Building Integrated Photovoltaic Thermal Collectors: Modelling and Experimental Investigation of Two Novel Cost-Effective Prototypes

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Abstract

This paper presents a comprehensive analysis of three different building-integrated solar systems. Specifically, two building-integrated photovoltaic thermal collector prototypes (alternatively water and air cooled) are investigated along with a building-integrated photovoltaic panel; these prototypes were fabricated and experimentally tested at University of Patras (Greece). Note that the active performance of such devices has already been investigated in other works. This chapter presents the analysis of the passive effects on a building's thermal behaviour caused by the integration of the devices. A suitable dynamic simulation tool, capable of assessing the whole device-building performance analysis, is outlined. A case study aimed at proving the potential of such code and showing the effects of the adoption of building integrated solar systems on a building's thermal behaviour is presented. The case study considers a simple dwelling unit in a multi-storey residential building, located in different weather zones and subject to diverse boundary conditions. The investigated collectors on the south facades of the building are integrated, and the associated passive effects are analysed. The analysis provides interesting outcomes from the point of view of energy and comfort.

1. Introduction

It is well known that the building sector is responsible for around 37% of the total primary energy consumption worldwide (European Council and Parliament); of this, 26% is due to residential and 11% to commercial buildings (Boermans et al., 2011; van de Bree et al., 2014). Several actions have been undertaken to overcome this problem and to reduce the impact of buildings (Buonomano et al., 2019). Specifically, significant efforts have been made to i) enhance building performance through the use of opaque and transparent elements and phase-change materials (Forzano et al., 2019), and also to ii) increase the efficiency of systems such as HVAC, lightning, etc. (Barone et al., 2016). The integration of innovative technologies based on Renewable Energy Systems (RES) plays a crucial role in this effort (Lin and Zhu, 2019). The use of RES in small building-integrated installation is currently much more widespread than in larger centralized plants (Wang et al., 2018), leading to a "prosumer" conception of buildings. In this sense, the building is not just an energy consumer, but it also becomes the producer of its own consumed energy (Toffler, 1980). Such an approach, which is easily applicable to small detached houses, creates some issues when a high-rise building is considered, as renewable energy devices (solar thermal collectors, photovoltaic panels, photovoltaic thermal collectors, etc.) require a certain amount of space for their installation in order to satisfy building needs (and also normative requirements). Sufficient space is usually available in the case of detached houses or small buildings (which typically have a higher surface/volume ratio, more space near the building, etc.), but this is not true in the case of high-rise buildings. In the case of the latter, it is uncommon to have enough space near the building (as such buildings are usually located in cities) or on the roof (which is small in relation to the total floor area and, thus, in relation to the overall energy demand). This problem is even greater if we consider the increasing trend for city living, the ever-

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increasing size of cities, and the consequent spread of high-rise living solutions.

1.1 BISS state-of-the-art

In this framework, one possible way to exploit distributed RES, despite the lack of space in the common high-rise metropolitan buildings, is to integrate solar devices into the building envelope (COST Action TU1205 (BISTS) 2015). For this reason, interest in Building Integrated Solar System (BISS) is con¬stantly increasing (COST Action TU1205 (BISTS) 2015). In the literature, several works have investigated Building Integrated Solar Thermal Systems (BISTS) (Agathokleous et al., 2019; Forzano et al., 2019; Barone et al., 2019b), Building Integrated Photovoltaics (BIPV) (Barone et al., 2019a, 2019b), Building Integrated Photovoltaics/Thermal collectors (BIPVT) (Barone et al., 2019b), etc. However, despite the advantages of the adoption of a BISS, some issues can be identified, such as the architectonical impact and the potentially high initial cost of the system (US Department of Energy, 2014). It should be noted that the economic cost (including of stand-alone solar devices) represents a significant obstacle for the diffusion of BISS (Maurer et al., 2017). Another issue, closely related to the question of building integration, is the varia-tion of a building's thermal behaviour (Barone et al., 2019a; Maurer et al., 2017). The building envelope integration of RES devices affects the system thermal behaviour with desired (free heating) or undesired (overheating) passive effects. Building heating and cooling loads and demands are therefore modified with respect to those of traditional buildings without a BISS. An analysis of several papers available on BISS reveals a number of areas of misunderstanding or lack of knowledge, such as: i) the fact that the initial costs of BISS are usually too high to guarantee a good market diffusion is not considered; ii) few analyses are presented in literature about the passive effects of BISS; iii) the effects of the adoption of BISS on energy and comfort are usually neglected by most studies; iv) most studies investigate a device in a certain weather zone or in a certain season; v) there is a lack of suitably dynamic simulation models capable of assessing the whole building/BISS system behaviour. This lack of knowledge is much more evident when BIPV and BIPVT are considered.

