A key review of building integrated photovoltaic (BIPV) systems

Article

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Review

A key review of building integrated photovoltaic (BIPV) systems

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ABSTRACT

Renewable and sustainable energy generation technologies have been in the forefront due to concerns related to environment, energy independence, and high fossil fuel costs. As part of the EU's 2020 targets, it is aimed to reach a 20% share of renewable energy sources in final energy consumption by 2020, according to EU's renewable energy directive. Within this context national renewable energy targets were set for each EU country ranging between 10% (for Malta) and 49% (for Sweden). A large share of renewable energy research has been devoted to photovoltaic systems which harness the solar energy to generate electrical power. As an application of the PV technology, building integrated photovoltaic (BIPV) systems have attracted an increasing interest in the past decade, and have been shown as a feasible renewable power generation technology to help buildings partially meet their load. In addition to BIPV, building integrated photovoltaic/thermal systems (BIPV/T) provide a very good potential for integration into the building to supply both electrical and thermal loads.

In this study, we comprehensively reviewed the BIPV and BIPVT applications in terms of energy generation amount, nominal power, efficiency, type and performance assessment approaches.

The two fundamental research areas in the BIPV and BIPVT systems are observed to be i) improvements on system efficiency by ventilation, hence obtaining a higher yield with lowering the panel temperature ii) new thin film technologies that are well suited for building integration. Several approaches to achieve these objectives are reported in the literature as presented in this paper. It is expected that this comprehensive review will be beneficial to researchers and practitioners involved or interested in the design, analysis, simulation, and performance evaluation, financial development and incentives, new methods and trends of BIPV systems.

Contents

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1. Introduction

Although electricity plays an essential role in modern society, still there are about 1.2 billion people living without access to electricity, mostly living in rural areas of Africa and Asia [1]. This fact highlights the importance of generating electricity from distributed sources, where renewables have a large presence, to meet local demands in such rural areas. According to the International Energy Agency the share of renewables in electricity generation is expected to rise up to 25% of the total power generation in 2018 [2]. Photovoltaics (PV) generated electricity is also estimated to double its share by 2018 compared to 2011 [2]. PV technology is rapidly-growing compared to other renewables, and, as a result, numerous studies have been conducted on this topic. As part of these studies, Building Integrated Photovoltaics (BIPV) systems play an important role in generating electricity. Some review studies have already been conducted in the literature, regarding BIPV systems but they either provide a very general overview without sufficient detail or are focused on a specific country or application type (e.g. solar façades). Kong et al. [3] reviewed various building energy efficiency options in China, within the context of eleventh five-year plan period. Within this context, they explained the subsidies given to BIPV projects and the application process for them. In [4], research about building integrated energy storage opportunities were reviewed, while the developments in China were also explained. In [4], BIPV systems were also considered as building integrated energy storage systems and were divided into three subgroups: BIPV systems with solar battery, Grid-connected BIPV systems and PV-Trombe wall. For grid-connected BIPV systems the grid was considered as an infinite cycle battery with a huge capacity. Quesada et al. [5], reviewed research conducted and developments achieved in the first decade of the 21st century related to opaque solar façades. They divided opaque solar façades into two subgroups, namely active and passive façades. As part of active solar façades, BIPV and BIPV/T systems were explained. They also categorized the studies conducted so far, considering their content, as "theoretical and experimental study", "development", "feasibility" and, "application example". It was concluded that both BIPV and BIPV/T technologies are favorable systems. Significant amount of energy can be produced with higher efficiency due to the cooling effect of the air flowing behind PV panels. Ref. [6] was the second part of the review study explained in Ref. [5], where the authors reviewed transparent and translucent solar façades with the same paper organization. Thus, semitransparent BIPV and BIPV/T systems were explained and reviewed as active façade systems. Jelle et al. [7], reviewed state of art BIPV technologies in their study. They first gave some information about current PV technologies and their classification, since BIPV applications generally follow the developments in PV cells. The authors reviewed BIPV products available in the market, and categorized them into four subgroups, namely foils, tiles, modules and solar cell glazing products. They concluded that new PV technologies would lead to more efficient and low-cost BIPVs, which would result in shorter payback periods. In [8], a comprehensive analysis of the important developments of various BIPV/T systems was provided. The BIPV/T systems, which were formed starting by early 90s, has attracted increasing interest since 2000 due to its potential to help design net-zero energy buildings by increased solar energy utilization. A wealth of papers report experimental and numerical studies related to the BIPV/T system design and effects of the BIPV/T system on the building performance. The BIPV/T systems studied are: air-based systems, water-based systems, concentrating systems and systems involving a phase change working medium such as BIPV/T with either heat pipe or heat pump evaporator. In [9], a building-integrated photovoltaics with the thermal energy recovery provides a very good potential for integration into the building which consumes zero energy but this technology is not in common use. The advantages are more certain than traditional PV systems of BIPVT. In [10], a BIPV/T system, the flow of a fluid, that is generally air, in a canal beneath PV panels gives way to recovery of a significant part of solar radiation as thermal energy. Thus, heat can be produced through BIPV/T systems to partially supply building demand. On the other side, the panel is cooled by recovered heat from the photovoltaic panel hence increasing its electricity generation efficiency. Shi and Chew [11] reviewed design of renewable energy systems. As part of their study, they also explained BIPV and BIPVT systems and gave examples from the studies conducted so far. In [12], pathways and research opportunities for the BIPV systems of the future were investigated, and PV development progress and its impact on BIPVs, new materials and solutions for BIPVs and their long-term durability were discussed in detail by giving examples from the literature. Low production cost, low environmental impacts and high efficiencies were considered as key factors for future BIPV systems. It was mentioned that retrofitting and relatively easy installation of BIPVs are very important because of the huge volume of existing buildings. It was also stated that governmental subsidies are of great importance to get the attention of the industry, and that especially solar cell glazing products present great opportunities, since they provide solar shading, daylight transmission and electricity production. Other important development is PCM technology. In [13], phase change materials are used for heat storage and passive electronic temperature control. All of the PV–PCM systems which were investigated have a power to laten the temperature increase of PV using PCM. If the organic cell efficiency increases, it may be appropriate to use a PCM to maintain an organic cell at an optimum production temperature. There is a certain potential of the PCM due to the high temperature of the PV. In [14], examples of BIPV/T systems in the literature were given as part of an overview of photovoltaic/thermal (PV/T) systems. In [15], advances, approaches and solutions related to BIPV applications in Solar Decathlon Europe houses were presented. As discussed in [16], a smaller portion of the photovoltaic industry constitutes BIPV, yet it is growing steadily. The lack of validated prediction simulations that are required to make the conscious economic decisions prevent the widespread use of BIPV. The project, which can take many years to compare the performance of BIPV panels to the estimation of photovoltaic simulation tools, has been undertaken by the National Institute of Standards and Technology (NIST). Input parameters which describe the electrical performance of BIPV panels exposed to various meteorological conditions are required for the existing simulation models. In the same study the authors have explained how to make experimental tests by providing the necessary parameters. Ref. [17] is related to the thermal analysis of double skin facades with BIPV panels. Studies were classified as theoretical and experimental in the literature and these studies are separated as naturally ventilated systems and mechanically ventilated with the external influences. Researchers have found it more important to investigate mechanically ventilated façades due to the flexibility of the system. Finally, researchers suggested Nusselt number correlations and convective heat transfer correlations with the relevant ranges of the Reynold's number.

In this paper, we present a comprehensive review of current developments in the BIPV and BIPV/T area and focus to subgroups according to study issue such as building application and experimental studies, simulation and numerical studies, cell module design studies, grid integration studies, and finally, policy and strategies studies. In the first part of the current study, the description of BIPV systems and their categorization are presented. BIPV and BIPV/T systems reported in the literature are then reviewed from the energetic, exergetic, economic and environmental aspects, while their types and performance indicators are given in a tabulated form. We then present available BIPV solutions in the market that meet a wide array of requirements. Finally, the main conclusions drawn are presented.

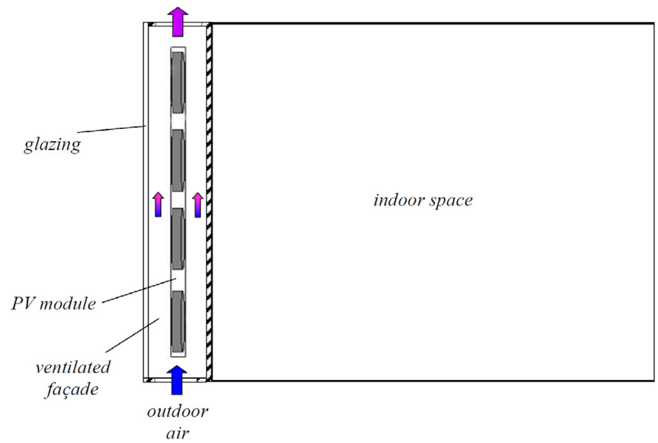

Fig. 2. Schematic of a BIPV system [22].

2. System description

PV systems used on buildings can be classified into two main groups: Building attached PVs (BAPVs) and BIPVs [18]. It is rather difficult to identify whether a PV system is a building attached (BA) or building integrated (BI) system, if the mounting method of the system is not clearly stated [7,19]. BAPVs are added on the building and have no direct effect on structure's functions [18]. On the other hand, BIPVs are defined as PV modules, which can be integrated in the building envelope (into the roof or façade) by replacing conventional building materials (tiles e.g.) [20]. Therefore, BIPVs have an impact of building's functionality and can be considered as an integral part of the energy system of the building. There are many parameters that need to be considered for the integration of PVs into the building envelope and they are shown in Fig. 1 [21].

A BIPV system is schematically illustrated in Fig. 2 [22]. As can be seen from the figure, the PV system is integrated to the façade of the building. The outdoor air enters the system from the bottom and leaves it from the top. During this process it absorbs the heat of PV modules, reducing their temperature which results in an improvement in their efficiency and lifetime. In some applications, a fan and an air duct is employed in the system in order to draw the heated air into the room to reduce the heating load in winter. Such systems are called BIPVT systems and benefit from solar energy both electrically and thermally. In Fig. 3, the schematic illustration of a BIPVT system is given [5].

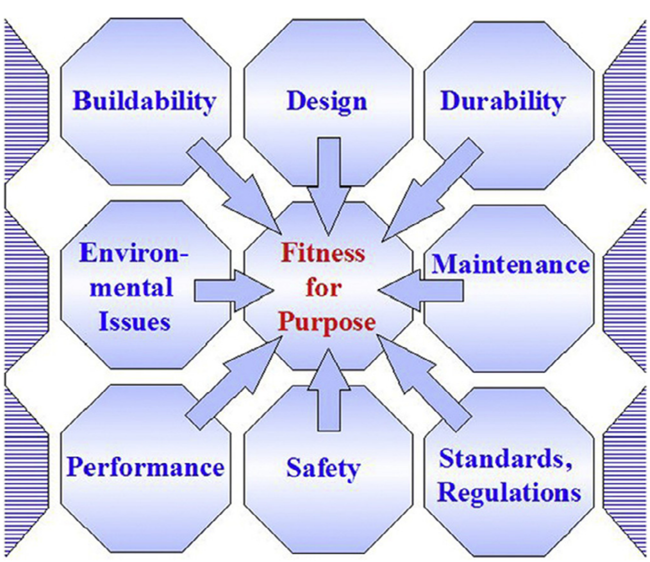

Fig. 1. Parameters for PV building integration [21].

The categorization of BIPV systems can be made according to solar cell type, application type or their names in the market. Solar PV technologies are divided into two sub-categories, silicon based and non-silicon based, while roof and façade integration are the only two types of application. On the other hand, the categorization described in [7] was used for the products in market. The BIPV products were divided into four categories, foils, tiles, modules and solar cell glazing, in Ref. [7], according to the description of the manufacturer or the material that is replaced by the BIPV product. A complete schematic of the categorization used in this study is given in Fig. 4.

3. Review of BIPV/BIPVT systems

In this section, BIPV and BIPVT systems have been comprehensively reviewed in terms of energy generation amounts, nominal power, efficiency, open circuit voltage (OCV), short circuit current (SCC), maximum power point (MPP), fill factor, their type and performance assessment. All papers are listed according to their publication years from past to present and available data given in the papers are presented in Table 1 [23–44,21,45–93,97,99,103–142]. If there are no data, it was indicated as "N/A". When "-" is used between two numbers, it means that the number on the left is the minimum value, while the right one is the maximum value found in study. On the other hand, values for different systems in the same study or results of the studied system under different conditions are separated with a ";" sign. In many papers, the type of the BIPV system was not explicitly stated. Thus, only the known parameter is marked and other cells are left blank in such cases. Based on the reviewed papers, it can be stated that there are many theoretical and experimental studies conducted so far, having a wide range of applications regarding energy generation capacities. Many studies are carried out in the world on BIPV. As shown in Fig. 5, building application studies in Spain, simulation studies in American continent, cell and module design studies in South Korea, grid, policy and strategy studies in Australia are more common. Most of the systems were energetically and economically evaluated, with some presenting environmental analyses as well. Exergetic assessment of BIPV and BIPVT systems, however, has been limited in the literature.

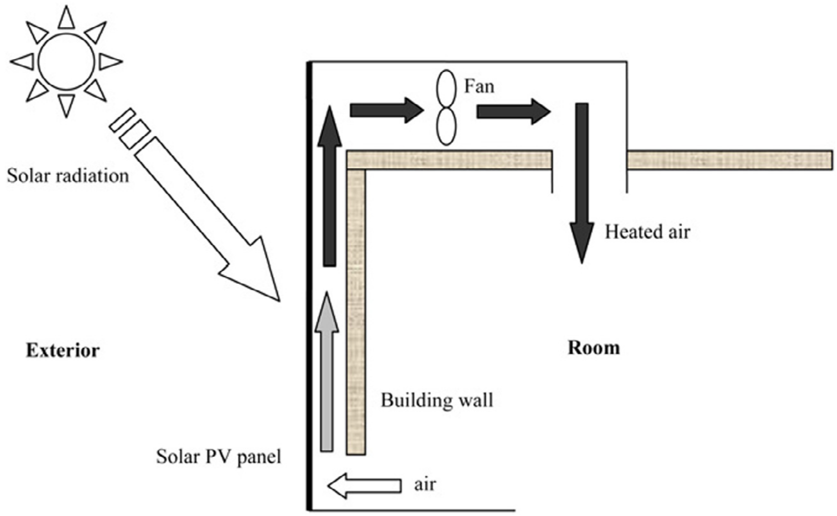

Fig. 3. Schematic illustration of a BIPVT system [5].

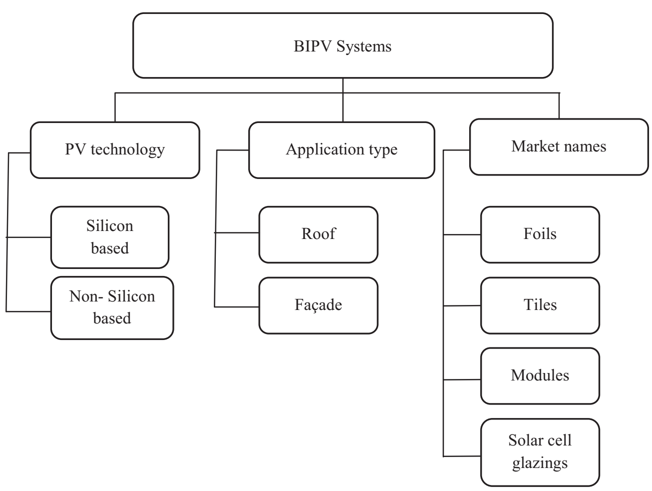

Fig. 4. BIPV categorization.

3.1. Building applications and experimental studies

Building application refers to experiments applied on the building or performed in the laboratory. Various analyses of prototype or system were performed. In general, module efficiency is low at high temperatures. Many studies are made in order to solve this fundamental problem. According to these studies, efficiency is increased by heat absorption at the back of the PV. In order to create this, studies were conducted such as using air or fluid to create a forced convection, opening alternative inputs between hot and cold area in PV, provide fresh air, PV's air gap changing and air gap to set the optimal level. In this way, increase in both the annual production and module life can achieved. Otherwise, shadowing effect, ambient temperature, the direction of the building and the slope of the PV have a significant effect in order to achieve higher power output and efficiency in the building applications.

Omer et al. [23] reported the monitoring results of two different BIPV systems. The first system installed was a thin film PV façade application formed with a 58° tilt angle. The second system consisted of monocrystalline PV roof slates and tilt angle 52°. The average annual system efficiency for the first BIPV system was 2%, while that of the second system was 3.6%. The capital costs for the first and second system were £34,560 and £17,550, while the annualized energy costs were 34.01 £/kWh and 3.69 £/kWh, respectively. It was also concluded that both of the systems were not cost effective at the then current price of energy in 2002.

