CLASSIFICATION OF PHOTOVOLTAICS IN BUILDINGS (BAPV AND BIPV): ILLUSTRATED WITH ZERO-ENERGY HOUSES

EDWIN RODRIGUEZ-UBINAS, ESRA TREPC & NOURA ALHAMMADI
Dubai Electricity and Water Authority, DEWA R&D Centre, United Arab Emirates

ABSTRACT

Zero-energy buildings are one of the most effective decarbonization strategies for cities. They are highly efficient buildings that can generate enough energy to meet their demand using renewables. Photovoltaics (PV) is a cost-effective way of generating renewable energy in buildings. Additionally, PV modules can be more than generation systems and be an essential part of the buildings, contributing to their appearance, thermal performance, and daylight harvesting. New policies and regulations around the world encourage the use of PV and bring more flexibility for their integration in buildings. Therefore, it is fundamental for regulators, researchers, and building professionals, to have a comprehensive PV in buildings categorization. As a response, the objective of this work was to develop a classification for building attached photovoltaics (BAPV) and building integrated photovoltaics (BIPV). The classifications resulted from an extensive literature review that helped to identify relevant aspects, criteria, and gaps in previous categorizations. It considers the application type, location, opacity, accessibility from the inside, and heat dissipation (a missing parameter in prior works). After summarizing the existing categories, describing the findings, and explaining the proposed classifications, the authors illustrated them using zero-energy houses.

Keywords: photovoltaics, photovoltaics ventilation, BAPV, BIPV, zero-energy buildings, solar decathlon.

1 INTRODUCTION

One of the most effective strategies to make our cities greener is implementing zero-energy buildings (ZEB) [1]. These buildings can generate enough energy to cover their demand using renewable energy sources [2]. Most ZEBs around the world generate their energy from photovoltaic (PV) systems, a solution for energy generation that has been used in buildings since the 1970s [3]. However, PV modules can be more than just energy generators attached to buildings. They can also be multifunctional elements seamlessly integrated into the architectural design. The Wohnanlage Richter residential complex in Munich, Germany designed in 1982 with polycrystalline cells on its curtain walls, is considered the first case of PVs integrated into the building design [4]. More recently, policies and regulations around the world encourage using PV in buildings and facilitate their integration. Consequently, it is fundamental to have a comprehensive classification of PV in buildings that considers all the relevant aspects of their applications and integration.

The most common differentiation between PV installation in buildings is related to their integration or not the building. A building attached photovoltaic (BAPV) is a solution in which the PV modules are superimposed or attached over already built building surfaces, having electricity production as the only or primary objective. On the other hand, building integrated photovoltaic (BIPV) technologies comprise multifunctional elements that, in addition to electricity generation, replace conventional building materials and construction elements on the roofs, walls, glazing, and sun control systems [5]–[7]. Several categorizations have been published in the last decade, utilizing different criteria and primarily focused on BIPV solutions. In most of them, the common criterion is the solution location (roof, wall, and exterior elements). In addition, BIPV systems have been categorized

WIT Transactions on Ecology and the Environment, Vol 260,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SC220041

by the type of BIPV products [8], [9]; by the type of systems and the way of integration into the building envelope [10]; and by their accessibility or not from the building interior, as the BIPV categories given in the standard EN 50583 [11]. Experts from the IEA Photovoltaic Power Systems Programme (PVPS) have valuably contributed to PV in buildings and recently published a BIPV categorization [12]. Additionally, researchers from the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) also conducted an influential categorization of BIPV categories has also been done by Frontini et al. [13].

Even though previous classifications consider several aspects of PV and their relationship with buildings, there is a need for a more comprehensive classification. Most of the classification efforts have been focused on the BIPV, and some essential aspects of the PV performance, such as the modules ventilation, are not part of the more complete categorizations. Therefore, the objective of this work was to develop a comprehensive classification for both BAPV and BIPV, considering the used criteria, strengths, and gaps in previous categorizations. The parameters of the proposed classification include the application type, location, opacity, accessibility from the inside, and ventilation. The relevance of ventilation in the performance of PV has been documented in the literature. However, even the most detailed classifications do not include ventilation or heat dissipation.

The remainder of this article is organized as follows: Section 2 explains the methodology, Section 3 summarizes the literature review, Section 4 describes the proposed classification, Section 5 illustrates the classification using zero-energy houses, and finally, Section 6 presents the conclusions.

2 METHODOLOGY

To provide a comprehensive categorization of PV in buildings that can be useful for regulators, researchers, manufacturers, and building professionals, the authors first established the research's topics and limits. Then, they carried out an in-depth literature review, analyzing the results and extracting the most relevant findings, as shown in Fig. 1.