1.2 Aim of the work

In this frameworkcontext, the main aim of this work is to fill some of the gaps in knowledge outlined in the previous paragraph by investigating the passive effects of different BISS prototypes on a building's thermal behaviour. To this end, two innovative Building Integrated low-cost flat-plate Photovoltaic Thermal (BIPVT) collector prototypes (with water and air as working fluids), whose active performance had already been investigated in previous studies, were considered in order to assess their passive effects. These prototypes were developed with the aim of creating economically affordable collectors made of very cost-effective materials. By means of these hybrid collectors, both electricity and thermal energy can be obtained. Specifically, the two prototypes, which both contain a polycrystalline PV module, differ in terms of the adopted working fluid: air and water. The low-cost heat extraction systems are used to increase the electric efficiency of the PV module by lowering its working temperature. Simultaneously, the obtained hot fluids can be exploited for different building uses (the hot air can be adopted for direct free space heating or supplied to the evaporator of a heat pump system, whereas the hot water can be used for feeding a hydronic heating system or for producing DHW). In order to investigate the passive effects of these two BIPVT prototypes under different boundary and working conditions, a suitably dynamic simulation model for complete system analysis was developed in the MatLab environment. This simulation tool, capable of assessing the energy performance and environmental impact of the presented devices, is also able to accurately assess their passive effects. The hygrothermal comfort analysis can be carried out by considering the mean radiant temperatures obtained with and without the considered BISS devices. The model developed in-house was also validated by means of experimental data as presented in previous published work (Barone et al., 2019c) (here, a very good agreement between numerical results and experimental measurements was achieved). Finally, in order to investigate the effects of the integration of the presented prototypes and to show the potentiality of the developed simulation tool, a suitable case study is discussed. Specifically, it refers to a single dwelling unit located in a multi-storey residential building, where the two BIPVT prototypes and a commercial BIPV panel) are alternatively integrated into the south-facing vertical façade (the BIPV is studied for the purposes of comparison). For the analysis, different European weather zones and boundary conditions were investigated. The results suggest that significant energy and economic savings can be achieved and useful design and operating criteria are outlined'.

2. Description of Prototypes

The developed BIPVT prototypes are briefly described in this section; more information can be found in Barone et al. (2019a, 2019b). Both PVT devices, built at the Renewable Energy Laboratory of University of Patras (Greece), were fabricated using the same PV panel (see Fig. 1). As is widely understood, the electrical efficiency of photovoltaic cells dramatically drops as the operating temperature rises. In order to improve the efficiency of photovoltaic cells by avoiding such overheating, two different heat extraction systems were created. Specifically, a cooling system was placed under the photovoltaic panel, composed of eleven PVC pipes (Fig. 2, left), and of two black galvanized steel sheets, shaped in such a way as to form sev¬en air ducts (Fig. 2, right), for the water and air-based devices respectively.

Fig. 1 – Polycrystalline PV module

Fig. 2 – Water (left) and air (right) PVT heat extraction systems

Further information regarding the geometrical an thermophysical data, the collector performance, etc., can be found in the two previous papers (Barone et al., 2019a, 2019b).

3. Simulation Model

In order to investigate the performance under different boundary and work¬ing conditions of the prototypes presented, two mathematical models were developed (Barone et al., 2019a, 2019b) for the water-based and the air-based prototypes, respectively. Such models, based on the Hottel-Whillier equation set (Duffie and Beckman, 2013), suitably modified to consider the PV panel as an absorbing plate, were experimentally validated, proving their reliability. Very good agreement between the measured and experimental data was found, as reported in Barone et al. (2019a; 2019b), ensuring the relia¬bility of the codes. Note that the BIPV mathematical model is derived by the BIPVT models by removing the part relating to heat extraction.