In [24], a 260 m^2 BIPV system was computationally modeled using ESP-r building energy simulation software. The modules were mounted on a building with an air gap of 250 mm. This gap allows the air to be heated, which is then used for water preheating. Three different design options, namely PV/C (BIPV + cooling of cells), PV/T (BIPV + air heating) and BIPV, were considered for the simulations. Annual energy production amount of these three scenarios were found to be 83,680, 83,584 and 83,205 MJ, respectively.

Yang et al. [25] experimentally investigated the performance of the first BIPV system installed. There was also an air gap between the PVs and the wall to allow cooling and increasing the efficiency. The results showed that the maximum power output occurred on the roof. The total annual energy output of the system was estimated to be 6878 kWh. The power price of the BIPV system was estimated to be between HK$ 1.5/kWh and HK$ 2/kWh, which was higher than the prices of electricity supplied by two local companies.

Mallick et al. [26] experimentally investigated a novel asymmetric compound parabolic PV concentrator and compared the results with a similar non-concentrating system. The results showed that the power ratio between these two systems was 1.62 for the same cell area. In other words, the maximum power point of the system with the PV concentrator was 62% higher than the non-concentrating one. On the other hand, the conversion efficiency of the non-concentrating system was 8.6%, while that of the concentrating system was 6.8. It was also reported that the average cell temperature of the novel system was 12 °C higher than the non-concentrating system.

In [27], a nonlinear first order stochastic differential equation for the heat transfer of a BIPV component was developed. The model was developed using a series of well-controlled experiments of a PV module consisting of 121 polycrystalline Si cells that cover an area of 1.44 m^2. It was concluded that the presented method is very useful for modelling nonlinear stochastic thermal phenomena in BIPV systems.

In Ref. [28], a BIPVT system was examined with three different configurations. The first configuration was the base case of unglazed BIPV with air flow under it. In the second configuration 1.5 m vertical glazed solar air collector was added to the system. In the third and last configuration a glazing over the PV was added.

Table 1
Summary of the BIPV systems studies examined [18–84,87,89,93–132].

Information of Article					Performance Indicators			BIPV Type										Peformance Assessment			
Item No	Investigators	Year Published	Type	Location	EnergyGeneration	Nominal Power (W)	Efficiency (%)	Silicon Based			Non-Silicon Based	Application Area		Cell Type				Energy	Exergy	Economic	Environmental
								Monocrystal	Polycrystal	Amorphous		Facade	Roof	Foil	Tile	Module	Solar Cell Glazing				
1	Omer et al. [23]	2003	Building App. and Exp.	Nottingham,UK	**56, 636 kWh/year***	*N/A*	**0.66, 3.6**	X			X	X	X		-	X		X		X	
2	Chow et al. [24]	2003	Building App. and Exp.	Hong Kong, China	**83205–83680 MJ/year**	*N/A*	*N/A*	X				X				X		X			
3	Yang et al. [25]	2004	Building App. and Exp.	Hong Kong, China	**6878 kWh/year**	**6600**	**9**	X				X	X			X		X		X	
4	Mallick et al. [26]	2006	Building App. and Exp.	Newtownabbey, N.I, UK	*N/A*	*N/A*	**6.6, 8.6**											X			
5	Jiménez et al. [27]	2008	Building App. and Exp.	Madrid, Spain	*N/A*	*N/A*	*N/A*	X	X			X				X		X			
6	Pantic et al. [28]	2010	Building App. and Exp.	USA	**19–40 kWh***	**7000**	**10.5–15**	X					X			X					
7	Corbin and Zhai [29]	2010	Building App. and Exp.	Boulder, USA	*N/A*	*N/A*	**14.5*–17.2***						X			X		X			
8	Chen et al. [30]	2010	Building App. and Exp.	Montreal, Quebec, Canada	**3265 kWh/year***	**2856**	**6.1**			X			X			X					
9	Chen et al. [31]	2010	Building App. and Exp.	Montreal, Quebec, Canada	**3265 kWh/year***	**2856**	**6.1**						X			X					
10	Agrawal and Tiwari [32]	2010	Building App. and Exp.	New Delhi, India	**745–1182 kWh/year**	**7200**	**16**	X					X			X		X	X		
11	Koyunbaba et al. [35]	2011	Building App. and Exp.	Izmir, Turkey	*N/A*	**27**	**4.52**			X		X						X			
12	Peng et al. [37]	2011	Building App. and Exp.	Nanjing, China	*N/A*	*N/A*	*N/A*			X											
13	Agrawal and Tiwari [33]	2011	Building App. and Exp.	New Delhi, India	**839.16–843.67 kWh/year**	*N/A*	**16**	X					X			X		X	X		
14	et al. [38]	2011	Building App. and Exp.	Florianópolis, Brazil	**1265–1110 kWh/kWp**	**10–12 kWp**	*N/A*			X			X					X			
15	Zogou and Stapountzis [39]	2011	Building App. and Exp.	Volos, Greece	*N/A*	*N/A*	**< 9**					X				X		X			
16	Yoon et al. [40]	2011	Building App. and Exp.	Daejeon, Republic of Korea	**1277 kWh/year**	*N/A*	**7**			X		X					X	X			
17	Santos and Rüther [41]	2012	Building App. and Exp.	Florianópolis, Brazil	**5.8, 12.3 GWh/year**	**5, 11 MWp**	*N/A*			X			X					X			
18	Ban–Weiss et al. [42]	2012	Building App. and Exp.	Berkeley, USA	**0.15–0.40 kWh/m²**	*N/A*	**5**			X			X					X			
19	Lodi et al. [44]	2012	Building App. and Exp.	Lleida, Spain	*N/A*	*N/A*	*N/A*	X				X				X		X			
20	Vats and Tiwari [34]	2012	Building App. and Exp.	New Delhi, India	*N/A*	*N/A*	**12**					X	X				X	X			
21	Han et al. [46]	2012	Building App. and Exp.	Hong Kong	**4.43–4.72**	*N/A*	*N/A*			X		X					X	X			
22	Bloem et al. [21]	2012	Building App. and Exp.	Lleida Spain	*N/A*	*N/A*	*N/A*		X			X									

(continued on next page)

Table 1 (*continued*)

Information of Article					**Performance Indicators**			**BIPV Type**										**Peformance Assessment**			
Item No	Investigators	Year Published	Type	Location	EnergyGeneration	Nominal Power (W)	Efficiency (%)	Silicon Based			Non-Silicon Based	Application Area		Cell Type				Energy	Exergy	Economic	Environmental
								Monocrystal	Polycrystal	Amorphous		Facade	Roof	Foil	Tile	Module	Solar Cell Glazing				
23	Drif et al. [47]	2012	Building App. and Exp.	Jaén, Spain	**10.62 kWh/day**	*N/A*	*N/A*	X				X				X		X			
24	Wittkopf et al. [48]	2012	Building App. and Exp.	Singapore	**12.1 MWh**	**142500**	**13.15**		X				X			X		X			
25	Defaix et al. [49]	2012	Building App. and Exp.	EU–27, Norway, Turkey, Croatia	**850 TWh/year**	**951 GWp**	**17.9**	X	X		X	X	X								
26	Koyunbaba and Yilmaz [36]	2012	Building App. and Exp.	Izmir, Turkey	**35.79 W/m^2 (max)**[a]	**27**	**4.27–4.65**			X		X					X	X			
27	Bambrook and Sproul [50]	2012	Building App. and Exp.	Kensington, Australia	**18.28 kWh/day**	**660 Wp**	**10.6, 12.2**	X					X			X		X			
28	Wei et al. [51]	2014	Building App. and Exp.	Shaanxi, China	**140 kWh/m^2**	*N/A*	*N/A*						X					X		X	
29	López and Sangiorgi [52]	2014	Building App. and Exp.	Milan, Italy	**0–1.32 kWh/day**	**31–85 Wp**	**6–17**	X		X	X	X					X	X			
30	Yang and Athienitis [53]	2015	Building App. and Exp.	Montreal, Quebec, Canada	N/A	*N/A*	**5 – 7.6**	X				X	X			X		X			
31	Bigaila et al. [55]	2015	Building App. and Exp.	Montreal, Quebec, Canada	*N/A*	*N/A*	**10–15**	X				X				X		X			
32	Roeleveld et al. [56]	2015	Building App. and Exp.	Toronto, Canada	*N/A*	*N/A*	*N/A*	X	X			X	X								
33	Yang and Athienitis [54]	2015	Building App. and Exp.	Montreal, Quebec, Canada	*N/A*	*N/A*	*N/A*	X				X	X			X					
34	Maturi et al. [57]	2015	Building App. and Exp.	Agrigento, Italy	*N/A*	**80 kWp**	*N/A*					X				X					X
35	Essah et al. [58]	2015	Building App. and Exp.	China	*N/A*	**6.5 kWp**	*N/A*	X	X			X	X					X			
36	Eke and Demircan [59]	2015	Building App. and Exp.	Mugla, Turkey	**46–125 kWh/ m^2.month**	**40.3 kWp**	**0.92**			X		X									
37	Timchenko et al. [60]	2015	Building App. and Exp.	Lyon , France	*N/A*	*N/A*	*N/A*					X		X							
38	Mirzaei and Carmeliet [61]	2015	Building App. and Exp.	Zürich, Switzerland	*N/A*	*N/A*	*N/A*	X	X				X								
39	Ritzen et al. [62]	2015	Building App. and Exp.	Heerlen, The Netherlands	*N/A*	**90–246 Wp**	*N/A*	X				X	X			X		X			
40	Chen and Yin [63]	2016	Building App. and Exp.	New York, United States	*N/A*	*N/A*	**10.48–15.82**	X					X			X		X			
41	Ordenes et al. [64]	2007	Simulation and Numerical	Florianopolis, Brazil	**42.6–144.5 MWh/ year**	**50–180**	**6.3–17**	X	X	X	X	X	X					X			
42	Tian et al. [65]	2007	Simulation and Numerical	Mexico, Brazil	N/A	*N/A*	*N/A*	X		X								X			
43	Bloem [43]	2008	Simulation and Numerical	Ispra, Italy	*N/A*	*N/A*	*N/A*	X	X	X		X				X		X			
44	Friling et al. [45]	2009	Simulation and Numerical	Ispra, Italy	*N/A*	*N/A*	*N/A*		X			X				X		X			

Table 1 (*continued*)

Information of Article					Performance Indicators			BIPV Type										Peformance Assessment			
Item No	Investigators	Year Published	Type	Location	EnergyGeneration	Nominal Power (W)	Efficiency (%)	Silicon Based			Non-Silicon Based	Application Area		Cell Type				Energy	Exergy	Economic	Environmental
								Monocrystal	Polycrystal	Amorphous		Facade	Roof	Foil	Tile	Module	Solar Cell Glazing				
45	Rüther and Braun [66]	2009	Simulation and Numerical	Florianopolis, Brazil	**654.8–1963.2 MWh/year**	**557000–1670000**	*N/A*		X									X			
46	Cheng et al. [67]	2009	Simulation and Numerical	Taipei, Taiwan	N/A	180	*N/A*	X	X			X	X					X			
47	Candanedo et al. [68]	2010	Simulation and Numerical	Montreal, Quebec, Canada	*N/A*	*N/A*	*N/A*			X			X			X		X			
48	Yoo and Manz [69]	2011	Simulation and Numerical	Seoul, Republic of Korea	**217.8 kWh/day**	**345**	**14.4**	X				X					X	X			
49	Cronemberger et al. [70]	2012	Simulation and Numerical	Brazil	–	**–**	**–**														
50	Hwang et al. [71]	2012	Simulation and Numerical	Yongin, Republic of Korea	**183–2785 MWh/year**	*N/A*	**10**	X	X			X				X		X			
51	Bigot et al. [72]	2012	Simulation and Numerical	University of La Runion, France	*N/A*	*N/A*	*N/A*		X				X					X			
52	Alonso et al. [73]	2012	Simulation and Numerical	Almeria, Spain	**8.25 kWh/m^2**	**92**	**4.7**			X	X		X					X			
53	Lu and Law [74]	2013	Simulation and Numerical	Hong Kong, China	**42–80 kWh/m^2.year***	**810**	*N/A*					X					X	X			
54	Yang and Athienitis [75]	2014	Simulation and Numerical	Montreal, Quebec, Canada	*N/A*	*N/A*	*N/A*			X						X		X			
55	Radmehr et al. [76]	2014	Simulation and Numerical	Newcastle upon Tyne, UK	*N/A*	**4 kWp**	*N/A*													X	
56	Kamel and Fung [77]	2014	Simulation and Numerical	Toronto, Canada	**310–820 kWh/month**	*N/A*	*N/A*	X	X	X			X			X		X		X	X
57	Veldhuis and Reinders [78]	2015	Simulation and Numerical	Twente, The Netherlands	**20.9–25.6 Wh/day**	*N/A*	*N/A*											X			X
58	Vuong et al. [79]	2015	Simulation and Numerical	Toronto, Canada	**8.18 kWh/day**	*N/A*	*N/A*					X						X			
59	Kim et al. [80]	2015	Simulation and Numerical	Chungnam , South Korea	**2.8–3 MWh/year**	*N/A*	*N/A*						X					X			
60	Rounis et al. [81]	2015	Simulation and Numerical	Montreal, Quebec, Canada	*N/A*	*N/A*	*N/A*					X	X								
61	Hailu et al. [82]	2015	Simulation and Numerical	Anchorage, USA	*N/A*	*N/A*	15					X	X								
62	Li et al. [83]	2015	Simulation and Numerical	Shen–yang, China	*N/A*	*N/A*	**0.1–0.21**									X		X			
63	Knera et al. [84]	2015	Simulation and Numerical	Tódź, Poland	**45–165 kWh/day**	*N/A*	*N/A*					X	X					X			X
64	Salem and Kinab [85]	2015	Simulation and Numerical	Beirut,Lebanon	**16.3–27.6 MWh/year**	*N/A*	*N/A*	X	X		X	X			X	X	X	X			
65	Kamel and Fung [86]	2015	Simulation and Numerical	Toronto, Canada	**2.8–4.7 kWh/day**	*N/A*	**0.5**		X			X	X			X		X			
66	Mulcué–Nieto and Mora-López [87]	2015	Simulation and Numerical	Manizales, Colombia	*N/A*	*N/A*	*N/A*						X								

(*continued on next page*)

Table 1 (*continued*)

Information of Article					Performance Indicators			BIPV Type										Peformance Assessment			
Item No	Investigators	Year Published	Type	Location	EnergyGeneration	Nominal Power (W)	Efficiency (%)	Silicon Based			Non-Silicon Based	Application Area		Cell Type				Energy	Exergy	Economic	Environmental
								Monocrystal	Polycrystal	Amorphous		Facade	Roof	Foil	Tile	Module	Solar Cell Glazing				
67	ElSayed [88]	2015	Simulation and Numerical	Cairo, Egypta	**942.85–2636.37 kWh/month**	*N/A*	**0.4**					X						X			
68	Sun et al. [89]	2015	Simulation and Numerical	Chengdu, China	**598.26 kWh**	*N/A*	**0.16**					X									
69	Mirzaei and Zhang [90]	2015	Simulation and Numerical	Nottingham, UK	*N/A*	*N/A*	*N/A*						X								
70	Akata et al. [91]	2015	Simulation and Numerical	University of Yaoundé I, Cameroon	**55.4 kWh/year**	*N/A*	**12**		X				X					X			
71	Bueno et al. [92]	2015	Simulation and Numerical	Missouri , USA	**74–227 MWh/year**	*N/A*	**19.7–21**	X					X			X		X			
72	Saadon et al. [93]	2016	Simulation and Numerical	Toulouse, France.	**20–81, 33–77 MWh**[c]	*N/A*	*N/A*									X	X	X			
73	Buonomano et al. [94]	2016	Simulation and Numerical	Naples, Italy	*N/A*	*N/A*	*N/A*	X				X	X			X		X		X	
74	Späth et al. [97]	2003	Cell/ Module Design	Petten, The Netherlands	**1000 Wh/m^2.year**	**5 Wp**	**6**									X		X			
75	Branker et al. [99]	2011	Cell/ Module Design	Kingston, Canada	*N/A*	*N/A*	*N/A*						X			X		X			
76	Vats et al. [103]	2012	Cell/ Module Design	New Delhi, India	**295–813 kWh**[*]	*N/A*	**6–16.5**	X	X	X	X		X				X	X	X		
77	Fathi et al. [104]	2012	Cell/ Module Design	Tipaza, Algeria	*N/A*	*N/A*	**18.62**	X										X			
78	Maturi et al. [105]	2014	Cell/ Module Design	Bolzano, Italy	*N/A*	*N/A*	*N/A*	X		X	X		X			X		X			
79	Kang et al. [106]	2015	Cell/ Module Design	Daejeon, Republic of Korea	*N/A*	*N/A*	*N/A*		X			X	X								
80	Myong and Won [107]	2015	Cell/ Module Design	Choongcheongbuk-do, Republic of Korea	*N/A*	*N/A*	**0.7–8.6**			X	X						X				
81	Cornaro et al. [108]	2015	Cell/ Module Design	Rome, Italy	**269–280 kWh/ m^2.day**	**2.32–50 kWp**	**4.5–13.1**	X		X		X						X			
82	Escarré et al. [109]	2015	Cell/ Module Design	Jaquet-Droz, Switzerland.	*N/A*	*N/A*	**19.1–11.4**[d]		X	X											
83	Virtuani and Strepparava [110]	2015	Cell/ Module Design	Canobbio, Switzerland	*N/A*	*N/A*	*N/A*	X	X	X		X						X			
84	Yu et al. [111]	2015	Cell/ Module Design	Beijing, China	*N/A*	*N/A*	*N/A*				X	X	X								
85	Mazzoni et al. [112]	2015	Cell/ Module Design	Italy	*N/A*	*N/A*	*N/A*														
86	Han and Park [113]	2015	Cell/ Module Design	Seongnam, Republic of Korea	*N/A*	*N/A*	*N/A*									X					
87	Zhen et al. [114]	2015	Cell/ Module Design	*N/A*	*N/A*	*N/A*	*N/A*	X	X			X				X					
88	Bakos et al. [115]	2003	Grid İntegration	Xanthi, Greece	**4000 kWh/year**	**2250**	*N/A*						X					X		X	

