciality Factors of Bifacial PV Modules. In 2022 IEEE 1st Industrial Electronics Society Annual On-Line Conference (ONCON) (December 2022), 1-6.

[67] P.K. Sahu, J.N. Roy, C. Chakraborty, S. Sundaram, A new model for estimation of energy extraction from bifacial photovoltaic modules, Energies 14 (16) (2021) 5089.

[68] K. Phimu, K.J. Singh, R. Sankar Dhar, Novel SPICE Model for bifacial solar cell to increase the renewable power generation,“ Devices for Integrated Circuit (DevIC), Kalyani, India 2021 (2021) 129–133.

[69] B. Durusoy, T. Ozden, B.G. Akinoglu, Solar irradiation on the rear surface of bifacial solar modules: a modeling approach, Sci. Rep. 10 (1) (2020) 13300.

[70] K. Dasgupta, A. Mondal, U. Gangopadhyay, Mathematical modelling of bifacial dual SIS solar cell and optimization of tilt angle, SILICON 14 (14) (2022) 8721–8731.

[71] A. Čampa, A. Valla, K. Brecl, F. Smole, D. Munoz, M. Topič, Multiscale modeling and back contact design of bifacial silicon heterojunction solar cells, IEEE J. Photovoltaics 8 (1) (2017) 89–95.

[72] J. Wong, S. Raj, J.W. Ho, J. Wang, J. Lin, Voltage loss analysis for bifacial silicon solar cells: Case for two-dimensional large-area modeling, IEEE J. Photovoltaics 6 (6) (2016) 1421–1426.

[73] S. Bouchakour, D. Valencia-Caballero, A. Luna, E. Roman, E.A.K. Boudjelthia, P. Rodríguez, Modelling and simulation of bifacial PV production using monofacial electrical models, Energies 14 (14) (2021) 4224.

[74] W. Gu, T. Ma, M. Li, L. Shen, Y. Zhang, A coupled optical-electrical-thermal model of the bifacial photovoltaic module, Appl. Energy 258 (2020) 114075.

[75] A. Abotaleb, A. Abdallah, Performance of bifacial-silicon heterojunction modules under desert environment, Renew. Energy 127 (2018) 94–101.

[76] J.P. Singh, A.G. Aberle, T.M. Walsh, Electrical characterization method for bifacial photovoltaic modules, Sol. Energy Mater. Sol. Cells 127 (2014) 136–142.

[77] S. Vergura, Simulink model of a bifacial PV module based on the manufacturer datasheet, Renew. Energy Power Quality J. 18 (456) (2020) 637–664.

[78] I. Shoukry, J. Libal, R. Kopecek, E. Wefringhaus, J. Werner, Modelling of bifacial gain for stand-alone and in-field installed bifacial PV modules, Energy Procedia 92 (2016) 600–608.

[79] H.L. Cha, B.G. Bhang, S.Y. Park, J.H. Choi, H.K. Ahn, Power Prediction of Bifacial Si PV Module with Different Reflection Conditions on Rooftop, Appl. Sci. 8 (2018) 1752.

[80] D. Riley et al., A Performance Model for Bifacial PV Modules,“ 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 2017, 3348-3353.

[81] B. Marion et al., A Practical Irradiance Model for Bifacial PV Modules, 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 2017, pp. 1537-1542.

[82] W. Gu, T. Ma, S. Ahmed, Y. Zhang, J. Peng, A comprehensive review and outlook of bifacial photovoltaic (bPV) technology, Energ. Conver. Manage. 223 (2020) 113283.

[83] C. W. Hansen et al., Analysis of irradiance models for bifacial PV modules, 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 2016, 0138-0143.

[84] A. Asgharzadeh, M. Abou Anoma, A. Hoffman, C. Chaudhari, S. Bapat, R. Perkins, D. Cohen, G.M. Kimball, D. Riley, F. Toor, et al., A benchmark and validation of bifacial PV irradiance models, in: 2019 IEEE 46th Photovoltaic Specialists Conference, PVSC, IEEE, 2019, 3281–3287.