In order to assess the passive effects of the prototypes, the two prototype models are linked, in this paper, to a Building Energy Performance Software (BEPS) package developed in-house. The adopted BEPS, called DETECt, had been previously developed and validated (Buonomano and Palombo, 2014; Buonomano, 2016; Barone et al., 2019c). A detailed description of the building simulation tool can be found in Buonomano and Palombo (2014). In order to connect mathematical model of the prototypes to DETECt, the generalized equation of the overall thermal losses for a Flat Plate Collector (FPC) (Duffie and Beckman, 2013), also adopted for PVT collectors, is:

$$\dot{Q}_{loss} = U_L \cdot A_C \cdot \left(T_p - T_a\right) \qquad \text{with } U_L = (U_t + U_e + U_b) \tag{1}$$

Equation (3) is modified as follows for building integration:

$$\dot{Q}_{loss} = (U_t + U_e) \cdot A_C \cdot \left(T_p - T_a\right) + U_b^* \cdot A_C \cdot \left(T_p - T_{air}\right) \tag{2}$$

Here, UL is the overall heat loss coefficient, which is the sum of top (Ut), back (Ub), and edges (Ue) loss coefficients, AC is the collector aperture area. The back loss coefficient, Ub, is suitably modified in Eq. (2), Ub*, to model the building integration. Specifically, it also considers thermophysical properties of the building, rather than only those of the collector, and connects the absorbing plate temperature (T_p) to that of indoor air (T_{air}) instead of outdoor ambient air (T_a). Consequently, when the collectors are integrated into the building envelope, the mathematical model is modified so that the collector back becomes the external layer of the wall and its back temperature is indirectly linked to building's indoor air temperature. More details are available in Agathokleous et al. (2019) and Barone et al. (2019a, 2019b)

4. Case Study

In order to show the capabilities of the developed dynamic simulation tool and analyse the passive effects on the building of the proposed integration of the prototypes, a suitable case study is here presented. Specifically, it refers to a dwelling unit located in a multi-storey residential building. A sketch of the reference building is shown in Fig. 3 (L. 4.7 m, H. 3.2 m, W. 3.5 m). Note that all the internal walls are adiabatic with the exception of the South facing wall, where a window is considered (L. 0.95 m, H. 1.6 m). The thermophysical properties of the building are presented in Table 1.

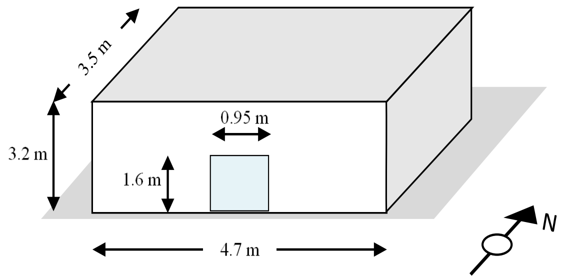

Fig. 3 – Reference building sketch

The reference building is enhanced by integrating in the South facing façade 9 water-based BIPVTs, 9 air-based BIPVTs, and 9 BIPVs, alternatively (see Fig. 4). The heat transfer fluid flow rates of the prototypes are equal to 0.0339 kg/s and 0.123 kg/s for water and air collectors, respectively. For the system based on the water-cooled device, a 360 l tank is considered.

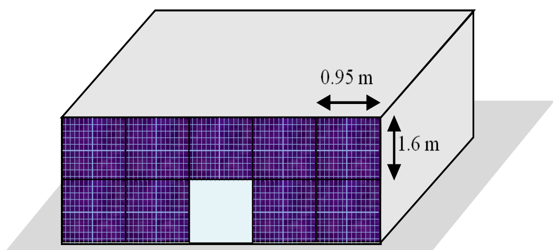

Fig. 4 – Proposed building sketch

To estimate the electricity consumption for space heating and cooling, a variable COP heat pump/chiller is modelled (Barone et al., 2016). To evaluate the system behaviour under different boundary conditions, three weather zones representing hot, temperate and cold European climates are investigated (Almeria, Naples and Milano, Table 2). In addition, three internal thermal loads (125, 150 and 500 W) and two ventilation flow rates (0.25 and 0.5 Vol/h) are simulated.

Table 1 – Building features

	Ext. wall	Int. wall	Window
Thickness [mm]	250	250	4/18/4
Thermal transmittance	1.2	-	4
Solar transmittance [-]	-	-	0.75

Table 2 – Considered climatic zone

Weather zone	**HDD [Kd]**	**CDD [Kd]**	**ISR [kWh/m²y]**
Milano	2733	435	1188
Naples	1479	727	1529
Almeria	783	961	1724

5. Results and Discussion

In this section, the results of the analyses carried out are presented in detail. Note that only the passive effects results (from the point of view of temperature, energy and comfort) are presented.

5.1 Temperatures Analysis

The adoption of a BISS changes the thermophysical behaviour of the building wall in which the considered devices are integrated. This phenomenon can be observed in Fig.s 5 and 6 where the Reference vs. Proposed systems external wall temperatures are reported for three sample winter and summer days, respectively. In these figures, four different systems are considered: i) the reference building (blue lines); ii) the proposed system with the BIPV panel (black lines); iii) the proposed system with the water-based BIPVT collector (red lines), iv) the proposed system with the air-based BIPVT collector (green lines).