Table 1 (*continued*)

Information of Article					Performance Indicators			BIPV Type										Peformance Assessment			
Item No	Investigators	Year Published	Type	Location	EnergyGeneration	Nominal Power (W)	Efficiency (%)	Silicon Based			Non-Silicon Based	Application Area		Cell Type				Energy	Exergy	Economic	Environmental
								Monocrystal	Polycrystal	Amorphous		Facade	Roof	Foil	Tile	Module	Solar Cell Glazing				
89	Huang et al. [116]	2004	Grid İntegration	Ireland, UK	*N/A*	*N/A*	**11–20**					X						X			
90	Crawford et al. [117]	2006	Grid İntegration	Geelong, Australia	**1.85–2.43 GJ/year**	**150**	*N/A*	X		X		X	X					X			
91	Chel et al. [118]	2009	Grid İntegration	New Delhi, India	**3285 kWh/year**	**2320**	**10.5**	X										X		X	X
92	Stamenic et al. [119]	2012	Grid İntegration	Vancouver,BC, Canada	*N/A*	**8.2 kWp**	**43–53**[b]					X				X		X			
93	Zeng et al. [120]	2012	Grid İntegration	Shanghai, China	–	–	–														
94	Ghani et al. [121]	2012	Grid İntegration	Hamilton, New Zealand	*N/A*	*N/A*	*N/A*											X			
95	Liu and Duan [122]	2012	Grid İntegration	Wuhan, China	*N/A*	*N/A*	*N/A*	X										X			
96	Liu et al. [123]	2012	Grid İntegration	Wuhan, China	*N/A*	*N/A*	*N/A*											X			
97	Celik et al. [124]	2015	Grid İntegration	Bornova, Izmir	**1605–5965 kWh/ year**	*N/A*	**12.3**						X					X		X	
98	Fathabadi [125]	2015	Grid İntegration	Tehran, Iran	*N/A*	*N/A*	**9.98**									X		X			
99	Wang et al. [126]	2015	Grid İntegration	*N/A*	*N/A*	*N/A*	*N/A*					X	X								
100	Seyedmahmoudi et al. [127]	2015	Grid İntegration	Victoria, Australia	*N/A*	*N/A*	*N/A*						X			X		X			
101	Keoleian and Lewis [128]	2003	Policy and Strategies	Ann Arbor, MI, USA	**49760–69970 kWh/ 20 year**	**2000**	**3.62–5.09**	X		X			X					X		X	X
102	Cheng et al. [129]	2005	Policy and Strategies	Taipei, Taiwan	*N/A*	*N/A*	*N/A*											X			
103	Jardim et al. [130]	2008	Policy and Strategies	Floriano'polis, SC, Brazil	*N/A*	**50–180**	**6.30–17.30**	X	X	X	X		X					X			
104	Alnaser et al. [131]	2008	Policy and Strategies	Bahrain	–	–	–														
105	Agrawal and Tiwari [132]	2010	Policy and Strategies	New Delhi, India	*N/A*	*N/A*	*N/A*	X	X	X	X		X			X		X	X	X	
106	Hammond et al. [133]	2012	Policy and Strategies	UK	**1720 kWh/year**	**2.1 kWp**	*N/A*			X			X		X			X		X	X
107	Cucchiella and Dadamo [134]	2012	Policy and Strategies	L'Aquila,Italy	**1196–1746 kWh/ year**	**200 (of a PV)**	**9–16**	x	x	x	x		X	X		X				X	X
108	Tsoutsos et al. [135]	2013	Policy and Strategies	Greece, Spain, UK, Cyprus, Romania, Croatia, Bulgaria	–	–	–														
109	Chae et al. [136]	2014	Policy and Strategies	New York, United States	**30–62 kWh/(m^2. year)**	*N/A*	**4.8–6.3**			X		X					X	X		X	X
110	Ng and Mithraratne [137]	2014	Policy and Strategies	Singapore	**1867–5297 kWh/ year**	*N/A*	**3.32–8.02**	X		X		X					X			X	X
111	Yang [138]	2015	Policy and Strategies	Melbourne, Australia	*N/A*	*N/A*	*N/A*	X	X	X		X	X								
112	Goh et al. [139]	2015	Policy and Strategies	Malaysia	*N/A*	*N/A*	*N/A*														
113	Cucchiella et al. [140]	2015	Policy and Strategies	L'Aquila, Italy	*N/A*	*N/A*	*N/A*													X	X
114	Belussi et al. [141]	2015	Policy and Strategies	San Giuliano Milanese, Italy	*N/A*	*N/A*	**6–15**	X	X	X	X				X			X			X
115	Yang and Zou [142]	2015	Policy and Strategies	Victoria, Australia	*N/A*	*N/A*	*N/A*	X				X	X							X	X

[*] Estimated by using given values or diagrams in the paper.
[a] The given value indicates the maximum energy generation achieved during the study.
[b] Given efficiency value of the PV array is calculated as a percentage of the peak power rating of the BIPV array at Standard Test Conditions.
[c] Given values are the range for winter and summer respectively.
[d] Given values are for white and standard module respectively.

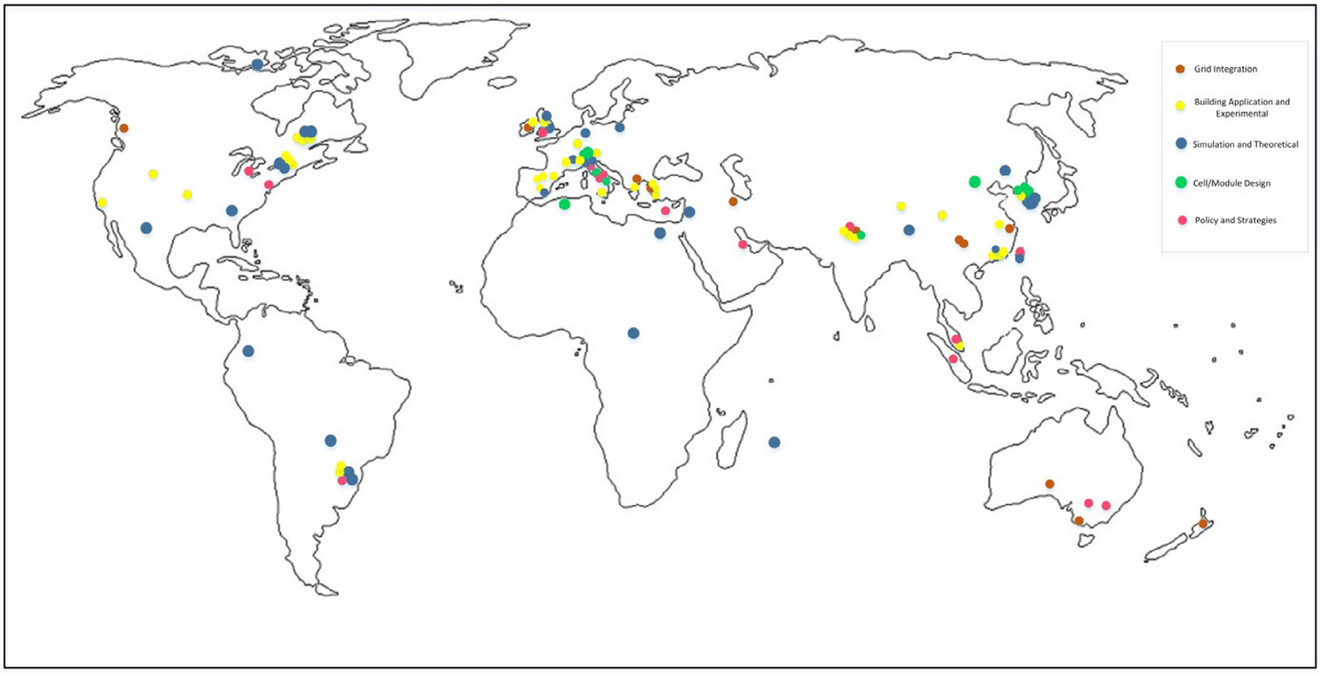

Fig. 5. Studies about the BIPV indicated on the world map according to the study area.

For all the configurations a 7 kWp It was stated that the preheated air in the first configuration was suitable for an HVAC system and preheating of water, while in the second and third configurations significant improvements in thermal efficiency were achieved. On the other hand, in the third configuration, the electricity production was decreased significantly due to excessively high PV panel temperatures.

Corbin and Zhai [29] a novel BIPVT was examined, absorbers, a thermal storage tank and a pump, by which water is circulated to the absorbers. Two different CFD models were created. In the first model, a standard, close to the roof surface, BIPV system was modeled, while in the second model, a liquid-cooled tube-fin absorber was located in the cavity to examine active heat recovery effects. The results showed that the second BIPVT could reach up to 5.3% more electrical efficiency compared to a natural ventilated system. The thermal and total efficiencies of the system were found to be 19% and 34.9%, respectively.

In [30], the air based BIPVT system of a solar house was thermally modelled. The BIPVT system was coupled with a ventilated concrete slab (VCS) system to also provide active solar heating. The annual electricity generation was estimated to be 3265 kWh. Three different technologies, a dryer, an air to water heat exchanger to produce domestic hot water, and a VCS were adopted to use the heated air by the BIPVT system. A quasi-two dimensional, control volume, steady state model was developed. It was stated that the model can be used for similar systems and is useful for air flow control. The results showed that the BIPVT system could significantly reduce PV operating temperatures, and could produce an important amount of thermal energy. The temperature rise of the air that passes through the collector on a sunny day with a flow rate of 250 L/s is found to be between 30 and 25 °C. This temperature rise is equal to a thermal energy gain of 8.5–10 kW. In [31], Unlike the previous study, a 3D control volume, explicit finite difference thermal model was developed for the VCS system. The design of the VCS system used in [30] was explained. The sizing of the VCS system was made for a typical sunny winter day in Canada, assuming an air flow rate of 250 L/s and air temperature of 40 °C for 4 h. The VCS system was experimentally investigated to assess its performance, and it was found out that it can store 9–12 kWh thermal energy within 6 hours with an air inlet of 35 °C and 200 L/s.

Agrawal and Tiwari [32], the use of BIPVT system was investigated. The system had an air blower which consumed 0.12 kWp and provided a 1.2 kg/s constant mass flow rate through the ducts. The performance of the system was examined for four parallel and serial connection combinations. The electrical and thermal exergies of the system was found to be 16,209 kWh/y and 1531 kWh/y, respectively, while the average overall thermal efficiency was 53.7%. It was also concluded that the parallel combination shows the best performance for constant air velocity, while the system connected in series gives better performance for constant air mass flow rate. In another similar study [33], the system was thermally modelled and analyzed under the climatic conditions of two Indian cities, Bangalore and Srinagar. The PV modules used in the system were described in Ref [32], it conducted a study to determine the temperatures of solar cell, duct air and room air for a BIPVT system applied to the rooftop of a laboratory building. Six fans, 12 W each, were employed to circulate the air through the ducts. The results showed that the proposed system is favorable for both moderate and cold climates in terms of yearly electrical energy and exergy production amounts compared to a conventional BIPV system. The electrical efficiencies were found to be between 12.5% and 16% while the thermal efficiencies were in the range of 50% to 54%. In [34], unlike previous two studies, performance of semitransparent and opaque BIPVT systems for roofs and façades were analytically assessed and two options were considered in the analysis: BIPVT system with air duct and without air duct. The air mass flow rate was taken between 0.85–10 kg/s for the systems with air duct. It was found that the difference between semitransparent and opaque BIPVT systems with air duct was 1.46 °C, while that of the systems without air duct was 9.80 °C. The differences for the systems located on the roof were 1.13 °C and 9.55 °C, respectively. The maximum room air temperature was found to be 22 °C, which occurred in the semitransparent BIPVT system without air duct, while the outdoor air temperature was 4.4 °C. It was also determined that increasing the air mass flow rate led to an increase in room air temperature for the semitransparent BIPVT system.

In [35], a BIPV Trombe wall was examined. For the experiments a 0.50 m air gap was left between the modules and the wall. There were two 0.08 m^2 air vents located on the wall to provide heating in winter. The results indicated that the simulation and test results were in good agreement. The electrical and thermal efficiencies on 5^{th} of February were found to be 4.5% and 20.3%, respectively. On the other hand, the natural ventilation mass flow rates were 0.013 kg/s and 0.035 kg/s for irradiations of 638.6 W/m^2 and 750.88 W/m^2, respectively. According to another trombe wall study, single and double glass and a-Si semi-transparent PV panels were evaluated and compared against each other In [36].The system was installed on a well-insulated test room, where covering brick, vertical bored brick, extrude polystyrene and plaster were used for the thermal mass. The nominal power of the PV panel was 27 W, while the OCV and SCC were 49 V and 1.02 A, respectively. There were two vents located on the upper and lower parts of the system, through which the air was transferred into/from the room by natural convection. The tests were carried out for two days, on 25^{th} and 26^{th} of February, and the results showed that the maximum electrical power rate was 35.79 W/m^2, while the electrical efficiency ranged between 4.27 and 4.65%.

In Ref. [37], architectural design aspects of BIPV systems, including (i) how to design BIPV systems, (ii) the lifetime of such systems, and (iii) whether to choose BIPV or BAPV, were studied in detail. The authors have also designed a novel mounting structure to solve issues related to maintenance and replacement of PV components. It was concluded that function, cost, technology and aesthetics are more important than high integration. It was also mentioned that due to the lower lifetime of PVs compared to the lifetime of buildings (50 years), easy maintenance and replacement of PV modules are important.

In [38], the yearly electricity generation amounts of two systems were analyzed. The first system was 3.072 kW_p BIPV system. Thin-film a-Si technology was used and it consisted of 24 flexible modules (128 W_p each). The second system was a curved, 12 kWp PV system and which system consisted of 88 flexible panels (136 Wp each) and were made of thin-film a-Si laminates. The results showed that the first system had a higher annual energy yield at 1265 kWh/kW_p, while the second system generated 1110 kWh/$kW_{p,}$ which is about 88% of the first system's. Also, in the summer period the yield of curved system was relatively higher. Thus, they concluded that a good compromise between form and function was reached in the second (more aesthetically) system. X"

In [39], transient thermal analysis of a BIPV system were experimentally conducted. The experimental setup consisted of a PV panel and a plexiglas panel. A hood was built on the exit of the frame and two axial fans with different capacities were employed. The experiments were carried out in three stages. In the first mode, no fan was used (natural convection), while in the second and third modes, fans were run at 110 m^3/h and 190 m^3/h flow, respectively. According to the results obtained on September 30th, the temperature change of air for different modes was between 4.5 °C and 8.9 °C, while the power range was 74.7–85.5 W. The lowest panel surface temperature occurred in Mode 3. The results suggested that overall heat transfer and cooling increased with higher air flow rates, thus increased fan capacities.