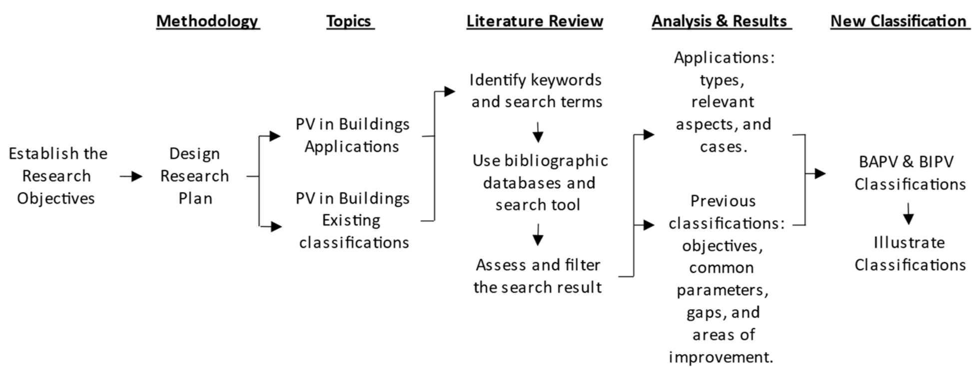

Figure 1: Methodology chart.

The studied topics and the resulting classifications included both BAPV and BIPV solutions. The literature review phase included the search for different ways to install PV in buildings and the existing PV in buildings categorizations. This phase had three parts, the keywords selections, the search in bibliographic databases, and the assessment and filtering of the results. These results were the base for analyzing types and relevant aspects of PV in building applications, as well as the strengths and opportunities for improvement of previous classifications. Finally, the authors developed the BAPV and BIPV classifications, applying the lessons learned from the literature.

3 LITERATURE REVIEW OF EXISTING CLASSIFICATIONS

Various classifications can be found in literature, which vary on purpose (e.g., market, research) or criteria (e.g., technology, spatial relationship with the buildings). This section introduces BAPV and BIPV solutions and summarizes the literature review of the most completed classification systems of PVs in buildings based on three criteria: electrotechnical, construction, and architectural design (aesthetics or visuals).

Conventional photovoltaics superimposed or attached over already built building surfaces with the only o primary purpose of energy generation are referred to as building applied photovoltaic (BAPV) or building attached photovoltaics [14]–[16]. While photovoltaics that, in addition to the energy generation, also serve as a building envelope element or an external component, meaning they are part of the building architectural design, are referred to as BIPV [12], [13].

Overall, BIPVs have more advantages than BAPVs. They can benefit in different areas such as energy conservation, material use, building function and aesthetics. However, in some cases, the tightness of the building envelope can be affected by the BIPV elements. Additionally, the durability of the BIPV system can be reduced since they do not perform in an autonomous mode but in coupled mode with other building envelope materials might lead to less longevity for this system [17].

3.1 Classifications based on construction and electrotechnical criteria

Moving further into more detailed based classifications, one of the most comprehensive classifications of PVs in buildings is proposed by the International Energy Agency (IEA) [12] as a part of their aim to help accelerate the penetration of BIPV products in the global market of renewables, giving them an equal playing field with BAPVs and other building envelope elements. These classification systems, created as a hierarchical classification approach based on a combination of two classification criteria, have five levels that go from the building to the PV cell scale, as Table 1 shows.

Table 1: IEA BIPV classification [12].

Criteria	Level	Parameters
Construction	I. Application	Integration, accessibility, and slope
	II. System	Location (roof, façade, external element)
Electrotechnical	III. Module	Transparency, planarity, mechanical rigidity, size, thermal insulation, and customization
	IV. Component	Module component (front cover, encapsulant, solar cells, back cover, frame, and edge sealing
	V. Material	Type of material of the module components

I. Application

The application level is based on the first international standard for BIPV, the ISO EN 50583 [11]. This standard sets health and safety protection requirements for PVs in buildings as both electrotechnical and construction components. This classification is presented as a reference for the requirements of PV that contain glass (considered as construction components in buildings), where the requirements vary based on the type of PV mounting system. Depending on where the PVs are integrated into the building; whether they are accessible or not; and whether they are sloped or not, there can be five mounting categories according to EN 50583 [11]:

- Category A: Slopped, roof-integrated, not accessible from within the buildings.
- Category B: Slopped, roof-integrated, accessible from within the buildings.
- Category C: Non-sloped (vertically) mounted not accessible from within the building.
- Category D: Non-sloped (vertically) mounted accessible from within the building.
- Category E: Externally integrated, accessible, or not from within the buildings.

II. System

The BIPV systems as a building envelope element have three groups: roof, façade, and external integrated devices. Each of them matched the EN 50583 application categories. For example, the roofs match categories A and B, the façades to C and D, and the external integrated devices to E. The groups can be further subdivided, as indicated below [12].