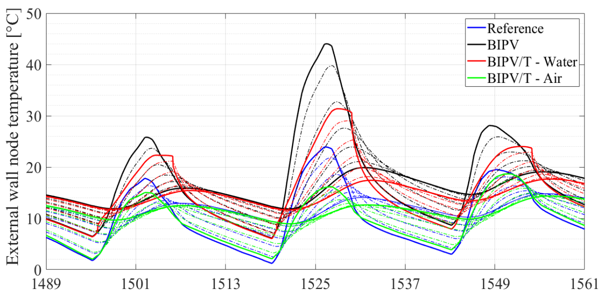

Fig. 5 – Reference vs. Proposed systems: external wall temperature time histories for three sample winter days (Naples, 250 W, 0.25 Vol/h)

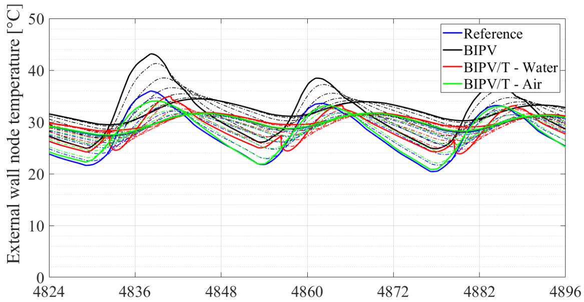

Fig. 6 – Reference vs. Proposed systems: external wall temperature time histories for three sample winter days (Naples, 250 W, 0.25 Vol/h)

For each wall, five temperature nodes are considered; two of these (continuous lines) refer to the superficial wall layers (not capacitive), while the other three (dotted lines) refer to the wall core thermal nodes (capacitive). By analysing the winter season (Fig. 5), several considerations can be made. The integration of BIPV (black lines) leads to a remarkable temperature increase with respect to the reference case (blue lines), this occurrence is due to the higher absorption coefficient of the PV sheet with respect of the standard building wall. A lower wall temperature peak with respect to the case of BIPV (but still higher than the reference case study wall) is reached when the water-cooled BIPV/T (red lines) is adopted. This is due to the cooling effect of the water flowing inside the collector. In addition, it is interesting to note that the wall temperature peak occurs at a later time, compared to the other solutions. This delay is due to the thermal capacity of the water inside the storage tank (the water-based device is the only one connected to a water loop including a hot-water storage tank). Finally, by considering the air-cooled BIPV/T (green lines), different behaviour is detected with respect to the other systems under consideration. Specifically, during the sunny hours, the air-cooled BIPV/T adoption returns a temperature wall decrease compared to the reference case study. This occurrence is due to the high cooling effect of the air flowing inside the collector (taken from the outdoor environment). Note that a different behaviour of the air-cooled BIPVT could be achievable by changing the operating conditions (e.g. if air was taken from the inside of the building and then exhausted). Trends similar to those detected for the winter season can also be noticed for the summer season (Fig. 6), with the exception of the water-based BIPV/T (red lines), which corresponds to a remarkable drop in temperature, occurring during the early morning hours. This is due to the very low temperature of the water flowing inside the collector during these hours – the storage tank connected to the water-cooled BIPV/T collector is drained in the evening by the users for domestic purposes. The hot water is then replaced with cold tap water (15 °C). When the circulating pump of the system is activated the next morning, the water, still cold inside the storage tank, cools down the external wall surface, causing the striking temperature drop shown in Fig. 6.

The variation of the thermal behaviour of the wall, caused by the adoption of the BISS, also affects, in turn, the indoor air temperature. This effect is shown in Fig. 7 for the same three sample winter and summer days and for the same weather zone (Naples) considered for Fig.s 5 and 6.

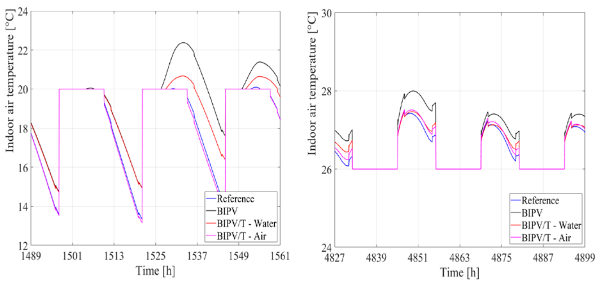

Fig. 7 – Reference vs. Proposed systems: indoor air temperature time histories for three sample winter and three sample summer days (Naples, 250 W, 0.25 Vol/h)