In Ref [40], the first practical BIPV application was experimentally investigated. Transparent thin-film a-Si cells were used on the windows. The PV array were connected 6 in series and 8 in parallel. The system was monitored for a two-year period and the monthly electricity generation amount was determined to be 48.4 kWh/kW_p, while the annually electricity generation amount was 580.5 kWh/kW_p. It was found out through the simulations that the electricity generation amount of the system can be improved up to 47% by changing the azimuth and shading effects.

Santos and Rüther [41] assessed the potential of two BIPV/BAPV systems for the existing 496 single-family residential buildings. The first system was a 2.25 kW_p c-Si system, while the second system was a 10 kW_p a-Si system installed. Four 125 W_p PV modules were used in the a-Si PV kit, while five 200 Wp modules were considered in the c-Si PV kit. The results showed that 87% of the PV kits would be able to generate 95% of the maximum theoretical potential, while only 3% of the systems would be able to generate 85% of the maximum theoretical output. It was also concluded that the kits would be able to produce 40% of the individual annual energy demand of the buildings.

In [42], electricity production and cooling energy saving effects of a BIPV system was evaluated. The system was made of thin film a-Si triple junction solar cells. The solar absorptance of the roof decreased from 0.75 to 0.38 after the BIPV installation. The results indicated that the daily energy output range of the system was 0.15 kWh/m^2 (in winter) – 0.4 kWh/m^2 (in summer) and the average system efficiency for the entire evaluation period was found to be 4.6%. Although the effect on HVAC energy consumption could not be determined due to the repairs on the HVAC system, the authors had concluded that such a BIPV system installed on an office building in Phoenix, AZ would result in 9.6 kWh/m^2 and 2.9 MJ/m^2 annual cooling and heating energy savings, respectively.

In [43], electrical and thermal performance of a PV system integrated as cladding components to building envelope was analyzed. The tests were conducted on a test reference environment (TRE). Four equal sized p-Si PV modules (121-cell glass-glass, 64-cell glass-glass, 121-cell glass-tedlar and 121-cell transparent tedlar-glass) were tested under different air flow conditions. The glass-glass 64-cell PV module showed the highest thermal efficiency while the glass-glass 121-cell PV module showed the worst electric behavior. Also, the electrical efficiency of the glass-tedlar PV module was higher than that of the tedlar-glass one. After that, the collected data were used for the development and validation of a mathematical model. In another TRE work [44], a double skin BIPV system was modeled. Experimental work was conducted in a test reference environment of Lleida (TRE-L). The TRE-L was a well-insulated wooden box, which can be rotated to any inclination. The experiments were carried out for two different inclinations (vertical and 30°) and seven flow rates, through a half year period. Grey-box model was selected as the stochastic method and Continuous Time Stochastic Modelling (CTSM) software was used for the modelling process. It was concluded that the two-state grey-box model described the dynamics of the system with enough accuracy. In [21], a Test Reference Environment (TRE), which allows evaluation of experimental data for electrical and thermal performance assessment of double skin BIPV systems, was presented. The requirements of a standard TRE, including the geometry, instrumentation, experiment procedure and calibration issues, were described referring to experience gained through the 10 years of development in different European research projects. It was concluded that although the assessment of electrical performance data was defined in IEC standards, they do not cover BIPV systems. The outdoor test environment described in the study was proposed as the common TRE for the evaluation of electrical and thermal performance of BIPV applications. According to another TRE study, Friling et al. [45] investigated mathematical modelling of the heat transfer of BIPVs since PV efficiency is closely related to its temperature. Experimental data was obtained from the TRE [38] mentioned above. The analysis showed that it was necessary to employ nonlinear state space models in order to obtain a satisfactory description of the PV module temperature. The results showed that the heat transfer increased when the forced ventilation is increased, and both the fins and a high forced velocity in the air gap contribute to increased heat transfer from the BIPV unit.

In Ref [46], a comparison study of naturally ventilated double-sided PV (PVF) and conventional clear glass façade (CF) was conducted. On the first cell there was only a clear glass and a shield on the façade, while on the second one, a PV layer consisting of a-Si PV cells was employed. It was shown that the indoor air temperature for PVF was lower than that of CF system. The results also indicated that the effect of module temperature on PV efficiency was very small for this type of cells. There was only a 0.29% decrease in the conversion efficiency for a temperature rise of 15.6 °C. It was concluded that besides electricity generation, the PVF system could also lead to energy savings by reducing the air conditioning load.

Drif et al. [47], presented a method for the assessment of energy losses related to partial shading of BIPV systems. PV modules were split into 9 sub-arrays (2.5 kW_p, each). Each sub-array consisted of 2 parallel strings with 10 PV modules in every string. The theoretically generated energy by 1 sub-generator was found to be 12.41 kWh for a day, while measurements indicated 10.62 kWh/-day. Therefore, the daily energy losses due to shading were found to be 1.79 kWh, which corresponds to 14.4% of the total generated energy by the BIPV system.

In [48], performance of a 142.5 kW_p on-grid BIPV system, which were grouped into 22 arrays with different orientation and tilt. An array consisted of two parallel strings with 18 modules in series. The average monthly energy generation was estimated to be 12.1 MWh, while the average monthly performance ratio was 0.81 according to the results. Several parameters, such as the difference between actual and statistical irradiance amounts, tilt angle, PV module temperature, partial shading and irradiance fluctuations, and their effects to systems performance were also presented.

In [49] Defaix et al. used the available statistical data to estimate the technical potential of BIPV in the EU-27. In the analysis they assumed that the BIPV would be based on a mix of crystalline wafer and thin film modules and had taken an average efficiency of 17.9%, and assumed a performance ratio of 0.8. The results showed that the technical potential of BIPV in the EU is 951 Gw_p, while the yearly energy generation potential was 840 TWh. It was concluded that this amount corresponds to more than 22% of the expected European electricity demand.

In [50], PVT system is designed as experimental, unglazed, single pass, open loop. For the minimum friction loss of the fluid in the system and at the channel to be created for mass flow rate between 0.02 and 0.1 kg/s a power input between 4 and 85 W is required. When the experimental results are examined, it is observed that the thermal and electrical efficiency increases as the mass flow rate increases. The thermal efficiency is between 28 and 55% and the electrical efficiency is between 10.6 and 12.2% for midday.

Wei et al. [51] compared the cost-benefits of domestic solar water heater (DSWH) and BIPV systems. The lifetime and energy production amount of the BIPV system were taken as 25 years and 140 kWh/m^2, respectively. The results showed that the BIPV system was more favorable only if a roof area of more than 6 m^2 exists. Otherwise DSWH systems were found to be more beneficial. It was also suggested to install DSWH systems to buildings having roof areas of up to 14 m^2, if the cost of BIPV is more than RMB 0.9/kWh.

In [52], the use of semi-transparent BIPV modules and their impact on human comfort were examined. The test facility consisted of two identical, 10 m^2 rooms. In the first test a thin film CIS PV module and a thin film with a CIS PV module showed better performance in terms of hygro-thermal comfort. The energy consumption for heating and lighting were found to be slightly lower for CIS PV module, while the energy generation amount was also higher than that of a-Si PV module. Second tests were conducted using a m-Si PV module instead of the a-Si PV module, where hygro-thermal comfort analysis again presented better results for the CIS PV module. The lighting demand of m-Si PV module was slightly higher than that of CIS. On the other hand, the m-Si PV module showed better results in terms of energy production (0.09–1.31 kWh/day).

Yang and Athienitis [53] investigated two inlet air based BIPVTs. The experimental setup which consist of 45° sloping and 2 tempered glass. Result indicate two inlet panel showed 5% more thermal efficiency compared with one input semi-transparent panel showed 7.6% more thermal efficiency according to another. Other than this, in addition design of two inlet panel to be preferred that is simple and cheap. Contrary to their previous study, in [54], Yang and Athienitis carried out performance evaluation of multi-inlet BIPVT system. One and two inlets solar simulator and BIPVT prototype was investigated for developing a correlation about heat transfer with convection. Results indicate four inlet panel showed 7% more efficiency according to one inlet, while no significant difference was found between four and five inlets.

In Ref [55], a BIPVT system was made for new type prototype which consist of m-Si panel, 5×10 cm insulation, 1030×548 dimension and 7 cm air gap. For the experimental study 8 moving lamps, each with a maximum power of 4.6 kW, were used. These lamps can be adjusted between 0° and 90°. The result of the experiment new types of solar collector shows similar thermal efficiency with UTC unglazed thermal collector, in addition this new model as the production of electricity 10% – 15% causes higher combined efficiency.

In [56], a BIPVT system which consists of air channel in between, PV layer, an insulation and plywood layer was investigated. There is a natural convective heat flux on the back of system. The system was located 0°, 45°, 90° in inclination angle which was used two different mass flow rate 174 kg/h and 232 kg/h. Optimal values were obtained at 45° angle and 232 kg/s mass flow rate. Results indicate for this orientation, average temperature is 43.8 °C, heat transfer coefficient of PV is 16.25 W/m^2K, heat transfer coefficient of insulation is 5.9 W/m^2K.

In [57], passive low cost strategy was developed for lower module temperature and increase life-time of module. Two type PV panels were used. These With Fin(WF) and No Fin(NF) panels connect in series. Experimental setup was prepared as illustrated Fig 6. Experimental results show that panel temperature can decrease by 5.2 °C and PV nominal power output can increase by 2.3% with this reduction. Annual energy generation and module life-time can increase by 1.2% and 31% respectively.

In Ref [58], 16 years old a-Si cell was made used for experimental performance analysis. System characteristics is 6 refurbished strings, of 18 modules connected in series. When experimental results considering, system total output was found 6.5 kWp. Power output of this old system increased less than 10% under standard test condition and when examining to the last 10 years, performance ratio is almost unchanged. Even if the need for additional work basically these results show that, given by manufacturers argument "it will perform over 80% after 20–25 years" is validated.

In [59], shading effect analysis of a BIPV system was performed. The building consist of 5 floor, each floor are installed with 3 a-Si (triple junction amorphous PV) modules on each array. When energy rating (kWh/kWp) were measures, it was revealed that an annual difference by 16% and a monthly difference between by 10% – 24% occur. Annual energy rating of first array is 1072 kWh/kWp, Annual energy rating of second array 885 kWh/kWp. Minimum electricity output was measured in November due to radiation is least compared with a whole year. If declination angle decreases, energy rating reduces. Shading effect has a significant effect as ambient temperature, the direction of the building and the PV's tilt angle.

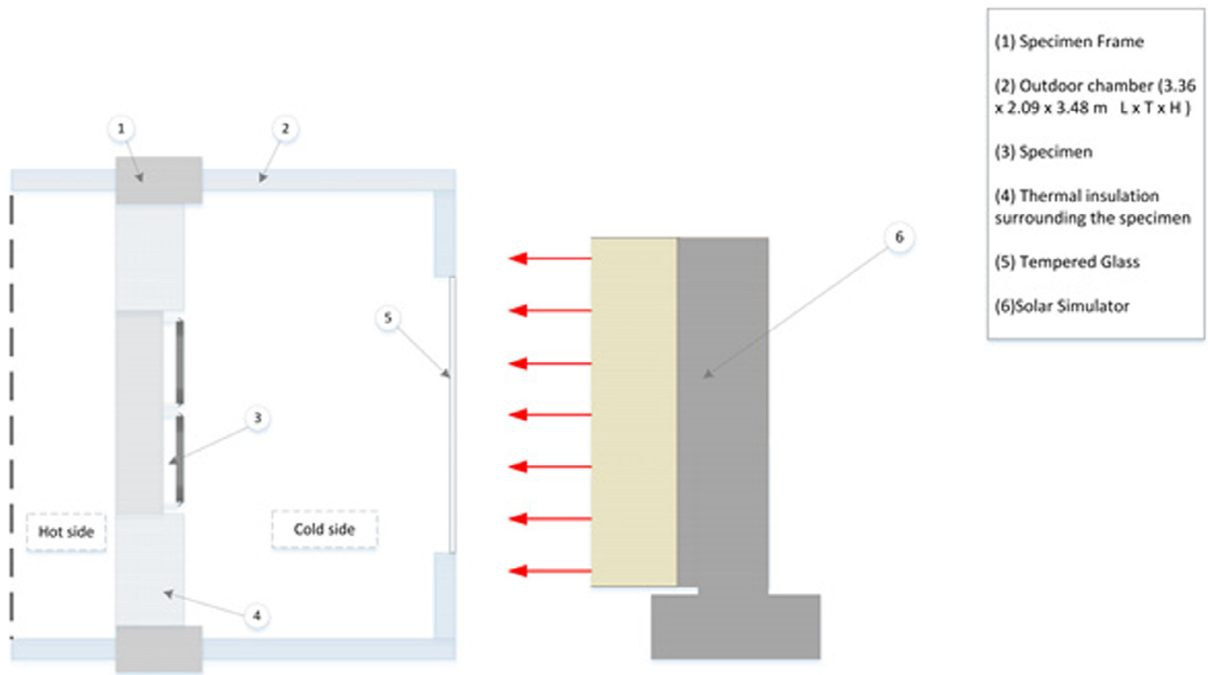

Fig. 6. An **e**xperimental setup of BIPV design with the aid of solar simulator [57].

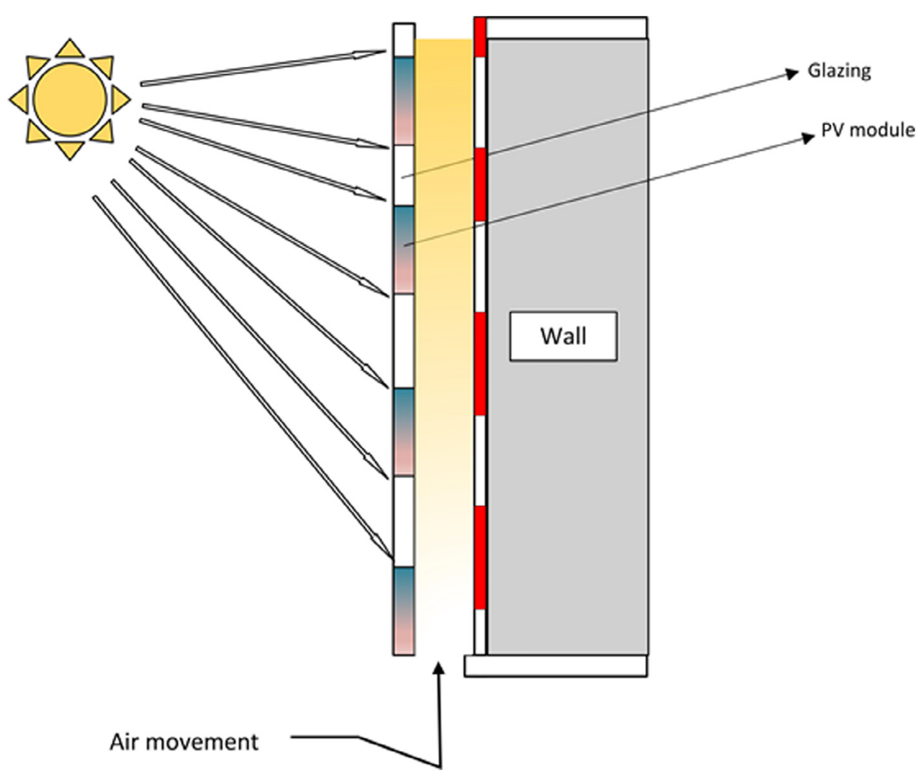

Fig. 7. A staggered configuration of PV module [60].

In [60], analyses of an open channel BIPV system were carried out which system specifications 1.5 m in height, 0.7 in depth, 0.1 in length. 3D calculation and natural convection analysis were provided between two wall for 3 different configurations (uniform, staggered, non-uniform) given in Fig. 7. Results show that alternative input should be opened between hot and cold zone. In this way, heat transfer with convection and chimney effect with mass flow rate increases.