[85] S.M. Moreno-Buesa, E. Muñoz-Cerón, G. Nofuentes Garrido, S. Gulkowski, J. de la Casa Higueras, J. Aguilera Tejero, Characterization of bifacial technology PV systems. Proceedings of the Institution of Mechanical Engineers, Part A: J. Power Energy 0(0) (2024).

[86] S. P. Aly, J. J. John, G. Mathiak, O. Albadwawi, L. Pomares and V. Alberts, A thermal model for bifacial PV panels, 2022 IEEE 49th Photovoltaics Specialists Conference (PVSC), Philadelphia, PA, USA, 2022, 0457-0459.

[87] E.M. Tonita, C.E. Valdivia, A.C.J. Russell, M. Martinez-Szewczyk, M.I. Bertoni, K. Hinzer, A general illumination method to predict bifacial photovoltaic system performance, Joule 7 (1) (2023) 5–12.

[88] M. Leonardi, R. Corso, R.G. Milazzo, C. Connelli, M. Foti, C. Gerardi, F. Bizzarri, S.M.S. Privitera, S.A. Lombardo, The effects of module temperature on the energy yield of bifacial photovoltaics: data and model, Energies 15 (1) (2022) 22.

[89] B. Rasheed, A. Safdar, M. Sajid, S. Ali, Y. Ayaz, Assessment of solar load models for bifacial PV panels, Front. Energy Res. 10 (2022) 1019595.

[90] S. Aneli, R. Arena, G.M. Tina, A. Gagliano, Assessment of thermal behaviour of bifacial ventilated photovoltaic facades through both fluid dynamic and experimental analyses. Available at SSRN: https://ssrn.com/abstract=4690709 or Doi: 10.2139/ssrn.4690709.

[91] G.M. Tina, F. Bontempo Scavo, S. Aneli, A. Gagliano, Assessment of the electrical and thermal performances of building integrated bifacial photovoltaic modules, J. Clean. Prod. 313 (2021) 127906.

[92] F. Johansson, B.E. Gustafsson, B. Stridh, P.E. Campana, 3D-thermal modelling of a bifacial agrivoltaic system: a photovoltaic module perspective, Energy Nexus 5 (2022) 100052.

[93] O. Hachana, B. Aoufi, G.M. Tina, M.A. Sid, Photovoltaic mono and bifacial module/string electrical model parameters identification and validation based on a new differential evolution bee colony optimizer, Energ. Conver. Manage. 248 (2021) 114667.

[94] E. Mouhib, L. Micheli, F.M. Almonacid, E.F. Fernández, Overview of the fundamentals and applications of bifacial photovoltaic technology: agrivoltaics and aquavoltaics, Energies 15 (2022) 8777.

[95] S. Armstrong, W.G. Hurley, A thermal model for photovoltaic panels under varying atmospheric conditions, Appl. Therm. Eng. 30 (11–12) (2010) 1488–1495.

[96] B. Wang, S. Jiang, Z. Tan, Thermal model of bifacial silicon photovoltaic modules with different backsheets under outdoor conditions, Int. J. Green Energy 20 (7) (2023) 691–700.

[97] M. Debbarma, K. Sudhakar, P. Baredar, Thermal modeling, exergy analysis, performance of BIPV and BIPVT: a review, Renew. Sustain. Energy Rev. 73 (2017) 1276–1288.

[98] J. Frank, M. Rüdiger, S. Fischer, J.C. Goldschmidt, M. Hermle, Optical simulation of bifacial solar cells, Energy Procedia 27 (2012) 300–305.

[99] J.E. Goncalves, T. van Hooff, D. Saelens, A physics-based high-resolution BIPV model for building performance simulations, Sol. Energy 204 (2020) 585–599.