- Façade: rainscreen façade, double skin façade, curtain wall, window, masonry wall.
- Roof: discontinuous roofing, continuous roofing, atrium/skylight.
- External integrated device: parapet, balustrade, canopy, solar shading.

III. Module

The modules classification follows the below criteria [12]:

- Transparency: opaque, translucent, semi-translucent, transparent, or semi-transparent.
- Planarity: flat or curved.
- Mechanical rigidity: flexible or rigid.
- Size: large, shingle (slate or tile), or regular.
- Thermal insulation: insulated or non-insulated.
- Standardization: standard or customized.

IV. Component

Typical PV modules have many components, such as interconnected solar cells encapsulated by a polymer (encapsulant) and covered on the front by a protective layer (glass or a polymer sheet) and at the rear cover layer (glass, a polymer sheet, or singular construction material) [12]. Additionally, they have metallic wires/ribbons to conduct the electricity, which are connected to a junction box installed outside the module. Finally, the frame (usually aluminium) is an optional component that provides additional structural support and is instrumental in the module’s mounting.

V. Material

The material of the PV modules component can be [12]:

- Front cover: low iron float glass or tempered glass, Polymeric front sheets.
- Encapsulant: poly (ethylene-co-vinyl acetate) (EVA), polyvinyl butyral (PVB), polyolefin (PO), ionomers; silicones (curing and non-curing systems).

- Active material/solar cells: crystalline silicon; mono-crystalline Si or polycrystalline Si; thin-film solar cells: CdTe, CIGS, CIS, a-SI, organic molecules, perovskites.
- Back cover: glass panes, construction material panels, polymer materials.
- Frame and edge sealing: aluminium, polysiloxane, polyisobutylene.

There are two other less comprehensive classifications but equally relevant. The first of these classifications is focused on the market and product segmentation in BIPV [13]. This classification includes available systems, prices, applications, and technologies (crystalline, crystalline thin film, thin film, and custom-made). The second and more recent also related to the BIPV market [3], and based on the primary material used as cladding's outer layer, the transparency, and the level of thermal protection, distinguishes the following three typologies: Glazed semi-transparent BIPV solution (with thermal properties), Opaque glazed BIPV solution (without thermal protection), and Opaque no glazed BIPV solution (without thermal protection).

3.2 Classification based on visual criteria

Photovoltaics (PV) visual dimension, or how they are perceived, is crucial for the social acceptability of this technology [18], and although it is difficult to assess objectively, some classifications are based on this dimension. For example, Cronemberger et al. proposed a novel classification of PV in buildings based on their appearance. They named this classification "Architectural Design Approach". Its subcategories are invisible (out of the sight of the people), added (visible – performing a specific function), highlighted (to enhance the image of the building), and leading (preponderant – determining building image) [19].

More recently, an attempt has been made to assess it through a descriptive model based on visual parameters, describing PVs as visual objects, no matter the materials and technologies used [18]. The authors of this classification identified a set of visual performance objectives and translated them into visual and technological requirements. This classification aims to facilitate dialogue among different stakeholders, offering an objective comparison. The classification has three scales: coarse (building envelope application and systems), medium (PV modules and framing system), and fine (PV module components and materials). To each of the three scales mentioned previously, they applied three visual terms pattern, patch, and matrix, as Table 2 shows. Finally, the assessment of all these visual terms can be qualitative or quantitative. Qualitative assessments refer to a colour as red and a size as small. In contrast, quantitative assessments refer to the colour in terms of RGB and the size in terms of cm.

3.3 PV in buildings: heat dissipation

The operating temperature is critical in the photovoltaic conversion process, affecting the modules' efficiency and power output. That is even more crucial in PV in buildings due to the lack of proper cooling from the poorly ventilated rear side [20]. In addition to the ventilation, PV modules' heat dissipation can be improved using PV thermal hybrid systems (BAPV/T or BAPV/T) [21]. These systems can be water, air, or phase change material based.

Researchers in Ljubljana (Slovenia), a city with high temperatures in the warmest months ranging between 25°C and 30°C, conducted outdoor experimental research to evaluate the PV modules' ventilation effect on their temperature. They found that the temperature of the (unventilated) roof integrated PV modules was 21.8°C higher than those installed in an open rack with an instantaneous plane-of-array irradiance equal to 1000 W/m^2 [22].

Table 2: Visual classification – Pattern–patch–matrix model [11], [12], [18].