Mirzaei and Carmeliet [61] integrated an experimental study of BIPV system with the width of the air gap (10 cm, 20 cm, 30 cm). Prototype is shown in Fig. 8. For this different air gap width were made temperature measurement and analysis. Result of the analy-

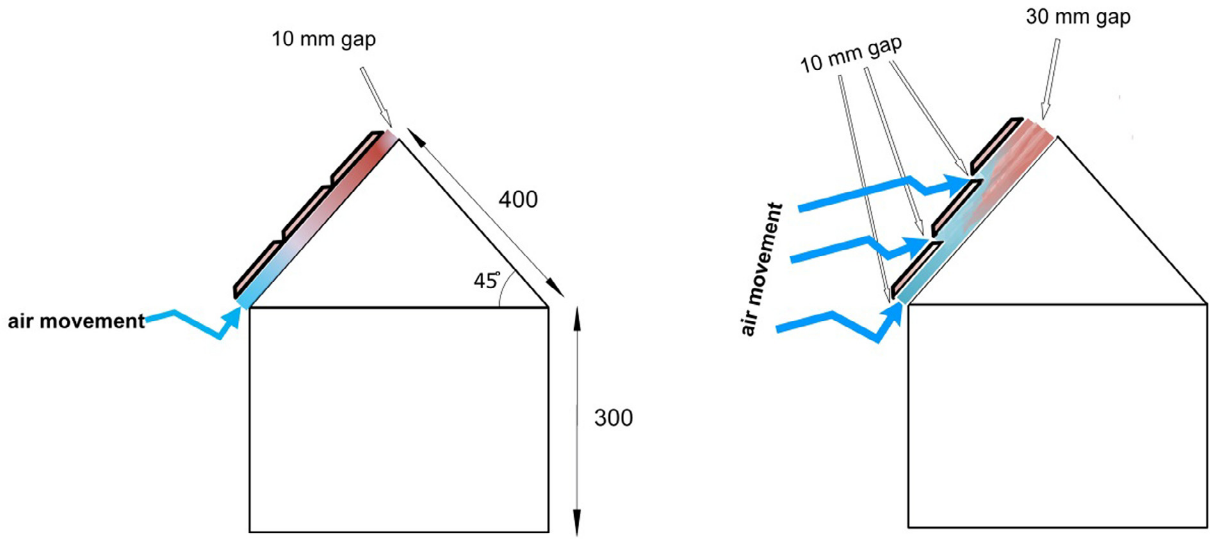

Fig. 8. A stepped layout of BIPV[61].

sis, when stepped layout identified, more ventilation is obtained compared with the flat layout. Side vortex contributes to non-uniform temperature distribution when considering 3D flow. Finally, we can say "The effect of the gap is more for high velocities."

In [62], there is four important topics for development PV market namely, PV integrated to building envelope, price decline, efficiency of PV and electrical storage. 3 field tests were made and investigated for various conditions such as backstring ventilation, condensation and coloring. According to field test 1, PV output power varies between 10% and 40% on spring and autumn day respectively. PV output reduce 0.5%. Because of 100% relative humidity, there is jeopardy of condensation for ventilated and non-ventilated arrays. If black module compared with color module, results of field test 2 show that difference of 10% was observed for PV output power, difference of 62% between vertical and zigzag type lineup. Zigzag type module lineup is more advantageous in autumn-spring period.

In [63], a BIPVT system design has been developed to be used for heating the liquid that was water by cooling the solar energy. The developed panel is as follows: an aluminum high density polyethylene (HDPE) functionally graded material (FGM) panel which is consist of aluminum water tubes. In this way, the temperature was reduced through easily transferring heat from panels to the water tubes. When the results of the laboratory studies are examined, there has been a significant increase in energy conversion efficiency both in terms of electrical production and heat collection. The module temperature at 37.5 °C was reduced to 32 °C with a flow temperature of 30 ml/min. As a result, the flow rate was increased to 150 ml/min. The solar radiation at 150 ml/min has been respectively electricity energy of 32.94 W and 44.91 W respectively for 800 W/m^2 and 1000 W/m^2 and efficiency were 14.51% and 15.8%.

3.2. Simulation and numerical studies

Simulation studies are of great importance for the analysis of the BIPV and BIPVT systems. Simulation work has increased in academic studies with improvement and expansion of recent technology. As a result of these developments, analysis and design of BIPV systems becomes easier and cheaper. Software packages that are used for analysis and design are summarized in Table 2. In general, modeling was carried out in order to determine BIPV performance

Table 2
Softwares used in the simulation studies.

Software	Purpose	Refs.
TRNSYS	Building Thermal Analysis and Simulation	[71,73]
	BIPV Analysis and Simulation	[79]
EnergyPlus	BIPV Analysis and Simulation	[55,70,79,83,126]
PHEONİCS	BIPV Analysis and Simulation	[79]
FLUENT	CFD Analysis and Simulation	[74]
ESP-r	Calculating the power output from the photovoltaic	[19,75,33]
PVsyst	PV modeling and data analysis	[50,60,76]
THERM	Energy simulations	[49]
MOSEK	Equations and Algorithms Solution	[116]
CIELAB	Systematic analysis of colors	[97]
MATLAB	Equations and Algorithms Solution	[37,48,111,115]
PROTEUS	Equations and Algorithms Solution	[115]
Green Building XML	BIPV Analysis and Simulation	[83]
VR4PV	Shadow factor	[69]
FORTRAN	Equations and Algorithms Solution	[77]
eQuest	Calculating the yearly electricity usage	[63]
RETScreen	Annual electricity generation	[25]

with detailed fluid and thermal analysis. In addition, theoretical calculations were pursued by software that solve complex mathematical equations. Simulation studies were made about performance evaluation, power generation, the energy potential of the façade, the effect of shading factors, power generation, electricity usage amounts, temperature analysis, CFD modeling, energy equation analysis and algorithm solutions.

In [64], the potential of BIPV technologies was assessed for six different PV technologies, namely m-Si, P-Si, amorphous silicon, cadmium telluride, copper indium diselenide (CID) and hetero-junction with intrinsic thin layer, were considered. The results showed that total annual energy generation amounts were between 42.6 MWh and 144.5 MWh.

In Ref [65], three different models of BIPV were used to evaluate the performance of a system. In the first model (Model A) monthly performance of the system in urban and rural areas was assessed, while in the second model (Model B) the hourly PV power output of urban and rural areas was calculated. The effect of spectral response of PV modules was considered in the third model (Model C) and the results were compared to Model B. The results showed that the hourly electrical output of Model B is slightly lower than that of Model C, but the difference is less than 6%. The urban PV conversion efficiency was higher than that of rural areas. It was also concluded that the solar radiation and other climatic data should be carefully selected to have a good prediction of the energy output.

In [66], potential energy demand reduction that can be achieved by a BIPV installation was evaluated. The nominal PV power was calculated to be between 557 kW_p and 1670 kW_p for different PV energy fractions between 33% and 100%, while the yearly energy generation amount was estimated to be between 654.8 MWh and 1963.2 MWh for the same fractions. It was also concluded that their large, free of shade and typically horizontal construction makes buildings ideal candidates for BIPVs.

In Ref [67], PVSYST 3.41 software was used to analyze the correlation between the optimal angle and latitude of a BIPV system. For this purpose, 20 different locations which lie in the northern hemisphere and having latitudes between 0° and 85° were selected. The results showed that approximately 98.6% of the optimal performance can be achieved when the latitude is used as the tilt angle instead of the optimum angle.

In [68], an open loop air based BIPVT system was developed as the steady state and transient models. According to results, steady state models generate rapid assessment of the energy balance and this system beneficial for design. Transient models generate more understand the value for development of control algorithms and system design optimization and this model preferable for experimental measurement due to contain thermal capacity effect.

In [69], the simulation programs were used for modelling a BIPV system as a shading device. The system consisted of 114 units and each panel was constructed of 230 solar cells. The electricity consumption results according to the experiments were found to be 221.5 kWh, while simulations estimated 217.8 kWh. The results showed that the air temperature of the remodeled system increases as it reaches higher flows, which potentially results in a reduced power generation while increasing the energy conservation effect, however.

In [70], solar irradiation potential for different type of surfaces (façades, roofs, etc.) was assessed. 78 cities were studied and only in 8 of them the optimum tilt angle was found to be equal to the latitude. Considering the roofs, it was shown that at least 85% of the maximum solar irradiation was available for an optimally tilted system facing north or west, while that of south facing roofs was found to be at least 66%. When façades were considered it was shown that a maximum of 60% of the irradiation was reachable. Therefore, it was concluded that BIPV systems could be considered not only for the roofs, but also on façades at low latitudes.

In [71], BIPV systems in two office buildings (Building A and B) were selected for the examination. Firstly, the yearly electricity usages of these buildings were determined. According to the simulation results, the annual electricity consumption of Building A was about 28,190,000 kWh while that of Building B was 46,800,000 kWh. On the second stage of the study, the electricity production amounts were analyzed. The maximum electricity generation on Building A was found to be 1,875 MWh/year. On the other hand, the maximum energy generation of Building B was found to be 2,785 MWh/year. These generation amounts accounted for 6.65% and 5.92% of the total electricity consumptions of Building A and B, respectively.

In [72], a BIPV system was tested. The experimental system was a test cell with dimensions of 0.6 m × 0.6 m × 1.0 m. The PV panels were located on the roof of the building and necessary data were collected. These data were used during the optimization process. The results indicated that the optimization led to a decrease on the standard deviations and maximum differences between the simulation and experiment results.

In [73], a PV system was integrated into a 1024 m^2. Two zones, 192 m^2 each, were covered with twelve opaque, a-Si thin film PV panels. The results showed that the electricity production of the system was 8.25 kWh/m^2.year. On the other hand, the overall efficiency of the system was found to be 4.7%. After that, the system was modeled using ANN, where Levenberg-Marquardt algorithm was used as training method. The results of the modeling indicated that ANN was suitable for modelling of the system studied.

Lu and Law [74] developed a methodology for the estimation of overall energy performance of semi-transparent, single-glazed PV window. Five different orientations, namely south, south-east, south-west, east and west, were considered in the simulations. The simulations were conducted in three parts: one-dimensional transient heat transfer model, power generation model and indoor daylight illuminance model. The results showed that the total heat gain from the windows could be reduced by about 65% when semi-transparent BIPVs were used. This reduction was then converted into energy consumption of air conditioning system, where COPs of 2.8 and 4.8 were assumed for water cooled and air cooled systems, respectively. The calculations revealed 900 kWh and 1300 kWh energy reductions for water and air cooled air conditioning systems, respectively. The energy generation amounts ranged between 40 and 80 kWh/m^2. It was evident from the results that the largest saving occurred thanks the cooling load reduction.

In [75], a BIPVT system was experimentally evaluated. In the first part of the study, a BIPVT prototype with single inlet was tested and an explicit finite difference control volume model was developed. The air flow rate in the channel was changed to give Reynolds numbers between 1,200 and 10,000, while the artificial wind speed was ranged from 1.6 to 3.5 m/s. In the second part, this model was used to study improved designs with multiple inlets and other heat transfer improvements. Firstly, the model was used for a system with two inlets and the results indicated a 5% increase in thermal efficiency. It also resulted in a 1.5 °C decrease in the peak PV module temperature. After that, a vertical glazed solar air collector was added to the end of the system and wire mesh was applied to this section. The increase in thermal efficiency after this improvement was found to be 10%.

In Ref. [76], North Cyprus was taken as a case study for evaluating the willingness to pay (WTP) for BIPV systems The proposed system consisted of 4 kW_p on-grid system. Its estimated cost and payback period was 6000 Euros and 3 years, respectively, when the excess of the electricity was sold with the price of 0.25 Euros/kWh. 265 heads of the households were taken as the sample of the study and the respondents were asked how much they would pay for the system. The results showed that individuals were willing to pay 6000 Euros including 25% for the installation of 4 kW_p BIPV system on average.

In [77], the TRNSYS model has been developed for the BIPVT system. Accordingly, the air source heat pump (ASHP) system was used for an archetype sustainable house (ASH). The maximum efficiency of the BIPVT system is 16%. Studies were made by considering 2 different flows which mass flow rates were 0.4 and 0.1 on the heat pump. As a result, 225 kg of carbon dioxide emission was prevented with this used modular design and an average of $ 24 per a month was made a profit in 2014.

Veldhuis and Reinders [78] pursued a detailed analysis of shadow effects on BIPV performance. A building has been simulated with a 3D model and it was analyzed with respect to various shadow situations. Results give information "how do we do more to optimize installation" and its indicate 4 PV module based on four connection type (series, parallel, two series connected cells such as 1 & 2 and cell in parallel and two series connected cells such as cell 1 & 4 and cell 2 & 3 in parallel) was analyzed. Energy output was obtained 20.9 Wh, 25.6 Wh, 24.2 Wh, 23.6 Wh, respectively

In [79], a BIPVT model was designed. The subject of this study is to provide information about the important differences between these two software packages: EnergyPlus and TRNSYS. For this purpose, a PV system which consisted of five serial connected 1 m × 1.2 m PV panels was designed. There is an air channel behind the PV system and was placed angle of 45°. The results indicated there are differences and inconsistencies such as sky temperature calculations, electrical models and wind speed that is used by each software.

In Ref [80], a room of a residential building was simulated. The roof is insulated between the cold room however no insulation is used between the roof and the hot room. The electricity production was calculated month by month for a whole year. According to the results of the study, the PV system with the cold roof has generated 7% more power than the one with the hot roof.

In [81], multiple inlet BIPVT system was investigated. System description of air channel height is 0.1 m, panel dimensions are 0.5 m × 1 m, each panel's frame 0.04 m. Solar simulator test was performed to measure the solar irradiation for 0°, 45°, 90° inclination angle. System was investigated for three total flow rates 100 kg/h, 200 kg/h and 300 kg/h. Results indicate, which is based on comparison of measured data with the simulated results, in terms of no external wind and no solar irradiation, the model was found for adequate estimation of the inlets.

Hailu et al. [82] investigated a two stage variable capacity air source heat pump (TS VC ASHP) system. This system consist of wall gap is 76.2 mm, air flow velocity is 1 m/s. The system as shown in Fig. 9. Thermal performance of the system was examined with two scenarios; (A) directly feeding atmosphere air to TS VC ASHP, (B) Coupling TS VC ASHP system with BIPVT on façade. Results indicate maximum COP is 5.31 for TS VC ASHP coupled with BIPVT system. Average temperature is 4.4 °C for this day. The same day COP is 4.2 for TS VC ASHP without couple to BIPVT system.

In [83], a CFD analysis of a BIPVT system was performed. System with an air source heat pump was designed. RNG k-ε turbulence model was chosen in the Viscous Model in fluent solving. Numerical simulation of the system was carried out. The system was thermally investigated based on different inlet velocities such as 2 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s. The COP of the air source heat pump system was found to be 4.6 for the optimal velocity (4 m/s).

Knera et al. [84] investigated façades potential by considering additional lighting from BIPV system for an office room. Modelling was made for annual energy requirement of the office room. It was considered to have 3 LED lamps in the room. Especially, electrical requirement increased when end of working hours in November, December and January. Results indicate based on the investigate of façade potential, the system must be applied to the southern façade. The lowest efficient façade is the north side.

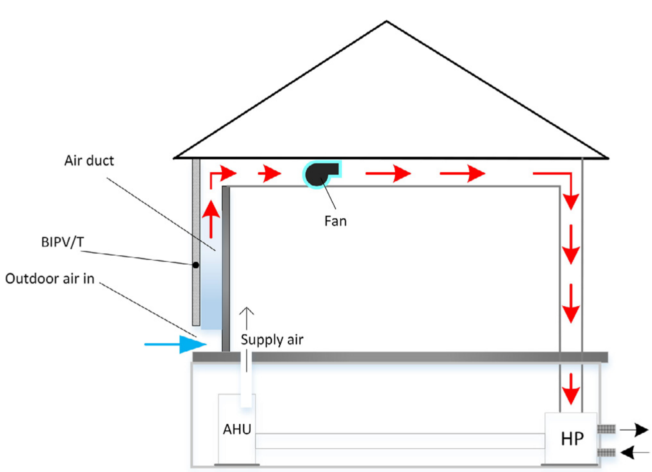

Fig. 9. Forced convection with a BIPVT system [82].

In [85], annual energy demand of a commercial building is 1460 MWh. A few parameters were taken on BIPV system. First parameter, system inclination angle was investigated between 0° and 90° with 10° intervals. Result show for first parameter, maximum energy generation has been 27 MWh/year. Vertical placement should not be preference due to both expensive and energy produced can only receive the 60%. Second parameter, how much area is required to reach target production value (27 MWh) for three type cells (m-Si, p-Si, thin film). This analyze results show the required area approximately same when m-Si and p-Si cell using for this study. If we consider p-Si cell is more cheap than m-Si cell, we should prefer to p-Si cell type module. Last parameter is aim to climate investigation with 30° inclination angle p-Si module for 4 different cities (Rome, Barcelona, Cairo, Beirut). Results indicate approximately same production amount was obtained for each cities.

Kamel and Fung [86] made modelling and characterization study on Transparent Building Integrated PVT (TBIPVT). A PV system was investigated for 0.2 mass flow. The system which consisted of total area 1.9 m^2. Results indicate TBIPVT module compared with opaque module, it was made obtained more thermal energy. If packing factor decrease from 0.9 to 0.5, thermal efficiency increase by 25% and electrical production decrease by 42%. Because available cell area is reduced. In addition, if packing factor is increased electrical production was also observed increase.