Starting from the winter season (Fig. 7, left), it is can be noted that higher indoor air temperatures occur during the hours in which the HVAC system is switched off, by adopting the BIPV and the water-cooled BIPV/T solutions (black and red lines respectively). This is due, as mentioned previously, to the free-heating effects caused by the integration of these devices in the building. Note that this increase in indoor air temperature implies a higher indoor thermal comfort perception with respect to the reference building. In addition, an energy saving can also be achieved during the hours in which the HVAC is switched on (not detectable from Fig. 7 due to the thermostat temperature). Both comfort and energy demand variations are described in more detail in the energy and comfort analysis sections. Note that, in the case of the adoption of air-cooled BIPV/T (purple line), lower indoor air temperatures are detected with respect to the reference case study, as can be seen in Fig. 5. By considering the summer season (Fig. 7, right), higher indoor air temperatures, compared to the reference case study, are almost always obtained by taking into account the proposed systems. Higher energy consumption for space cooling and lower indoor thermal comfort levels are therefore expected during the summer season.

5.2 Thermal Power/Energy Analysis

The variations in indoor air temperature, shown in the previous section (Fig. 7), affect the required thermal power for space heating and space cooling. Fig. 8 shows the HVAC system thermal power time histories for the same three winter (left) and three summer (right) sample days previously considered.

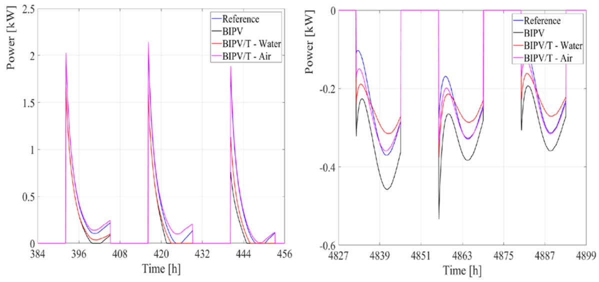

Fig. 8 – Reference vs. Proposed systems: thermal power time histories for three sample winter and three sample summer days (Naples, 250 W, 0.25 Vol/h)

Starting with the winter season (Fig. 8, left), several considerations can be made. The adoption of the BIPV and water-cooled BIPVT systems (black and red lines respectively) returns, as can be seen in Fig. 7, a lower thermal power demand for space heating with respect to the reference case study (blue line) due to the free heating effect of the BISS. It is interesting to note that in several hours the entire space heating need is covered by the BISS positive passive effect. By considering the air-cooled BIPVT prototype (purple line), the opposite effect can be detected: a higher thermal power demand for space heating with respect to the other solutions is obtained. This higher consumption, which is also seen in the temperature trends previously discussed (Fig. 7), is caused by the negative overcooling effect of the device due to the cold air flowing inside the collector. During the summer season (Fig. 8, right), the adoption of a BISS generally increases the thermal power demand for space cooling purposes due to the negative over-heating effect. As an example, the BIPV (black lines) returns a higher thermal power demand if compared to the reference case study (blue lines). A different situation is instead detected by considering the water and air-cooled BIPVT (blue and purple lines, respectively). Here, during the first hours of the day the adoption of these systems creates a lower thermal power demand for space cooling. By comparison, a higher demand is detected later in the day. This behaviour is in accordance with the temperature trends presented in Fig. 7.

From the results shown so far it is clear that the effect of the adoption of a BISS on the building thermal behaviour is strictly dependent on the season and on the hour of the day. This implies that the convenience linked to the building integration of such systems (from the point of view of passive effects) should be assessed on a seasonal/yearly basis. For this reason, the seasonal thermal energy demands are reported in Fig.s 9, 10 and 11, for Almeria, Naples and Milan, respectively. Note that in these figures the bar above and below the zero line represents the thermal energy demanded for space heating and space cooling, respectively. From the figures, it is possible to note that the adoption of a BISS generally returns lower energy consumption for space heating (positive free-heating effect) and higher energy consumption for space cooling (negative over-heating effect) with respect to the reference building (blue bars), as expected. By analysing the BIPV (black bars), it can be noted that this solution returns the highest effects magnitude (highest winter energy savings and highest summer energy demand increases) for all the considered case studies.