Visual scale	Terms	Description	Defined by
Coarse, medium, and, fine	Pattern	A specific arrangement of spatial elements, often referred to as spatial structure or patch structure.	Geometry; density
	Patch	Surface area that differs from its surroundings in nature or appearance.	Size; shape; position; border; colour; transparency; texture
	Matrix	Background cover type in a landscape, with an extensive cover and high connectivity (not all landscapes have a definable matrix).	Transparency; colour

A study investigated the effect that the variation between cell temperature and ambient temperature has on the performance of unventilated BIPV, and open rack mounted PV placed on a roof in the south of Greece [23]. This study resulted in an efficiency power coefficient of $-0.30\%°C^{-1}$ for the ventilated free-standing PVs and a coefficient of $-0.45\%°C^{-1}$ for the unventilated ones, reaching the conclusion that the difference between cell and ambient temperature decreases with increasing wind speed, and it highlights the critical role of adopting cooling measures in cases of high temperatures and unventilated modules.

A more recent experimental work in South Africa compared open-rack mounted PV modules with others installed on a sloped roof with gaps of 50 mm, 100 mm, and 150 mm. Its results reflect that in the cases, the heat dissipation factors of the open-racked modules were higher than those installed on the roof. For example, at a 15° tilt angle, the heat dissipation factor of the open-racked were 30.91 W/m^2K and 3.65 Ws/m^3K, and the ones on the roof were 24.41–24.58 W/m^2K and 3.67–5.10 Ws/m^3K [24].

3.4 Findings and reflexions

There are many categorizations of PV in buildings in the literature. Some are very detailed, going from the systems to the component levels. Likewise, research groups and international platforms are working actively to share the potentiality of PV in the built environment and have been involved in developing the different categorizations. However, the classification efforts have focused on BIPV modules and systems, leaving aside the BAPV possibilities, even those intended to reduce the negative effect on the building's appearance.

Also, heat dissipation, an essential aspect of PV performance, is not included in the current classifications. Similarly, PV thermal hybrid systems are not included in the more comprehensive categorizations. Furthermore, the authors found that it is crucial to have easily expandable classifications, to accommodate other concerns (aesthetics, for example) or to address different stakeholders' needs.

4 PROPOSED PV IN BUILDINGS CLASSIFICATION

The proposed classification system initially has five fields or categories: type, location, opacity, heat dissipation, and accessibility. Table 3 presents the potential subcategories for each of these fields. However, the classification is flexible enough to permit the addition of new fields and subcategories. For example, to have a complete description of the solution, including its visual and aesthetic values, a sixth and seventh field can be added to describe the architectural approach and the visual classification.

Table 3: Options for each classification field and their identification codes.

Field 1 **Type**	Field 2 **Location**	Field 3 **Opacity**	Field 4 **Heat dissipation**	Field 5 **Accessibility**
BA: **BA**PV **BI**: **BI**PV	**Rf**: **R**oof **f**lat **Rt**: **R**oof **t**ilted **Rc**: **R**oof **c**urved **Wa**: **Wa**ll **Wc**: **C**urtain **w**all **Wd**: **D**ouble skin **Co**: **Co**ntinuous[2] **Es**: **E**xt. **s**hading **Eg**: **E**xt. **g**uardrail **Ep**: **E**xt. **p**orch **Ea**: **E**xt. **a**trium **Ef**: **E**xt. **f**loor **Ed**: **E**xt. **d**etached structure	**Op**: **Op**aque **Os**: Semi**O**paque[1] **Tr**: **Tr**anslucent	**Vf**: **V**entilation **F**ree (non-restricted) **Vr**: **V**entilation **r**estricted **Vn**: **V**entilation **N**o **Vi**: **V**entilation towards an **I**nterior space **Tw**: **T**hermal using **w**ater **Ta**: **T**hermal using **a**ir **Tp**: **T**hermal using **P**CM	**An**: **N**on-**a**ccessible from within the interior **Ai**: **Ac**cessible from within the interior **Ae**: **A**ccessible **e**xterior elements

[1] Refer to opaque modules separate to let pass the light, encapsulated in translucent cover and back panels.
[2] Refer to continuous architectural envelopes with non-discontinuities between walls and roofs.

This paper focused on the initial five fields. The first refers to the main categorization of PVs in buildings, BAPV and BIPV. The location is the second field, and its options are the roof, wall, continuous envelopes, and exterior elements. The continuous envelopes are contemporary architectural solutions in which there is a differentiation between the façades and the roof finishing; the envelope of the façade continues and covers the top of the building. Opacity level constitutes the third field and initially has three options, opaque, semi-opaque and translucent. In terms of the heat dissipation field, there are several potential options, going further than a simple distinction of ventilated or not. There is a distinction between free (non-restricted) ventilation, restricted ventilation, and ventilation towards the interior space – the latest for PVs that have direct contact with the inner space of the building. In the case of BAPV/T and BIPV/T, it must be specified if the system extracts the heat of the modules using water, air, or PCM. Lastly, the accessibility field adopts the accessibility options from the EN 50583 standard [11], where the "An" option will correspond to categories A (roof) and C (walls), "Ai" will correspond to categories B (roof) and D (walls), and the "Ae" to the category E.