In [87], in order to reduce the losses due to shadow factor, many studies were conducted in Colombia. For this purpose, azimuth angle was made calculating and simulation results were plotted. Results show annual solar radiation increases. Results indicated that for each 3 degrees increase in latitude, annual solar radiation increased by 8% approximately. Another result from the study, every type of roof is suitable in everywhere in Colombia, however façade applications are not suitable for places below of the 7 degrees' latitude.

In Ref [88], air gap variations were designed with 3 different program in order to determine optimal air gap type in BIPV system. Concluded that optimal air gap for reducing the PV temperature should be 120 mm if the PV is flat. Also, the nearest point should 60 mm and the further point should be 150 mm if the PV is inclined. If the PV temperature increases, the efficiency is decreases. Optimizing the air gap would decrease the heat transfer of a PV with the inclination angle of 80° and 132 kWh/m^2 electricity production. Thus, the cooling load of the components and the CO_2 emission can decrease approximately 50%.

In [89], shading type BIPV is an important system for decreasing the energy use. Studies were made based on various parameters which are tilt angle, window to wall ratio of construction, overhang length. Result show that PV module generates more electricity at the smaller tilt angle. If tilt angle exceeds 40°, PV output power is reduced. When tilt angle become 80°, annual power output is 106.8 kWh/m^2, reduced by 27% compared with the largest value of 146.4 kWh/m^2. If tilt angle and overhang length increases, power output increases. Maximum electricity production is 598.26 kWh when the tilt angle of PV 70° and the length of the overhang 0.4 m.

Mirzaei and Zhang [90] made simulation study of 3D CFD model. PV which consist of 30 mm air gap was applied mesh and then thermal analysis was made on the 3D model. Analysis results indicate it is composed of the highest surface temperature at the lowest speed (0.5 m/s) and it tends to decrease at speeds over 2 m/s. The main reason of this, related to wind of convection increase on air gap between PV and wall.

In [91], building integrated semitransparent photovoltaic thermal system (BISPVT) system was investigated. The system area of 36.45 m^2 which consist of 30 PV modules and peak power of 5.4 kW. Results reported that annual thermal energy output is 76.66 kWh for total thermal efficiency is 56.07%. Maximum heat was taken from fins to air stream is 25.485 Wh and annual heat extracted from fins is 55.4 kWh.

In [92], two types of m-Si panel (SPR-343J-WHT-U, SPRNE-245-WHT-D) were applied to a building façade. PV slope angles were taken 45°, 135°, 225°, 315°. Annual energy production of these angles were found for SPR-343J-WHT-U model 375.9 kWh, 377.3 kWh, 380.4 kWh, 266.3 kWh, respectively, for SPRNE-245-WHT-D model 365.6 kWh, 148.6 kWh, 133.6 kWh, 659.5 kWh. Based on this results, sufficient energy production can possible for 37 households if global average energy consumption considered that be 167 kWh and 71 t CO_2 emissions may be blocked.

In [93], the performances of three different types of semi-transparent BIPV (opaque, 30%, 50%) were examined using simulations for three cities of France (Nice, Paris. Lyon) under summer and winter climate conditions. The study results indicated that the electricity production based on module type for Nice, Paris and Lyon in the winter climate are 4–8.1 MWh, 2.4–5.9 MWh, 2–4 MWh, respectively, while it is 6.8–7.5 MWh, 4.7–5.5 MWh, 3.4–4 MWh in summer.

In [94] a simulation model of a flat plate BIPVT system was performed economically and energy analysis. There are 3 different arrangements for this system analysis (building and stand alone, roof BIPVT collectors, façade/roof BIPVT panels). As a result, End user was affected from alternative design options these are integrated and non-integrated, but It is recommended to install this system for new buildings to be built in the coming years due to the costs will decrease current market will develop in the future.

3.3. Cell/module design studies

Development of BIPV technology has revealed to development of the module and the necessity of increasing efficiency. Studies on this issue includes analysis about different types of modules or consisting of different types of components for new buildings. The studies related to the design of semitransparent color aesthetical PV module reveals that it is more efficient when this type of module Compared with standard module. New type white modules is promising to obtain a higher efficiency of conservation and in terms of low temperature module. Other than this, as a new type of module design which has created a sandwich-like structure which consist of top thin-film, polyurethane in middle and organic color-plate at the back side. In terms of the characteristics of the material of the new structure showed better performance. Dye sensitized solar cell is a significant improvement for BIPV. Over the last two decades, several efforts are being directed to thin-film technologies aiming significantly reduced manufacturing cost per Wp. These thin-film technologies are mainly based on CdTe, CIGS and amorphous Si. Nevertheless, present manufacturing and materials challenges are limiting their growth on PV market; these are mainly related to high processing temperatures (>500 °C) and environmental concerns related to Cd and Te. Following this high growth of thin-film technologies, another PV device emerged with potential for low-cost fabrication and versatile applications, as flexible or light-weight products: the dye-sensitized solar cells (DSCs) [95]. State of the art lab DSCs, also known as Grätzel solar cells, attained 13% energy conversion efficiency on small area devices [96]. This technology is an important type of thin-film photovoltaics with special interest for building integration applications. As discussed in previous sections, BIPV envisages the incorporation of photovoltaic panels, but so that these elements become actually an integral part of the building. In particular, the photovoltaic cells must have properties similar to the materials that are currently used on the buildings and must be cost-competitive. These properties are patterns, transparency, colors, mechanical resistance compliant to the application and long lifetime. Of course, besides the ones listed before, the photovoltaic modules must have the capability to produce energy when installed in facades, mainly in the vertical position. This means that the PV panels should take efficient advantage of tilted and diffuse radiation. It is interesting to realize that DSCs fulfill the majority of these requirements. Additionally, DSCs enable a stable efficiency for a temperature range up to 60 °C, unlike silicon technologies that strongly decreases the efficiency with temperature. DSC technology uses mainly non-toxic and cheap raw-materials and spends less energy during the manufacturing process than conventional PV technologies, making it an environmentally friendly product.

In [97], these unique features when compared to other technologies make DSCs suitable for applications such as: solar protection fins and louvers, sun protection panels and canopies, facade cladding for curtain facades and rear-ventilated facades, double facades, semi-transparent window areas, sliding shutters, street furniture.

Following these enthusiastic features, various design concepts of DSCs prototypes were already installed and their potential was assessed. The first European laboratory working on the scaling-up of DSCs was ECN (Energy Research Center of the Netherlands) developing several modules of DSCs with different designs (Z-type, current collecting and monolithic). The sizes varied between 100 and 900 cm^2 and maximum efficiencies of 5.5% under standard conditions were reached. The cell-photocurrent stability during 10,000 h of light soaking at 2.5 suns was confirmed by an external entity.

In [98], the greatest drawback pointed to DSCs is related to the still low-efficiency compared to conventional Si-based PV devices. Though, the standard parameters considered to compare energy harvesting efficiency, such as the efficiency measured under standard test conditions and expressed in watt peak (Wp), may lead to an incorrect estimation of the real amount of energy produced by a specific PV technology. In particular, in realistic outdoor BIPV installations, the gap of energy production between DSCs and other available technologies is lower than expected due to geographical localization, non-perpendicular alignment with the sun and cloudy environments. These demonstrates the encouraging performances of DSC under real outdoor conditions.

In Ref [99], actually, in terms of energy production, DSCs are able to convert efficiently both direct and diffuse light. This allows DSCs to be able to absorb the non-perpendicular incident solar radiation without needing complex sun tracking systems with a minimal efficiency loss; able to start producing electricity earlier in the day and finish later and with high adaptability to cloudy weather. However, only a more consolidated large-scale production of DSC panels may allow an extensive verification of the expected beneficial characteristics of DSC technologies, e.g. in terms of response to light intensity and diffuse light and the angular dependence of efficiency.

In [100], in 2007, a glass façade with integrated DSC modules of 30×30 cm^2 in a total area of 70×200 cm^2 was displayed. A decorative design was reached by using a structured-scattering layer of white porous ZrO_2. Generated data showed that during sunny days DSCs modules generated 10% more electricity than single-crystalline Si-devices of the same nominal power (Wp). Also, in cloudy days DSC modules produced 20% more electricity (although the total electricity produced was obviously lower than production during sunny days). DSCs overpassed the energy generation of single-crystalline Si-devices with the same nominal power mainly from drawn until mid-morning and from mid-afternoon to the sunset.

In Ref [101], the first exterior solar window facade was installed. A total surface area of 300 m^2 was installed with 1400 DSC modules, each 35×50 cm^2, and with 5 different shades of red, green and orange, giving the ensemble a warm and dynamic aspect. DSCs not only produce electrical energy from solar energy, but they also shade the building from direct sunlight, reducing the need for air conditioning.

In [102], another important project will be developed during 2015 by G2E and Fibag, installing more than 6000 m^2 of building facades. The most important high profile showcase is the Science Tower in Graz Austria, built by SFL-Fibag. This project is one of the largest BIPV project, where about 2000 m^2 of DSC will be fully integrated into the building envelope.

Vats et al. [103] worked on A roof integrated PV application with air duct and different PV technologies, such as m-Si, p-Si, a-Si, CdTe, CIGS and HIT, and different packing factors (0.42, 0.62 and 0.83) were considered in the energy and exergy analysis. A fan was employed in the system to draw the air into the room with a mass flow rate of 0.85 kg/s. The results showed that decreasing the packing factor from 0.83 to 0.42 results in a decrease of 10 °C on module temperature, which led to a 0.2–0.6% improvement in efficiency. The maximum annual electricity production occurred in HIT system with 813 kWh, while the maximum annual thermal energy was 79 kWh for a-Si system with 0.62 packing factor. Thermal energy and exergy in HIT system (0.62 packing factor) was found to be 83 kWh and 32 kWh, respectively.

In [104], effects of replacing the glass used in BIPV systems with a polymer material were studied. Doped PMMA was selected as the polymer, and its spectrometry was experimentally investigated. After that, PC1D solar cell simulation software was used in order to evaluate the conversion efficiency of solar cells. The results indicated that the efficiency of the silicon solar cell had increased by 5% after the replacement. It was concluded that the use of PMMA on silicon solar cells could reduce the cost of the system, and also increase the photoelectric energy production.

In Ref [105], a linear model of BIPV system relating the module temperature with the ambient temperature, incident solar radiation flux and Ross coefficient (k) was developed. The main purpose of the study was to present the k values for different types of PV, 6 different PV modules, 1 CIGS, 4 m-Si and 1 a-Si with different stratigraphy, were investigated through the tests. All modules were installed with 30° inclinations and an azimuth angle of 8.5°. The k values ranged from 0.033 to 0.037 Km^2/W for the glass-glass modules, while that of glass-tedlar modules found to be between 0.029 and 0.032 Km^2/W.

Kang et al. [106] investigated design of asymmetric BIPV. Design mainly was porpused to capture more efficient light with asymmetric angular placement on the photovoltaic surface. In Fig. 10, the schematic illustration of BIPV surface is given. Two type design called V-groove and glazed was investigated for different tilt angles. Optimal asymmetric surface angle was taken between 30° – 77° and −23.5° – 23.5 for blazed and V-groove type surface, respectively. Most optimal values were found as blazed type, asymmetric surface angle 30° and vertical placement. Result show that V_{oc} = 0.88 Fill Factor = 48% for this optimal design. In this way it has been optimized, annual energy production of the system can achieve increase of 15%.

In [107], semi-transparent color glass-to-glass (GTG) PV module. A lot of color was chosen appropriate to 3D color lazer technology. Solar cubes were created. Each of these cubes area is 1.43 m^2 which of types, namely, Transparent back glass(TBC) yellow module, TBC orange module, TBC green module, Opaque back contact (OBC) sky blue module, hybrid type light blue. Results reported that P_{max} value has declined with color and T value of back glass. In addition to OBC type module is the best way to achieve the target color with high conversion efficiency. Finally, aesthetic sky blue color is best for OBC module module with 7.2% efficiency.

In Ref [108], dye sense cell type solar panels was compared with a-Si and m-Si BIPV panels in terms of electricity. When experimentally results was evaluated, average watt-peak value of DSC modul more than 12% and%3 according to a-Si modul and m-Si modul, respectively. If the comparison is made about amount of energy generation of DSC panel and m-Si panel, DSC showed higher efficiency from start of the test until the middle of September. Optimal performance month is August compared with other type module. For these reasons, DSC module better than a-Si and m-Si modul.

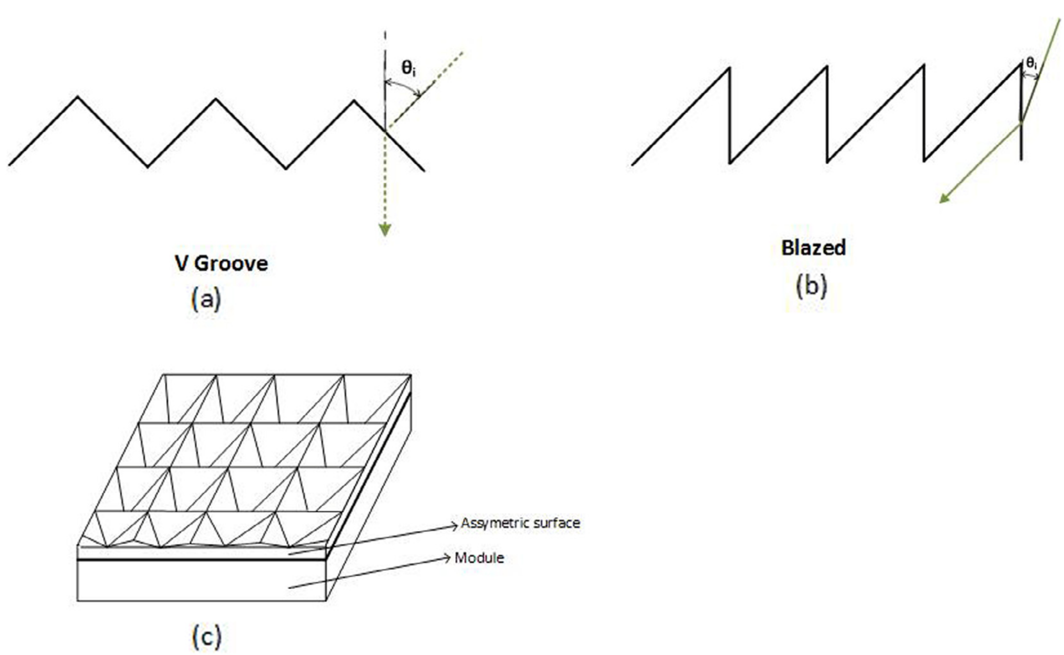

Fig. 10. (a) Angular illustration of V groove type asymmetric surface, (b) Angular illustration of Blazed type asymmetric surface, (c)A BIPV module with asymmetric surface [106].

In [109], new types of white PV module which can be obtained conservation over 10%. 9 heterojuntion solar cell which dimensions of 55 x 60 cm were connected in serial. When analysis is evaluated, loss of efficiency is around 40% for the white module because it reflects most of the light which can be converted into electricity but module temperature is lower due to reflect light compared with other modules. The white modules values were obtained as Voc = 0.714, FF = 74.4, Efficiency = 11.4. Compared with standard module, V_{oc} value less than 1.8%, FF value more than%4, Efficiency less than 40.2%.

Virtuani and Strepparava [110] investigated performance of a-Si and c-Si module from different perspectives. Results indicate main loss mechanism of c-Si technology was occurred temperature loss due to high temperature coefficient in summer. In contrast main loss mechanism of a-Si module was occurred spectral effect and deterioration situation. This deterioration situation was due to Stabler-Wrensky effect and lower of average temperature.

Huacong et al. [111] designed a new type module. We could consider like a sandwich to new design. New type module which consist of thin film on top, polyurethane(PU) in the middle and color organic-coated plate was located behind. When the new design through a series of tests, results obtained is as follows; power output of each unit is 65 W, flexural capacity is 0.6 kN/m^2, bonding straight 0.15 Mpa the thermal conductivity coefficient 0.024 W/m^{2}K.

In [112], dyes, the so-called co-sensitizing NIR dyes, were used in this study for specific applications and the aim is to increase the efficiency of the solar cell by increasing the absorption of the two dyes through gold nanoparticles in the dyes that called NIR. Researchers had made many tests for the shape preservation on products and optical properties of gold nanorods (GNRs). One can say that metallic nanoparticles are not expensive and plasmonic effects of metallic nanoparticles are utilized with same techniques for photocatalytic applications.