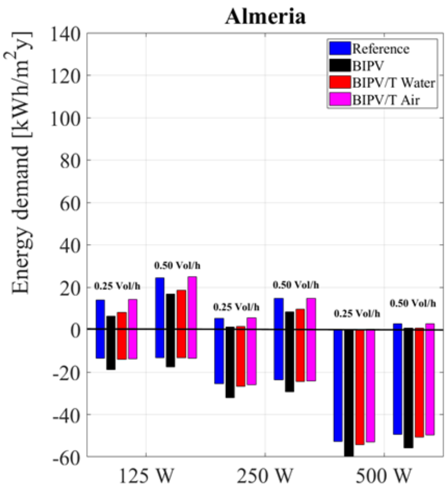

Fig. 9 – Reference vs. Proposed systems: thermal energy demands for space heating and space cooling (Almeria)

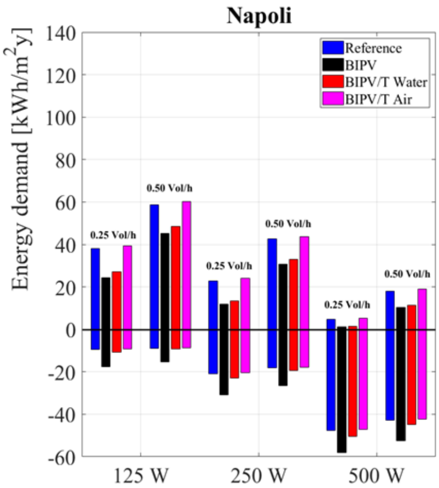

Fig. 10 – Reference vs. Proposed systems: thermal energy demands for space heating and space cooling (Naples)

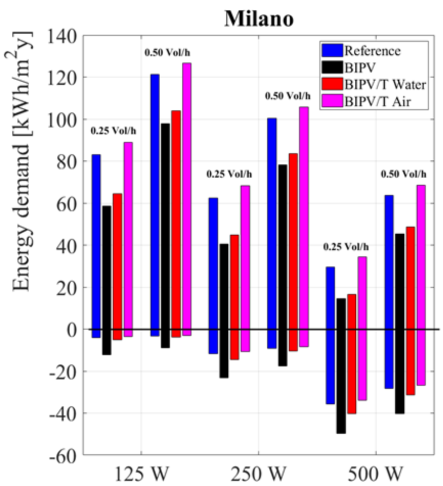

Fig. 11 – Reference vs. Proposed systems: thermal energy demands for space heating and space cooling (Milan)

A similar behaviour, but lower in magnitude, occurs by considering the water-cooled BIPVT (red bars). On the other hand, very low variations can be seen in Fig. 9 if the air-cooled BIPVT (purple bars) is considered. Small differences are detected only in case of the cold-dominated weather zone (Milan), especially for space heating purposes. The small variation in terms of demanded thermal energy, which is obtained by considering the air-cooled BIPVT, is in accordance with the very slight temperature variations returned by the technology and already shown in Fig.s 5, 6 and 7 with respect to the reference building.

The seasonal results shown in Fig.s 9, 10 and 11 imply the yearly results presented in Fig.s 12, 13 and 14 in case of Almeria, Naples and Milan, respectively. Specifically, here the annual outcomes are reported in terms of yearly electricity savings with respect to the reference building for all the proposed case studies. Note that these results are a trade-off between the negative summer effects and the positive winter effects. From the figures, interesting considerations can be made. First, it is possible to note that the performance of BIPV and water-cooled BIPVT (black and red bars respectively) increases with the increase of the space heating demand (higher heating degree days (HDD), higher ventilation flow rate, lower internal loads). The opposite occurs for the air-cooled BIPVT (blue bars), for which the performance increases with the increase of the cooling loads (higher cooling degree days CDD, lower ventilation flow rate, higher internal loads). This discrepancy is due to the temperature behaviour shown in Fig.s 5, 6 and 7. BIPV and water-cooled BIPVT, which return higher system temperatures with respect to the reference case study, perform better in weather zones where the effect of the winter season is greater than the summer season. Conversely, lower system temperatures are achieved for the air-cooled BIPVT.

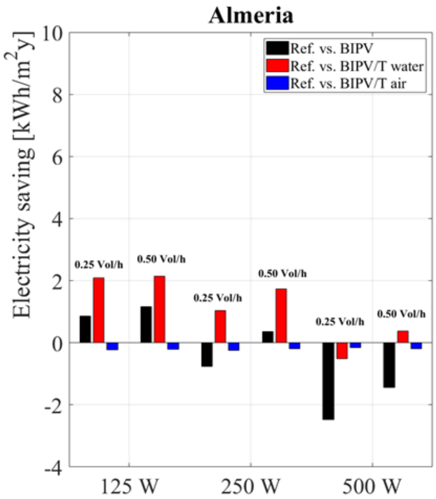

Fig. 12 – Reference vs. Proposed systems: yearly electricity savings (Almeria)