The classification name follows the order of the fields, and each subcategory is identified by two letters. For example, **BA_RfOpVr_An** corresponds to PV modules **attached** to a flat **roof, opaque**, with **limited** (restricted) **ventilation,** and **non-accessible** from within the interior. The following sections will detail the potential options for each field, starting from the first filed distinction between BAPVs and BIPVs.

4.1 BAPV classification

As mentioned previously, the primary purpose of BAPV solutions is to generate electricity. Typically, they are installed on rooftops but can also be on walls.

BAPV categories are defined by the options selected in each field. The options for the second field, "Location", are roof and wall. In terms of opacity, considering that the primary purpose of generating energy, usually the modules are opaque. Moving on to the fourth field, generally, BAPVs are ventilated. However, this ventilation can be free (non-restricted) or restricted. Lastly, in terms of accessibility, these systems are not accessible from within the interior space. Fig. 2 illustrates the potential classifications of BAPV solutions.

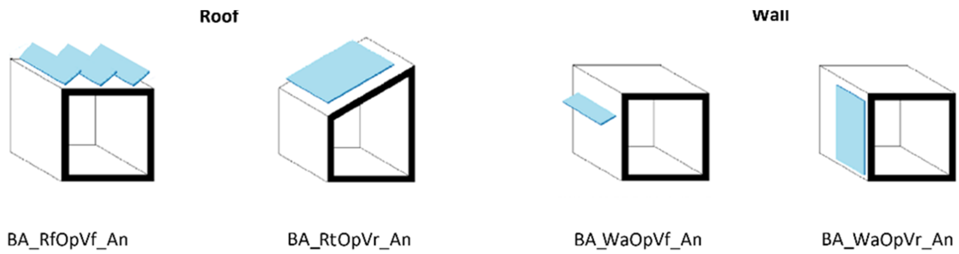

Figure 2: BAPV classification. The roof classifications apply to flat, tilted, and curved roofs.

PV modules in BAPV solutions can be installed, taking or not into account the appearance of the buildings. If the goal is to produce as much energy as possible, the appearance of the building is not relevant. Therefore, the modules are installed with the best possible azimuth and tilt angle without considering the installation's look and giving the modules free ventilation (Fig. 2(a) and (c)). However, if there is a secondary goal of reducing the impact of the building aesthetic, the PV modules are fitted close to the building envelope, parallel to the roof or walls surfaces (Fig. 2(b) and (d)).

4.2 BIPV classification

Starting from the second field, BIPVs can replace construction elements on roofs, walls, continuous envelopes, and building exterior elements. Therefore, there are more options for BIPV. In terms of opacity, unlike the BAPV, they can be either opaque, semi-opaque or translucent. In addition, they can be directly integrated into the building envelope, constituting ventilated façades or roofs, defining spaces, or bringing protection.

The fourth field, the level of ventilation, varies according to the location, mounting systems, and way of integration. All ventilation options apply to BAPVs: free ventilation, non-ventilated, restricted ventilation, and ventilation towards an interior space. Similarly, in terms of accessibility, all three options apply to BIPVs: non-accessible form within the interior, accessible form within the interior, and accessible exterior elements. Fig. 3 shows the potential classifications for BAPV.

5 CLASSIFICATIONS ILLUSTRATE USING ZERO-ENERGY BUILDINGS

The authors selected the zero-energy houses of the Solar Decathlon Middle East (SDME) 2018 to illustrate the application of the proposed classification. Solar Decathlon Middle East [25] is an international competition organized by Dubai Electricity and Water Authority (DEWA) under an agreement with the Dubai Supreme Council of Energy and the US Department of Energy. It challenges university students to design, build and operate sustainable zero-energy houses. This competition is created to demonstrate innovation in design and technology for potential zero-energy buildings (ZEBs) in the region [25]. In the 2018 edition, fifteen teams representing countries and universities reached the final phase of the competition. All the houses have PV on their roofs. In addition, some of them integrate PV elements as opaque and transparent components, as Figs 4 and 5 show.