In Ref [113], study of material characterization and proses improvement was made about dye sense solar cell (DSSC) sealant. Expansion of electrolyte causes the breakage of the filler in the module. Investigation of the effect of the curing process is performed for sealant material. For this purpose, curing process was made to specimen of sealant with UV and shadow moire technique is used for measure to coefficient of thermal expansion. Finite element analysis was carried out to optimize the curing process. If the curing time is shortened, coefficient of thermal expansion became smaller and maximum stress of sealant. As a result, for more rugged DSC module a longer curing time is recommended.

In [114], IEC61215 method was used for operating temperature method of BIPV module. Same environment condition was taken with IEC61215 method which consist of radiation is 800 W/m^2, environment temperature is 200 °C, wind speed is 1 m/s. Looking at the results for simulated home between grid-connected and open-circuit modules must note that there is a difference 7 °C. It has been found that temperature differences between the cell and module back for insulated glass module. The largest temperature difference is seen over 15 °C when radiation approaching to 900 W/m^2.

3.4. Grid integration studies

Studies about grid integration usually focus on increasing the efficiency of the system with changes to the configuration of the PV. Organized this way energy distribution systems are intended reduction of losses and to enhance the efficiency of obtained energy. Efficiency of the system can be increased according to DC output power of PV storage system with selecting DC operations about recommended in the housing. Energy is partially lost in the grid throughout electronic components, transformers, and long distribution lines. Solution is to avoid unnecessary integration of grid and to backup resources the grid with BIPV system. Finally, phase change materials (PCMs), which are used for heat storage and passive electronic temperature control, absorb a huge amount of energy as latent heat.

In Ref. [115] Bakos et al. used a computerized renewable energy technologies (RETs) assessment tool to perform feasibility analysis of a grid-connected BIPV system. The BIPV system, which is the first BIPV system, had a capacity of 2.25 kWp. The system consisted of 3 sinusoidal inverters (850 W nominal power of each). The energy production amount and the cost of the system was estimated to be 4,000 kWh/year and 24,000 €, respectively. The payback period was found to be between 20 and 50.1 years for different subsidy amounts ranging between 0% and 60%.

In [116], the use of phase change material (PCM) was experimentally and numerically investigated for controlling the temperature rise of a BIPV application. The model was used to investigate different parameters such as, ambient temperature, insolation, system geometry and PCM. It was also concluded that it was the only validated PV/PCM model and it provided a detailed insight into the thermal performance of PCM when used for PV temperature control applications.

In [117], life cycle assessment of two different types of PV cells combined with a heat recovery unit was carried out, and payback periods were determined. First system consisted of two 75 W -Si PV modules with a total area of 1.26 m^2, while in the second system a heat recovery unit was added to benefit from the wasted heat produced by the PV modules. In the third system a-Si PV modules were used instead of c-Si PV modules. The energy payback period was found to be between 12 and 16.5 years for the first system, between 4 and 9 years for the second system, and lastly between 6 and 14 years for the third system.

Chel et al. [118] developed a simplified model for sizing and life cycle cost assessment of BIPV systems in their study. They applied their methodology to an actual case study of 2.32 kW_p PV system. The system had two subarrays: first one consisted of 32 PV modules (35 W_p each) and the second one consisted of 16 PV modules (75 W_p each). The unit cost of electricity from BIPV was estimated to be US$0.46/kWh. However, it decreases to US$0.37/kWh when carbon credit potential of the system was considered. Besides, the capital cost for the BIPV system was found to be US$6963/$kW_p$. The total annual energy generated by the system was 3285 kWh, while the payback period was calculated to be 10 years.

In [119], the performance of a BIPV powered electrolyzer and fuel cell system was optimized. The system consisted of a BIPV array, a battery, a boost converter, an inverter, a buck converter, an electrolyzer, a compressor, an H_2 storage tank, a gas pressure regulator and two fuel cell stacks. The nominal power of the BIPV system was 8.2 kW_p and it was vertically mounted on the south façade of the building. The results of the study showed that the controller was able to operate the electrolyzer smoothly using the BIPV generated electricity, and suggested that systems with such configurations were viable.

In [120], a multi-functional utility interface of BIPV systems based on cascade converter, which had two operation modes, was presented. First operation mode was as grid-tied inverter under normal insolation, while the second one was as active power filter (APF) under low insolation or night time. Simulation result validated the feasibility of the proposed system, and it was concluded that the proposed system could optimize the use of existing components in grid-connected BIPV systems.

In [121], an artificial neural network (ANN) was proposed by the authors to estimate the conversion efficiency of a BIPVT system. The results of 288 simulations were used for training, validation and testing of the network. The results indicated that the ANN could be used for estimating the BIPVT output under various operating conditions. Although it was very time consuming and computationally intensive to get the necessary numerical simulation data, after the training process, the ANN was fast and could be used for interpolation of values within the limits of the training set.

In Ref. [122], an energy efficiency evaluation method for BIPV systems with different power configurations was presented. Case I represented strong irradiance and slight shade, Case II represented strong irradiance and severe shade, Case III represented weak irradiance and slight shade, Case IV represented weak irradiance and severe shade and lastly, Case V represented electrical parameters mismatch of PV modules. The maximum available power of the system was found to be 5,315.6 W for Case I, 2,818 W for Case II, 195.43 W for Case III and 60.17 W for Case IV. The results indicated that the integrated converters could keep each PV module in the AC module and PV-DCBM based system working at its own MPP. It was also shown that AC module and PV-DCBM based systems were the most favorable solutions for BIPV systems due to their superior anti-shading and anti-mismatch features.

In [123], modelling and energy balance based coordinate control of a PV DC building module (PVDCBM) based BIPV system were proposed. The system consisted of PVDCBMs and a centralized inverter, where each PVDCBM in the system had an individual MPPT system, enabling to extract the maximum power from the PV module. An experimental setup, consisted of two PVDCBMs and a centralized inverter, was built in order to validate the developed model and the control strategy. The results validated the proposed model and control strategy, with satisfactory dynamic response and the steady state performance.

In Ref [124], analysis of spatially fixed PV array was made about arrangements to be made for maximum energy storage. For this purpose, repayment period was analyzed so that the PV fixed with the best electrical arrangement for the annual production amount and different configurations. 12 PV which consist of 12.3% efficient, 125 W nominal power. Generally, Series-Parallel system and Total cross tied (TCT) connection was used in electric connection. TCT connection was compared with SP system. If various configurations (2×12, 3×8, 4×6, 6×4, 8×3, 12×2) and solar energy costs in Turkey $ 0.5/kWh were taken for calculation of payback period, it found average 1.67 years. Payback time varies considerably with different configurations and different electrical arrangements (SP and TCT). Only possible to increase the efficiency of the system with changes the configuration of the PV.

In [125], PV inverter battery compartment of independent BIPV is given information about the new plan developed. Firstly, part of this inverter battery was configured in parallel. Homogeneous array of PV modules was configured and which were showed how to improve energy efficiency. Theoretical results were obtained using the Lambert W function. When obtained results compared with theoretical results, energy efficiency of the converter-battery section of the PV 10% increase was verified. Obtained results which in simulation/theoretical studies were confirmed.

In [126], a building was investigated about distribution network with Mixed Integer Linear Programming (MILP) which a mathematical algorithm. It has been presented a proposal by examining the energy consumption of the building with BESS (battery energy storage system) and BIPV system. When results of the study were analyzed active power consumption of smart meters can be minimized with the help of two-way communication based on information which daily pricing, weather, and customer preferences. BIPV become more compatible to distribution network with this proposed algorithm.

In [127], micro grid technology is an important subject of BIPV studies. BIPV efficiency of the system can be increased if DC operations selecting in the proposed housing according to DC output power of PV storage system. Another topic is MPPT (maximum power point tracking) which plays an important role on the amount of energy which can be extracted from the production unit. Produced energy is lost throughout electronic components, transformers, long distribution lines in the grid. The best way to deal with grid and backup resources grid should avoiding unnecessary integration with BIPV system.

3.5. Policy and strategies

The information below regarding BIPV technology gives information about strategies to be followed and barriers to development. Basically, the willingness of the developer and incentives to be applied to investors which should be increased. Also, communication of all stakeholders should increase about developments concerning of BIPV.

In Ref. [128] a life cycle model was applied to an amorphous silicon PV roofing shingle considering different locations across the US. A 2 kWp PV system with 6% conversion efficiency and 20 years of life was selected and electricity generation amounts, payback periods, electricity production efficiencies and total mass of air pollutant emissions avoided were calculated for each region. The electricity production efficiencies were found to be between 3.62% and 5.09%, while the payback periods were between 3.39 and 5.52. It was also concluded that the BIPV systems had the largest air pollution reduction benefits in cities where coal and natural gas are used for electricity generation, not in cities with the greatest insolation and displaced conventional electricity.

In Ref. [129] an empirical approach was reported for evaluating the annual solar tilted planes irradiation with inclinations and azimuths between 0° and 90° for BIPV applications. The researchers also validated the developed regression equations by using an established measurement system with five pyranometers. It was also concluded that the developed method could be used to evaluate the annual irradiation on a BIPV envelope and solar energy applications in architectural planning.

In [130], the potential of on-grid BIPV was investigated. For this purpose, six different commercially available PV technologies were considered and the results were compared. These six PV technologies were a-Si (1.12 m^2 module area, 64 W rated power, 6.3% efficiency), CdTe (0.72 m^2 module area, 50 W rated power, 6.9% efficiency), CIS (0.73 m^2 module area, 60 W rated power, 8.2% efficiency), p-Si (0.64 m^2 module area, 75 W rated power, 11.6% efficiency), m-Si (1.26 m^2 module area, 170 W rated power, 13.5% efficiency) and HIT (1.18 m^2 module area, 180 W rated power, 17.3% efficiency). It was indicated that even for the least efficient technology there is enough space on the roofs to accommodate PV systems that can enable at least 30% PV penetration level.

In [131], a model that allows calculating the sustainable building index (SBI), which ranges between 0.1 and 1.0, was developed. Nine drivers (subsidies, environment etc.) and fifteen barriers (such as high capital cost and long payback period) were ranked by the authors according to their importance. The proposed model was applied to Bahrain and the SBI was found to be 0.47, which indicates that extensive effort should be made so that BIPVs or building integrated wind turbines (BIWT) could be used. It was also indicated that the proposed model can be used globally to create a global SBI database to allow developers, investors etc. to evaluate the use of BIPVs or BIWTs.

In [132], a BIPVT system was dynamically modelled to determine energetic, exergetic and economic performance. The proposed system had six serially connected ducts under the PV modules, through which the air was circulated with a 0.72 kW_p air blower with a constant mass flow rate of 1 kg/s. Six different PV cell technologies, namely mono-crystalline silicon, poly-crystalline silicon, EFG ribbon crystalline silicon, amorphous silicon, cadmium telluride and copper indium gallium selenide, were considered for the model. The results showed that mono-crystalline BIPVT system was found to be more energy and exergy efficient compared to other cell technologies, while the most economical system was the amorphous silicon system. The energy efficiency of this system was found to be 33.54% while the exergy efficiency was 7.13%. It was also concluded that the cost of generated electricity from the system (US $ 0.1009/kWh) was very close to the cost of energy generated through the conventional grid.

In [133], performance of a domestic BIPV system was assessed using energy analysis, environmental life-cycle assessment (LCA) and economic analysis. The embodied energy of the system was found to be 83 GJ, while the displaced energy payback period was found to be 4.5 years. The capital cost for the system was estimated to be £10,500 – £13,000. The economic analysis indicated that net present value (NPV) for the best case was only £1,300 with a payback period of 15 years.

Cucchiella and D'Adamo [134], presented some performance indicators used for the estimation of energetic and environmental impacts of BIPV systems which located in different cities of Italy, namely Roma, Milan and Palermo. Different types of PV cells, such as CdTe, CIS, p-Si and c-Si, were used in the analysis as well. The minimum energy payback time among all options was found to be 1.8 years (CdTe PV cells, Palermo), while the maximum of it was 2.9 years (p-Si PV cells, Milan). Greenhouse gas per kilowatt hour ratios were found to be between 71 and 92 g/kWh, while the energy return on investment values were between 6.4 and 10.2 years. The greenhouse gas payback time and greenhouse gas return on investment values were also calculated to be between 2.5–3.3 and 5.7–7.4, respectively. It was stated that these metrics could be used by policy makers for the establishment of incentives and decision making.

In [135], the lack of adequately skilled workforce for PV/BIPV installation and maintenance was addressed. It was stated that this situation could result in poorly installed systems and creating a negative impact on the industry. The PVTRIN project, supported by the European Commission, addressing this fact was explained in detail.

In [136], the overall energy performance of BIPV windows was evaluated This model was used to calculate heating/cooling energy consumption, electricity generation, and greenhouse gas emission rate for each case, and to show the effects of optical and electrical parameters of the cells. The annual electricity generation amounts ranged from 30 kWh/m^2 to 62 kWh/m^2. It was also found that in all cases the annual HVAC energy consumption was reduced. The highest saving potential was determined to be $12,000/year, while the maximum green-house gas emission reduction was found to be 68.14 tons of CO_2 eq/year.

In Ref [137], the life cycle environmental and economic performance of BIPV windows systems was investigated. The effect of the BIPV system on day lighting and heat gain/loss amount of the building was also considered in the analysis. The results indicated that the energy payback time was between 0.68 and 1.98, while the energy return on energy invested (EROEI) range from 1.98 to 34.49. The life cycle energy showed a decrease between 19 and 55% for all modules, compared to the base case. It was stated that, the payback periods of some modules went below zero after the consideration of governmental subsidies, while that of the half of the remaining ranged from 1.1 to 13.1 years.

In [138], technical risks and barriers about software and hardware is important in BIPV application. These risks was investigated in various stage such as design, construction and installation stage, commission stage, operation stage. Barriers and their solutions are mentioned in each stage. The fundamental barrier of BIPV is niche market and high cost of that complex system for all stakeholders. The spread of this technology depend on develop to these solutions and to deploy correctly solutions between stakeholders.

Goh et al. [139] given information about how can keep studying with the intent to develop entrepreneurship and awareness on researches of BIPV. Developers is the major factor of BIPV that is lagging evolutionarily because of increase on prices of houses with the BIPV systems. Developers that are related with the development of BIPV are ineffective. Accordingly, the first stage is related with developers' application subject, in the second stage suggestions for problems that are related with the applicable solutions thoroughly are offered and ideas are corroborated with an agreement. Furthermore, 3rd stage is about the detailed planning process for the selection of BIPV by developers. When considered as a result, developers seem willing about it. All needed to be made to facilitate or raise the communication between stakeholder or developers or investigators and to frequently inform them about studies, researches, developments which are related with this topic. Additionally, the future situation of BIPV should be determined correctly and later they should be shared information with developers, researchers or stakeholders.

In [140], BIPV system was analyzed. Comparisons were made about renewable energy, cost analyses. When we evaluate analysis results that are studied from different perspectives can say that according to renewable energy installation that is 134 MW in Italy, 8.5tCO2 eq and 2000€ can be gained for each kW in terms of economic and environmental impacts. If they are unknown or there is a excess unbalance can be determined using the f_{pv} (1 year) method. These investigations will be beneficial for all countries willing to implement the PV development policies.

In Ref [141], The objective of study, ceramic tile prototype produced as a industrial product. Optimization of ceramic tile is investigated Life Cycle Assessment (LCA) based on ISO 14,040 international standard, production stages were examined, market price of PV technology has been compared. Result show that When considered the whole life cycle of a building, both decrease in material usage is provided and more electricity production is achieved with less environmental impact.

Yang and Zou [142], evaluated BIPV technology in terms of their costs, benefits, risks, barriers and possible improvement strategies. It's stated that in order to increase the applications of BIPV it is important to decrease the costs which is pretty much dependent on having the right policy and incentive support and the key supply chain members.

4. BIPV applications: Overall outlook

At present, BIPV systems still represent a small share of the PV market mainly due to the mistaken belief that BIPV integrations are more expensive than conventional roof installations and that the strong incentives given in the past were associated only with "utility" products and not-distributed generation (solar parks). Under this scenario, it is mandatory to carry out an effort for developing and breaking into the market of multifunctional BIPV solutions capable of satisfying the demands of main stakeholders in the building sector in a holistic manner (cost, aesthetic, technical and structural needs) taking into account the benefits associated with building users. Obviously, without forgetting the application of essentially technical concepts supported by Energy Efficiency, Renewable Energy Sources (RESs) and Distributed Energy Sources (DESs) directly pointed to new energy models based on NZEB Nearly Zero Energy Buildings (NZEBs) or Zero Emission Buildings (ZEBs) and green building certifications as PASSIVHAUS Standard, BREEAM Certification or LEED certification.