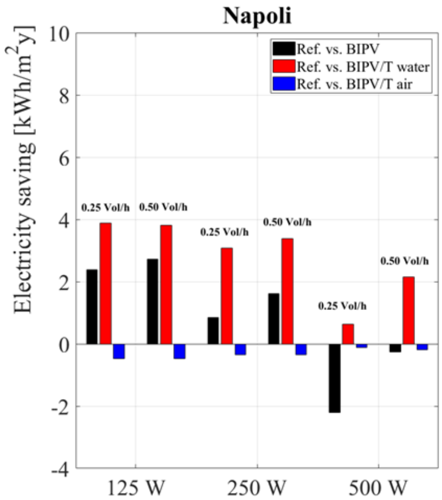

Fig. 13 – Reference vs. Proposed systems: yearly electricity savings (Naples)

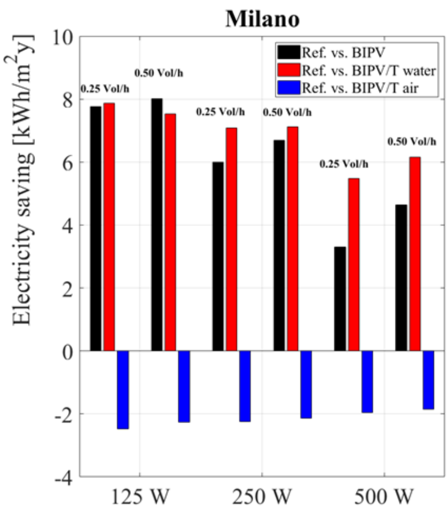

Fig. 14 – Reference vs. Proposed systems: yearly electricity savings (Milan)

By analysing each system singularly, it is possible to note that the adoption of water-cooled BIPVT (red bars) returns the highest savings for almost all the considered case studies. The only exception, where this system returns an energy increase, is in Almeria (internal gains set at 500 W, and ventilation flow rate equal to 0.5 Vol/h), where disadvantages in summer outweigh the benefits in winter.

Lower savings (i.e. higher energy demand) are detected by adopting the BIPV system (black bars). The higher system temperatures reached by the wall integrating this device with respect to the others (see Fig. 5, Fig. 6 and Fig. 7) imply a higher building heating demand for this system to be convenient. This is also demonstrated by the results for Milan (internal gains set at 125 W, and ventilation flow rate equal to 0.25 and 0.50 Vol/h). Here, the very high heating demand makes the adoption of BIPV more convenient than the water-cooled BIPVT.

The air-cooled BIPVT (blue bars), on the other hand, always return a worse performance with respect to the reference case study (negative primary energy saving), in accordance with the temperature time histories shown in Fig.s 7 and 8 and with the thermal energy one of Fig.s 9, 10 and 11. However, it should be noted that the adoption of this device in hot weather zones returns a negligible energy increase. By comparison, the lower PV panel temperature (reached thanks to the cooling air and the produced hot air itself) should be considered in the overall system convenience (together with the higher productivity and longer life). Note also that the air-cooled BIPVT behaviour is mainly due to the operating condition investigated in this paper; the considered prototype takes air from the outdoor environment instead of from the building indoor environment. This means that the temperature of the air entering the collector is always somewhat low, causing the subsequent overcooling effect previously described. Different results, and thus different performances could be achieved with different air intake strategies (e.g. if air is taken from the inside of the building and exhausted or adopted to enhance the heat pump COP during the winter).

5.3 Comfort analysis

The modifications to the thermal behaviour of a building due to adoption of the BISS also affects, in turn, the perception of indoor thermal comfort. This is due to the variation of both indoor air (see Fig. 7) and wall (see Fig. 5 and Fig. 6) temperatures affecting the indoor thermal comforts levels. In this section, an analysis of the thermal comfort when BISS are considered is presented. In order to conduct this investigation, the number of hours in which the indoor thermal comfort is satisfied was estimated. Following this, the variation of the number of comfort hours obtained in one year between the proposed and the reference case was assessed. Specifically, comfort conditions are considered when the Predicted Mean Vote (PMV) is included in the range of ± 0.5. The results of such analysis are reported in Fig. 15 for all the considered case studies in terms of comfort hour variation.