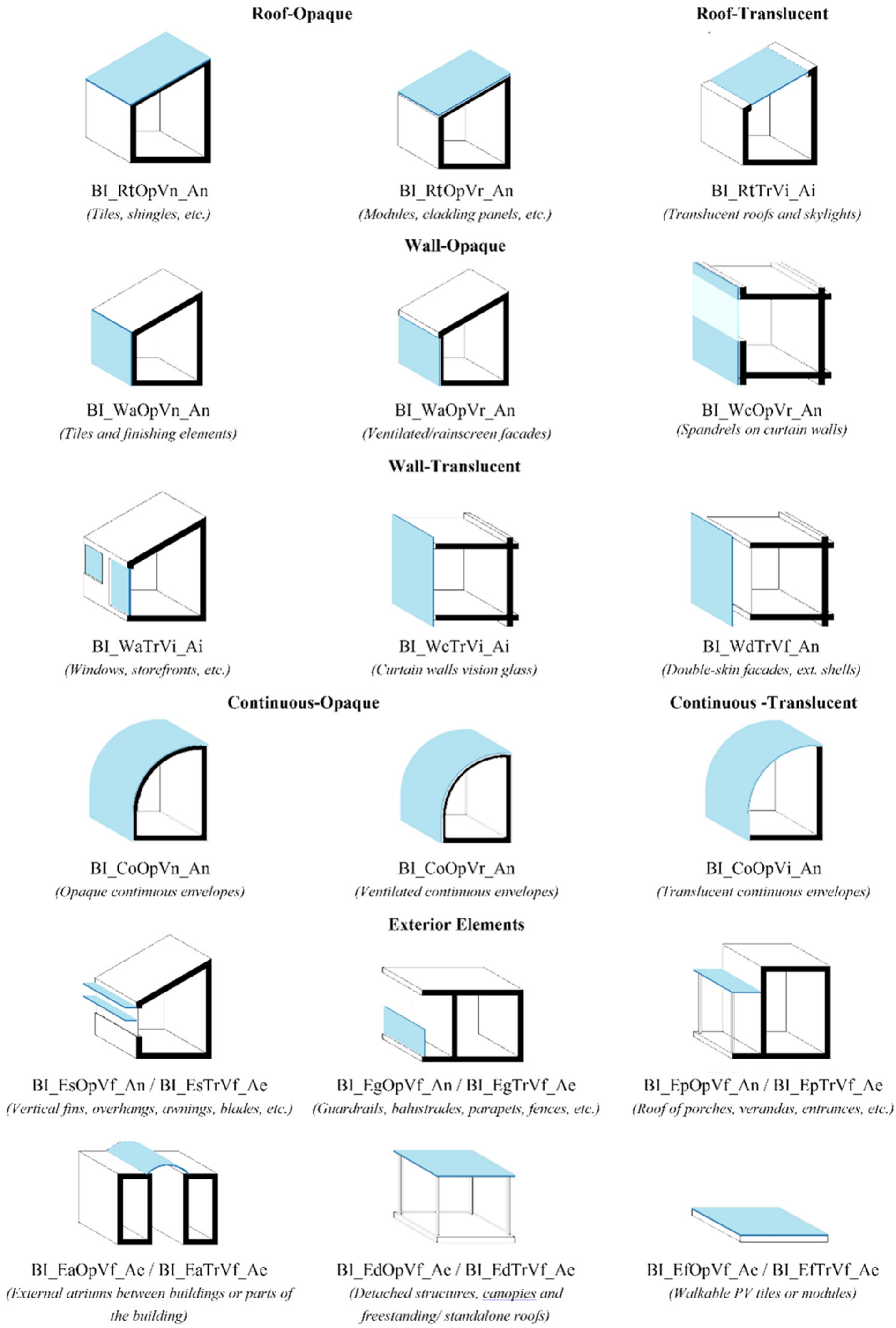

Figure 3: BIPV classification.

Figure 4: BIPV ventilated façade at BX house. *(Source: SDME Organization.)*

Figure 5: BIPV window at VT house's foyer. *(Source: SDME Organization.)*

The proposed classification facilitated the analysis of the houses under analysis in its five fields: type, location, opacity, heat dissipation, and accessibility accessible form within the interior or exterior. As expected, the preferred location for installing the PV elements was the roof, and as commented before, all the houses have PV on their roofs. That is justified by the high solar angles of the Middle Eastern countries. Additionally, in residential projects, the roof is less crowded than in commercial ones, bringing more space for the PV modules.

The houses presented tilted and flat roofs (typical roofs in arid climates), as Fig. 6 shows. Five teams placed the PVs parallel to the flat roof (AUD, BX, UOS, VT, and part of the HW), and four teams have the tilted PVs on the flat roof (AST, NCT, KS, and part of SUR). In the case of sloped roofs, all the PVs were placed parallel to the roof (UOW, USI, HW, TUE, part of the HW, and part of the SUR). Among them, two teams, HW and SUR, have part of the roof flat and another part sloped. The PVs are installed parallel to the flat and sloped roofs in these cases. AUR and NCT teams designed on-the-roof terraces shaded by PV canopies. Similarly, UOS roofed its balcony with PV modules, and BX, AST, and KSU shaded their courtyards with PV structures. In the case of BX, this PV shade is retractable.