[100] K. Jäger, P. Tillmann, C. Becker, Detailed illumination model for bifacial solar cells, Opt. Express 28 (4) (2020) 4751–4762.

[101] N. Martín-Chivelet, J. Polo, C. Sanz-Saiz, L.T. Núñez Benítez, M. Alonso-Abella, J. Cuenca, Assessment of PV module temperature models for building-integrated photovoltaics (BIPV), Sustainability 14 (3) (2022) 1500.

[102] F. Nicoletti, M.A. Cucumo, N. Arcuri, Building-integrated photovoltaics (BIPV): A mathematical approach to evaluate the electrical production of solar PV blinds, Energy 263 (2023) 126030.

[103] L. Stamenic, E. Smiley, K. Karim, Low light conditions modelling for building integrated photovoltaic (BIPV) systems, Sol. Energy 77 (1) (2004) 37–45.

[104] L. Walker, J. Hofer, A. Schlueter, High-resolution, parametric BIPV and electrical systems modeling and design, Appl. Energy 238 (2019) 164–179.

[105] M. Hsian Saw, Y.S. Khoo, J.P. Singh, Y. Wang, Enhancing optical performance of bifacial PV modules, Energy Procedia 124 (2017) 484–494.

[106] G. Raina, S. Sinha, A simulation study to evaluate and compare monofacial Vs bifacial PERC PV cells and the effect of albedo on bifacial performance, Mater. Today. Proc. 46 (11) (2021) 5242–5247.

[107] J.C. Blakesley, G. Koutsourakis, D.E. Parsons, N.A. Mica, S. Balasubramanyam, M. G. Russell, Sourcing albedo data for bifacial PV systems in complex landscapes, Sol. Energy 266 (2023) 112144.

[108] M.H. Shahverdian, H. Sayyaadi, A. Sohani, An optical-based comparative study to detect best configurations for installation of monofacial and bifacial PV technologies, Sol. Energy 266 (2023) 112184.

[109] V. Durković, Ž. Đurišić, Extended model for irradiation suitable for large bifacial PV power plants, Sol. Energy 191 (2019) 272–290.

[110] C. Ghenai, F. Faraz Ahmad, O. Rejeb, M. Bettayeb, Artificial neural networks for power output forecasting from bifacial solar PV system with enhanced building roof surface Albedo, J. Build. Eng. 56 (2022) 104799.

[111] E. Ortega, S. Suarez, J.C. Jimeno, J. Rubén Gutierrez, V. Fano, A. Otaegi, J. M. Rivas, G. Navas, I. Fernandez, S. Rodriguez-Conde, An statistical model for the short-term albedo estimation applied to PV bifacial modules, Renew. Energy 221 (2024) 119777.

[112] G. Raina, S. Sinha, Experimental investigations of front and rear side soiling on bifacial PV module under different installations and environmental conditions, Energy Sustain. Dev. 72 (2023) 301–313.

[113] S. Xu, C. Li, W. He, W. Chu, Z. Hu, B. Lu, Experimental study of bifacial photovoltaic wall system incorporating thermochromic material, Sustain. Cities Soc. 106 (2024) 105372.

[114] M. Chen, W. Zhang, L. Xie, B. He, W. Wang, J. Li, Z. Li, Improvement of the electricity performance of bifacial PV module applied on the building envelope, Energ. Buildings 238 (2021) 110849.

[115] D. Murillo-Yarce, J. Alarcón-Alarcón, M. Rivera, C. Restrepo, J. Muñoz, C. Baier, P. Wheeler, A review of control techniques in photovoltaic systems, Sustainability 12 (24) (2020) 10598.

[116] C. Bordons, F. Garcia-Torres, M. Ridao, Model Predictive Control of Microgrids, Springer International Publishing, Cham, Germany, 2020.

[117] J. Drgoňa, et al., All you need to know about model predictive control for buildings, Annu. Rev. Control. 50 (2020) 190–232.