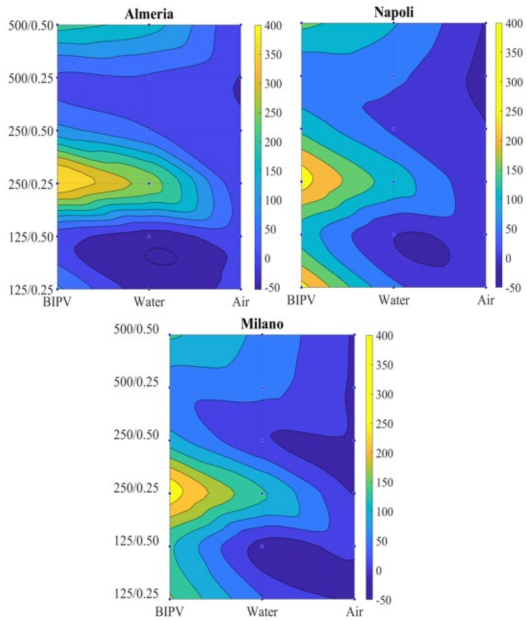

Fig. 15 – Reference vs. Proposed systems: yearly thermal comfort hour variation for all the considered case studies

By comparing Fig. 15 to Fig. 12, Fig. 13 and Fig. 14, it is possible to note that the best solutions, from the point of view of comfort and energy point do not always match. As an example, from Fig. 15 is possible to note that the application of the water-cooled BIPVT located in Naples (internal gains set at 125 W, and ventilation flow rate equal to 0.25

and 0.50 Vol/h) reports a decrease in comfort hours (~ -50 hours/year), although it represents the best solution from the point of view of energy (see the same case study results from Fig. 13). By comparison, in the case of the BIPV located in Almeria (internal gains set at 500 W, and ventilation flow rate equal to 0.25 and 0.50 Vol/h), a comfort increase is detected (~ +150/200 hours/year), whereas the same case studies return a worse energy performance (see Fig. 12).

In general, it can be seen that the integration of BIPV is always the best solution from the point of view of comfort. Its convenience increases with an increase in HDD, due to the greater influence of the cooling season, which maximizes the benefits of the higher wall/indoor air temperature (see Fig. 5, Fig. 6 and Fig. 7). The convenience in adopting the water-cooled BIPVT, on the other hand, depends on the selected weather zone and boundary conditions. The application of this device leads to both an increase and decrease in comfort as a function of the considered case study (ranging from -50 to +150 hours/year). Finally, the worse comfort performance was achieved through the adoption of the air-cooled BIPVT (especially in case of the cold dominated weather zones – Milan). This is due to the over-cooling effect discussed above, and depends on operating conditions of the collectors (Fig. 5, Fig. 6 and Fig. 7).

6. Conclusions

This paper has discussed the effect of the building integration of several BISS devices. Specifically, two innovative low-cost BIPVT collectors (water and air cooled) prototypes were considered for this study, along with a BIPV panel. One of the main novelties of these prototypes is the low initial cost achieved by the adoption of cost-effective materials. The experimental campaigns, the mathematical models developed and the performance of these devices have been discussed in previous papers. In this paper, an analysis of the passive effects of the prototypes when integrated into the building envelope was presented. The prototypes were purposely conceived to be integrated into the building envelope. Specifically, a dynamic simulation model, capable of assessing the performance of the devices coupled to the building was presented. A suitable case study was presented, aimed at investigating the convenience of the presented prototypes from the point of view of their passive effects, and at showing the potentiality of the developed simulation tool. The case study referred to a single-family dwelling unit, located in a multi-storey residential building, where the two prototypes are integrated into the South vertical façade along with those of a BIPV panel. From the analysis, conducted for several weather zones and boundary conditions, a number of interesting outcomes are obtained, such as:

i) non-negligible energy savings for space heating and cooling can be achieved by adopting the BIPV and the water-cooled BIPVT in cold and mild weather zones;
ii) air-cooled BIPV can be a good solution, in summer dominated weather zones, to increase PV efficiency while producing hot air without affecting the energy consumption of a building (negligible passive effects);
iii) in terms of the indoor comfort condition, the best performance is achieved with the BIPV; however interesting benefits are also obtained with the water-cooled BIPVT.

A further case-by-case analysis is required to analyse the convenience of these systems in different applications.

Nomenclature

Symbols

A	Area [m^2]
BIPV	Building Integrated Photovoltaic
BIPVT	Building Integrated Photovoltaic Thermal
BISS	Building Integrated Solar Systems
CDD	Cooling Degree Days
HDD	Heating Degree Days
HVAC	Heating Ventilation and Air Conditioning
PV	Photovoltaic
T	Temperature [K][°C]
U	Heat loss coefficient [W/m^{2}K]

Subscripts/Superscripts

a	outdoor air
b	back
c	collector
e	edge
air	indoor air
p	absorbing plate

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