Regarding roof integration, the teams developed several types of BAPV and BIPV solutions. Four teams chose BAPVs roof systems (AUD, NYU, UOS, and USI), eight teams chose BIPVs (AUR, BX, HW, KSU, NCT, SUR, TUE, UOW, and VT), while two teams had both BAPV and BIPV (AST and BU). In relation to the visual image and the architectural design approach of the PV roof systems, many teams (BU, SUR, UOS, and VT) opted for "invisible applications". They intentionally locate the PV modules out of people's sight [19]. Regarding façade integration, BX integrated strips of PV modules in the east, south, and west ventilated façades, and VT utilized PV glass in the window of their house foyer, as shown in Figs 5 and 6.

Most of the teams in the SDME 2018 edition decided to use opaque solutions. However, the BU and BX teams use semi-opaque PV modules as roofs of their courtyards. VT was the only team that used a transparent solution.

Heat dissipation is crucial for the optimum performance of the PV modules, and it is even more critical in the Middle East due to its high temperature and irradiance. Therefore, the PV modules in teams like AST and NYU that opted for standard BAPV solutions have non-restricted rear ventilation. Similarly, the modules as roofs for courtyards, terraces, and balconies might have even better ventilation, as in the cases of AUR, BX, BU, KSU, NCT, and UOS. However, the BAPV systems installed parallel to the roof and the BIPV on the

AST: BA_RfOpVf_An + BI_EpOpVf_Ae.

AUD: BA_RfOpVr_An.

AUR: BI_EdOpVf_Ae.

BU: BA_RfOpVr_An + BI_RfOsVf_Ae.

BX: BI_EaOsVf_Ae + BI_WaOpVr_An.

HW: BI_RtOpVr_An.

KSU: BI_EdOpVf_Ae.

NCT: BI_EdOpVf_Ae.

NYU: BA_RfOpVf_An.

SUR: BI_RtOpVr_An.

TUE: BI_RtOpTw_An.

UOS: BA_RfOpVr_An + BI_EpOpVf_Ae.

UOW: BI_RtOpTw_An.

USI: BA_RtOp_An.

VT: BI_RfOpVn_An + BI_WaTrVi_Ai.

Figure 6: Proposed classification implemented on the SDME 2018 houses. *(Source: SDME Organization.*

www.witpress.com, ISSN 1743-3541 (on-line)

roof integrated as invisible applications or ventilated façades do not affect or enhance the houses' architecture but reduce the rear ventilation level. Therefore, they fall into the "restricted ventilation" category.

Two teams, UOW and TUE, designed a roof solution in which PV elements look like standard roof materials. For this, they adjusted their roof's shape and tilt angle to get optimum solar energy harvesting and seamless integration of their solar tiles and modules. In addition, these two teams used PV thermal hybrid solutions that ensure the correct heat dissipation and have as sub-product hot water that can be used for domestic needs.

Finally, accessibility from within the interior or the exterior is a criterion established by the EN 50583 standard [11]. That information is relevant for regulations due to its implications for structural, fire, and in-use safety. Only the PV glass of the VT house is accessible from within the interior of the house. Additionally, the PV canopies and porches can be accessible from the exterior of the houses.

6 CONCLUSION

Given the significance of comprehensively classifying photovoltaics in buildings, the author conducted an in-depth literature review of the different applications and the existing categorization of PV in buildings. Then, they proposed a unified and flexible classification that responds to diverse stakeholders' interests using the lesson learned in their research.

Excellent works on PV in buildings and several categorizations have been published in the last decade. However, most classifications focus on BIPV, not including BAPV solutions. In addition, the heat dissipation has not been addressed, and even the most detailed categorization does not include PV thermal hybrid solutions.

The proposed classification covers both BAPV and BIPV. The initial five fields are application type, location, opacity, ventilation, and accessibility. Once the classification was developed as implemented in the Solar Decathlon Middle East zero-energy houses. Finally, the findings from the classification's definition and its utilization were that:

- The proposal structure is flexible to be expanded to consider new fields and subcategories.
- The initial proposal is complete enough to address the BAPV and BIPV solutions found in the literature.
- Relevant aspects for the PV performance as the heat dissipation is taken into consideration, as well as PV thermal hybrid solutions such as BAPV/T and BIPV/T.
- Code and safety consideration as the EN 50583 standard.

The authors will keep working to improve their proposed classification and use it in the analysis of zero-energy buildings, hoping to contribute to the discussion of the harmonization of the PV in Buildings classifications.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dubai Electricity and Water Authority (DEWA) for funding this research, SDME organizers for sharing the photos and information of the houses, and Dr Sgouris Sgouridis, Director of Research in DEWA R&D, for his valuable input.