[118] J. Rawlings, D. Mayne, M. Diehl, Model Predictive Control: Theory, Computation, and Design, (2nd ed.)., Nob Hill Publishing, Madison, WI, USA, 2017.

[119] B. Kouvaritakis, M. Cannon, Model Predictive Control: Classical, Robust and Stochastic, Springer International Publishing, Cham, Germany, 2016.

[120] A basic working principle of Model Predictive Control. Available at:https://en.wikipedia.org/wiki/Model_predictive_control, [accessed September 2024].

[121] Z.G. Liu, Z. Guo, Q. Chen, C. Song, W. Shang, M. Yuan, H. Zhang, A review of data-driven smart building-integrated photovoltaic systems: Challenges and objectives, Energy 263E (2023) 126082.

[122] G.Q. Xinxin, S. Qi, Z. Mingfeng, Z. Qi, L. Shuangshou, L. Weiran, Operation optimization strategy of a BIPV-battery storage hybrid system, Result. Eng. 18 (2023) 101066.

[123] D. Aelenie, R.A. Lopes, L. Aelenei, H. Gonçalves, Investigating the potential for energy flexibility in an office building with a vertical BIPV and a PV roof system, Renew. Energy 137 (2019) 189–197.

[124] A.K. Athienitis, J. Bambara, B. O'Neill, J. Faille, A prototype photovoltaic/thermal system integrated with transpired collector, Sol. Energy 85 (1) (2011) 139–153.

[125] P.V. Wouters, Development of procedures for overall performance evaluation of hybrid photovoltaic building components, PV-Hybrid-PAS Final Report (1998).

[126] S. Li, J. Joe, J. Hu, P. Karava, System identification and model-predictive control of office buildings with integrated photovoltaic-thermal collectors, radiant floor heating and active thermal storage, Sol. Energy 113 (2015) 139–157.

[127] J.A. Candanedo, A.K. Athienitis, Simplified linear models for predictive control of advanced solar homes with passive and active thermal storage. International High Performance Buildings Conference at Purdue (2010),1-8. West Lafayette, Indiana, USA.

[128] A.M. Sigounis, C. Vallianos, A. Athienitis, Model predictive control of air-based building integrated PV/T systems for optimal HVAC integration, Renew. Energy 212 (2023) 655–668.

[129] J.A. Candanedo, A. Athienitis, Application of predictive control strategies in a net zero energy solar house. proc. 26th Conference on Passive and Low Energy Architecture (PLEA) (2009), 1-6. Quebec City, Canada.

[130] M. Fotopoulou, P. Drosatos, S. Petridis, D. Rakopoulos, F. Stergiopoulos, N. M. Nikolopoulos, Predictive control for the energy management in a district of buildings equipped with building integrated photovoltaic systems and batteries, Energies 14 (2021) 3369.

[131] Y. Zhou, S. Cao, J. Hensen, A. Hasan, Heuristic battery-protective strategy for energy management of an interactive renewables–buildings–vehicles energy sharing network with high energy flexibility, Energ. Conver. Manage. 214 (2020) 112891.

[132] M. Lovati, X. Zhang, Impact of electrical vehicle (EV) penetration on the cost-optimal building integrated photovoltaics (BIPV) at a small residential district in Sweden, IOP Conf. Ser.: Mater. Sci. Eng. 609 (2019) 072066.

[133] H. Wang, K. Meng, Z. Y. Dong, Z. Xu, F. Luo, K. P. Wong, A MILP Approach to Accommodate More Building Integrated Photovoltaic System in Distribution Network. IEEE Power & Energy Society General Meeting (2015),1-5. Denver, CO, USA.

[134] M. Sechilariu, B. Wang, F. Locment, Building integrated photovoltaic system with energy storage and smart grid communication, IEEE Trans. Ind. Electron. 60 (4) (2012) 1607–1618.