REFERENCES

[1] D'Agostino, D. & Mazzarella, L., What is a nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of Building Engineering*, **21**, pp. 200–212, 2019.

[2] Torcellini, P., Pless, S., Deru, M. & Crawley, D., *Zero Energy Buildings: A Critical Look at the Definition*, National Renewable Energy Lab. (NREL), Golden, CO, 2006.
[3] Corti, P., Bonomo, P., Frontini, F., Mace, P. & Bosch, E., *Building Integrated Photovoltaics: A Practical Handbook for Solar Buildings' Stakeholders*, 2020.
[4] Chen, T., An, Y. & Heng, C.K., A review of building-integrated photovoltaics in Singapore: Status, barriers, and prospects. *Sustainability*, **14**(16), 10160, 2022. DOI: 10.3390/su141610160.
[5] Osseweijer, F.J.W., van den Hurk, L.B.P., Teunissen, E.J.H.M. & van Sark, W.G.J.H.M., A comparative review of building integrated photovoltaics ecosystems in selected European countries. *Renewable and Sustainable Energy Reviews*, **90**, pp. 1027–1040, 2018. DOI: 10.1016/j.rser.2018.03.001.
[6] Leslie, H., *Energy and the New Reality 2: Carbon-Free Energy Supply*, Earthscan: London, 2010.
[7] Berger, K. et al., International definitions of 'BIPV', Natural Resources Canada, 2018.
[8] Fedorova, A., Hrynyszyn, B.D. & Jelle, B.P., Building-integrated photovoltaics from products to system integration: A critical review. *IOP Conference Series: Materials Science and Engineering*, **960**(4), 42054, 2020.
[9] Jelle, B.P. & Breivik, C., State-of-the-art building integrated photovoltaics. *Energy Procedia*, **20**, pp. 68–77, 2012.
[10] Verberne, G. et al., BIPV products for façades and roofs: A market analysis. *29th European Photovoltaic Solar Energy Conference and Exhibition*, pp. 3630–3636, 2014.
[11] European Standard, EN 50583-1: 2016.
[12] Bonomo, P. et al., Categorization of BIPV applications. 2021. www.iea-pvps.org.
[13] Frontini, F., Bonomo, P. & Chatzipanagi, A., Building integrated photovoltaics. *Swiss BIPV Competence Centre, SUPSI*, 2015. http://repository.supsi.ch/7202/1/160112_BIPV_digitale.pdf.
[14] Ghosh, A., Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive Review. *J Clean Prod*, **276**, 123343, 2020.
[15] Peng, C., Huang, Y. & Wu, Z., Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy Build*, **43**(12), pp. 3592–3598, 2011.
[16] dos Santos, Í.P. & Rüther, R., The potential of building-integrated (BIPV) and building-applied photovoltaics (BAPV) in single-family, urban residences at low latitudes in Brazil. *Energy Build*, **50**, pp. 290–297, 2012.
[17] Celadyn, W. & Filipek, P., Investigation of the effective use of photovoltaic modules in architecture. *Buildings*, **10**(9), p. 145, 2020.
[18] Scognamiglio, A., A trans-disciplinary vocabulary for assessing the visual performance of BIPV. *Sustainability (Switzerland)*, **13**(10), 2021. DOI: 10.3390/su13105500.
[19] Cronemberger, J., Corpas, M.A., Cerón, I., Caamaño-Martín, E. & Sánchez, S.V., BIPV technology application: Highlighting advances, tendencies and solutions through Solar Decathlon Europe houses. *Energy Build*, **83**, pp. 44–56, 2014. DOI: 10.1016/j.enbuild.2014.03.079.
[20] Skoplaki, E., Boudouvis, A.G. & Palyvos, J.A., A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting. *Solar Energy Materials and Solar Cells*, **92**(11), pp. 1393–1402, 2008. DOI: 10.1016/j.solmat.2008.05.016.

[21] Yang, T. & Athienitis, A.K., A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. *Renewable and Sustainable Energy Reviews*, **66**, pp. 886–912, 2016. DOI: 10.1016/j.rser.2016.07.011.
[22] Kurnik, J., Jankovec, M., Brecl, K. & Topic, M., Outdoor testing of PV module temperature and performance under different mounting and operational conditions. *Solar Energy Materials and Solar Cells*, **95**(1), pp. 373–376, 2011. DOI: 10.1016/j.solmat.2010.04.022.
[23] Kaldellis, J.K., Kapsali, M. & Kavadias, K.A., Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. *Renew Energy*, **66**, pp. 612–624, 2014.
[24] Owen, M., Pretorius, J., Buitendag, B. & Nel, C., Heat dissipation factors for building-attached PV modules. https://ssrn.com/abstract=4119337.
[25] Solar Decathlon Middle East. https://www.solardecathlonme.com.