Thus, a niche market is already opening with large expectations even thinking on a short-term basis. For instance, the goals defined by the EU till 2020 requires 3% of all public buildings have to be renovated per year until 2020 [143]. Furthermore, a EuroAce investigation shows that if all existing buildings in Europe could be submitted to a necessary and deep retrofit until 2050, at least 5 million of annual buildings would be involved across the EU over the next forty years [144]. Specifically, in the EU there are about 160 million buildings, which represent about 40% of the primary energy consumption and 2/3 of CO_2 emissions [145]. Most of them have been designed and built without taking into account passive energy-efficiency strategies as well as the integration of RESs for satisfying active energy demand. In this sense, they count with disproportionate energy consumptions coming from exploitation of fossil fuel resources. In this sense, a BIPV niche market was already opened. There are several BIPV solutions, which will be described as in the following.

One of the BIPV solutions more demanded in the construction market is the Multifunctional PV façade. It is an innovative constructive solution really useful for providing active and passive benefits to the buildings that need to be retrofitted or new construction ones. This solution provides the building mainly with the following advantages:

- In-situ electricity generation avoiding losses coming from energy transportation through the application of sustainable concepts as distributed generation.
- Thermal envelope benefits depending on the design and PV glass configuration could be achieved with around 15–35% of energy savings. Furthermore, heat recovery applications can be implemented in combination with envelope solutions as pre-heating flow for winter seasons.
- Daylight entrance directly in relation to design of semi-transparent PV glass according to the lighting needs of the building.
- Acoustic benefits due to the behavior of multifunctional façade are similar to conventional glass façades from the point of view of meeting the same standards for construction applications.
- Aesthetical added value associated with a pretty visual aspect own of the silicon technology integrated in constructive solutions as ventilated façade or double skin.
- Easy installation. It needs a simple structural and mounting system composed by aluminum staples, brackets and profiles.
- Protection against the action of harmful atmospheric conditions. The internal structure is less susceptible to weather conditions with the installation of ventilated façade or double skin constructive solutions.

However, not all buildings can incorporate this solution. It will depend on the combination of several requirements:

- Aesthetic requirements directly in relation to the compatibility in terms of the appearance considering existing surrounding area.
- Dimensional requirements focused on customization capacity, distance between multifunctional facade and existing solid wall, the electrical/storage equipment area and minimum area needed for the integration (minimum installed power: 1 kW).
- Functional requirements mainly focused on shadow limitation, optimal orientation and compatibility with existing insulation materials (for ventilated façade solution) or the state of electricity grid.

Nowadays, there are two types of constructive solutions for increasing the thermal envelope of buildings or PV Multifunctional Façade: ventilated façade and double skin. The architectural principle is the same in both cases, however there are significant differences depending on the type of application. The main difference between both architectural approaches is the distance between the façade and the existing wall. In the case of Ventilated Façade, the gap is in the range of 10–30 cm to maximize the passive properties of the thermal envelope through the prioritization of configurations based on opaque glass. In contrast, Double Skin Solutions are more focused on other properties as daylight entrance or ease of performing maintenance work between walls, these solutions include distances between 1 and 1.2 m, being more common the design with semitransparent patterns.

A PV Skylight ensures optimization of the photovoltaic generation providing at the same time bioclimatic properties of thermal comfort inside the building, as most of the UV and IR rays are absorbed by a silicon-based material that acts as a sunscreen. In addition, it is possible to design and manufacture double glazing where the outer glass is photovoltaic and the passage of natural light is allowed.

In PV Curtain Wall applications, traditional glass used in building curtain walls can be replaced by photovoltaic glass, optimizing the envelope performance and allowing on-site energy generation. In this type of integration, the photovoltaic glass should have a transparency degree in order to permit the entrance of natural light into the building.

PV Canopy is a constructive solution that combines power generation with solar protection properties against adverse weather conditions. The energy generated by the PV system can supply nearby buildings or can be injected into the grid, achieving a significant economic benefit. Some important factors that must be taken into account when designing the canopy are the orientation, the minimum slope, dimensions or wind and snow loads.

PV Walkable Floor has been developed for first time by ONYX [146] and it is already patented. The system consists on the installation of photovoltaic tiles, triple laminated glazing units based on a-Si solar cells to be integrated as a walkable floor. The PV tiles comply with the anti-slip regulation and supports 400 Kg in point load test.

PV Parking Lot solution consists on a Photovoltaic Parking structure where the PV installation guarantees on-site power generation to supply the batteries of an electric car. The aesthetic sense of this solution seeks maximum possible energy production and maximum protection from adverse weather conditions, such as rain and wind by a locking structure integrated in the module, formed by a mobile timber panel over the outer face of the photovoltaic panels.

New trends in BIPV solutions are focused on applications as diverse as PV urban mobility [91] such as benches, tables or canopies. These innovative solutions have been developed with the aim of making the traditional outdoor furniture as charging points for Electronic Devices, offering free access points to passers where they have the possibility of charging their Devices (Phones, Tablets, etc.)

All these BIPV solutions ensure an enormous future for the distributed energy approaches as an energy-efficient measurement for retrofitting as well as smart solar solutions for new buildings designed under sustainable criteria.

System prices ($/Wp DC) have a significant effect on PV deployment. Typically, the installed prices of BIPV systems are higher than PV system prices, but the cause of these price premiums—higher costs, higher margins, or other considerations— and the potential for price reductions remain uncertain according an NREL study [147]. In this 2011 study, a bottom-up analysis of components and installation cost of BIPV systems reveals that there is a potential for c-Si BIPV to achieve a lower installed system price ($\$5.02/W_p$) than rack-mounted c-Si PV systems ($\$5.71/W_p$), which are ubiquitous. Even though the PV installed cost has decreased since then, the relative positions of PV and BIPV systems holds true. BIPV cases' potential savings come mainly from eliminating the cost of module-mounting hardware and from offsetting the cost of traditional building materials. It should be noted however that the BIPV systems would have lower efficiency (performance) as compared to rack mounted PVs (due to less optimal inclination angle and higher operating temperatures). From this perspective, it is concluded in [147] that c-Si BIPV systems may achieve a lower levelized cost of electricity (LCOE) than rack-mounted c-Si PV if their installed system prices is at least 5% less.

5. Concluding remarks

BIPV technology is a promising addition to the mix of renewable energy generation technologies. In this paper, we provided a comprehensive review of the current state of the art in the BIPV technology. We have started with a brief description of BIPV systems, and then reviewed the current literature in detail. We have also summarized the previously conducted studies in a tabulated form. The main conclusions we have drawn from the results of the present study may be listed as follows:

- Basic BIPV technology and applications have been extensively studied in the literature. In recent years, research efforts focus on novel designs to increase the efficiency both at the system level (eg. new system configurations, new cooling methods) and also at the PV cell level (e.g. new photovoltaic materials).
- BIPV/T systems began to be developed in early 1990's. This system made great progress in early 2000s which consumes zero energy but this technology is not in use commonly now, due to a higher cost compared to PV and BIPV. It is a promising technology due to its high efficiency and both heat and electricity production. It is clear that there will be significant developments in this field in the coming years.
- The majority of the BIPV performance assessment efforts focus on energetic aspects while the exergetic studies are very low in numbers, and have not been comprehensively performed. There is a wide range of BIPV electric generation capacity reported, ranging from a few MWhr/yr to more than 100 MWhr/yr, with efficiency values ranging from 5% to 18%. In addition, both façade and rooftop BIPV applications are equally common in the literature.
- There are important factors such as shadowing effect, ambient temperature, the direction of the building and the slope of the PV to get higher power output and high efficiency in experimental applications. Analyzes were made for different situations which one or more of these factors were changed together. The ambient temperature condition that has a high effect on the efficiency is a study area for researchers frequently.
- Computational analysis and simulation studies constitute a large part of the studies in the recent years because they are easier and cheaper for system analysis and design. Simulation and numerical studies are pursued for understanding performance, power generation capacity, the energy potential of the façade, the effect of shading factors, electricity usage amounts. The greatest advantage of simulation studies is easily changing the system for different configurations. Two most commonly used software in simulation is TRNSYS and EnergyPlus software.
- Cell/module design is undoubtedly one of the most important points to achieve high efficiency and power output. Studies related with designs that altered with different components showed that higher efficiencies have been achieved by getting low module temperatures with the basic studies in new type modules. In recent years, there are studies about different colored panels in order to cool the module. Besides, the aesthetic advantage of the new BIPV cell/module designs should appeal to the end user and hence enable widespread adaptation.
- Mostly, silicon based PV cells have been employed in the reported BIPV demonstrations. In the last decade, there has been an increasing amount of interest in BIPV systems parallel to the overall developments in photovoltaic cell technology which brought the costs down, making such BIPV investments feasible. It is worth noting that the developments in the dye-sensitized solar cell technology offer a promising solution for BIPV applications.
- Another important point that affects the power output is the grid integration of renewable energy sources when the BIPV system is considered as a whole. The purpose of this approach is to minimize the loss of electricity on electronic components, transformers, and long distribution lines by altering the configurations of the distribution systems.
- The wide range of BIPV solutions offered in the market helps develop sustainable buildings. Researchers have studied issues such as as directing, analyzing and giving information for the dissemination of the correct use of policy and information on studies. It can be concluded that the information sharing should be increased between stakeholders and technological developments, and incentives to attract investors should be provided on this issue.

The authors expect that this comprehensive review will helpful for those pursuing design, simulation and performance assessment of BIPV systems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jestch.2017.01.009.

References

[1] http://www.reelcoop.com/ (Access date: 10th Jun, 2016).
[2] International Energy Agency, Renewable energy medium-term market report – market trends and projections to 2018, 2013.
[3] X. Kong, S. Lu, Y. Wu, A review of building energy efficiency in China during "Eleventh Five-Year Plan" period, Energy Policy 41 (2012) 624–635, http://dx.doi.org/10.1016/j.enpol.2011.11.024.
[4] C. Li, R.Z. Wang, Building integrated energy storage opportunities in China, Renewable Sustainable Energy Rev. 16 (2012) 6191–6211.
[5] G. Quesada, D. Rousse, Y. Dutil, M. Badache, S. Hallé, A comprehensive review of solar facades. Opaque solar facades, Renewable Sustainable Energy Rev. 16 (2012) 2820–2832. doi:10.1016/j.rser.2012.01.078.
[6] G. Quesada, D. Rousse, Y. Dutil, M. Badache, S. Hall, A comprehensive review of solar facades. Transparent and translucent solar facades, Renewable Sustainable Energy Rev. 16 (2012) 2643–2651. doi:10.1016/j.rser.2012.02.059.
[7] B.P. Jelle, C. Breivik, Røkenes H. Drolsum, Building integrated photovoltaic products: A state-of-the-art review and future research opportunities, Sol. Energy Mater. Sol. Cells 100 (2012) 69–96, http://dx.doi.org/10.1016/j.solmat.2011.12.016.
[8] T. Yang, A.K. Athienitis, A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems, Renewable Sustainable Energy Rev. 66 (2016) 886–912, http://dx.doi.org/10.1016/j.rser.2016.07.011.
[9] V. Delisle, M. Kummert, A novel approach to compare building-integrated photovoltaics/thermal air collectors to side-by-side PV modules and solar thermal collectors, Sol. Energy 100 (2014) 50–65, http://dx.doi.org/10.1016/j.solener.2013.09.040.
[10] P. Karava, C. Mohammad Jubayer, E. Savory, S. Li, Effect of incident flow conditions on convective heat transfer from the inclined windward roof of a

low-rise building with application to photovoltaic-thermal systems, J. Wind Eng. Ind. Aerodyn. 104–106 (11–12) (2012) 428–438, http://dx.doi.org/10.1016/j.jweia.2012.03.026.
[11] L. Shi, M.Y.L. Chew, A review on sustainable design of renewable energy systems, Renewable Sustainable Energy Rev. 16 (2012) 192–207, http://dx.doi.org/10.1016/j.rser.2011.07.147.
[12] B.P. Jelle, C. Breivik, The path to the building integrated photovoltaics of tomorrow, Energy Procedia 20 (2012) 78–87, http://dx.doi.org/10.1016/j.egypro.2012.03.010.
[13] M.C. Browne, B. Norton, S.J. McCormack, Phase change materials for photovoltaic thermal management, Renewable Sustainable Energy Rev. 47 (2015) 762–782, http://dx.doi.org/10.1016/j.rser.2015.03.050.
[14] V.V. Tyagi, S.C. Kaushik, S.K. Tyagi, Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology, Renewable Sustainable Energy Rev. 16 (2012) 1383–1398, http://dx.doi.org/10.1016/j.rser.2011.12.013.
[15] J. Cronemberger, M.A. Corpas, I. Cerón, E. Caamaño-Martín, S.V. Sánchez, BIPV technology application: Highlighting advances, tendencies and solutions through Solar Decathlon Europe houses, Energy Build. 83 (2014) 44–56, http://dx.doi.org/10.1016/j.enbuild.2014.03.079.
[16] A.H. Fanney, B.P. Dougherty, M.W. Davis, Short-term characterization of building integrated photovoltaic panels, J. Sol. Energy Eng. 125 (1) (2003) 13–20, http://dx.doi.org/10.1115/1.1531642.
[17] R.A. Agathokleous, S.A. Kalogirou, Double skin facades (DSF) and building integrated photovoltaics (BIPV): A review of configurations and heat transfer characteristics, Renewable Energy 89 (2016) 743–756, http://dx.doi.org/10.1016/j.renene.2015.12.043.
[18] S. Barkaszi, J. Dunlop, Discussion of strategies for mounting photovoltaic arrays on rooftops, Sol. Energy (2001) 333–338.
[19] I.B. Hagemann, Gebäudeintegrierte Photovoltaik: Architektonische Integration Der Photovoltaik in Die Gebäudehülle, Müller, Köln, 2002.
[20] A. Henemann, BIPV: Built-in solar energy, Renewable Energy Focus 9 (14) (2008) 16–19, http://dx.doi.org/10.1016/S1471-0846(08)70179-3.
[21] J.J. Bloem, C. Lodi, J. Cipriano, D. Chemisana, An outdoor test reference environment for double skin applications of building integrated photovoltaic systems, Energy Build. 50 (2012) 63–73, http://dx.doi.org/10.1016/j.enbuild.2012.03.023.
[22] B. Coelho, A. Oliveira, REELCOOP project: research cooperation in renewable energy technologies for electricity generation, SolarPACES (2013) 26–29.
[23] S.A. Omer, R. Wilson, S.B. Riffat, Monitoring results of two examples of building integrated PV (BIPV) systems in the UK, Renewable Energy 28 (2003) 1387–1399, http://dx.doi.org/10.1016/S0960-1481(02)00257-4.
[24] T.T. Chow, J.W. Hand, P.A. Strachan, Building-integrated photovoltaic and thermal applications in a subtropical hotel building, Appl. Therm. Eng. 23 (2003) 2035–2049, http://dx.doi.org/10.1016/S1359-4311(03)00183-2.
[25] H. Yang, G. Zheng, C. Lou, D. An, J. Burnett, Grid-connected building-integrated photovoltaics: A Hong Kong case study, Sol. Energy 76 (2004) 55–59, http://dx.doi.org/10.1016/j.solener.2003.09.007.
[26] T.K. Mallick, P.C. Eames, B. Norton, Non-concentrating and asymmetric compound parabolic concentrating building fa??ade integrated photovoltaics: An experimental comparison, Sol. Energy 80 (2006) 834–849, http://dx.doi.org/10.1016/j.solener.2005.05.011.
[27] M.J. Jiménez, H. Madsen, J.J. Bloem, B. Dammann, Estimation of non-linear continuous time models for the heat exchange dynamics of building integrated photovoltaic modules, Energy Build. 40 (2008) 157–167, http://dx.doi.org/10.1016/j.enbuild.2007.02.026.
[28] S. Pantic, L. Candanedo, A.K. Athienitis, Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems, Energy Build. 42 (2010) 1779–1789, http://dx.doi.org/10.1016/j.enbuild.2010.05.014.
[29] C.D. Corbin, Z.J. Zhai, Experimental and numerical investigation on thermal and electrical performance of a building integrated photovoltaic-thermal collector system, Energy Build. 42 (2010) 76–82, http://dx.doi.org/10.1016/j.enbuild.2009.07.013.
[30] Y. Chen, A.K. Athienitis, K. Galal, Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept, Sol. Energy 84 (2010) 1892–1907, http://dx.doi.org/10.1016/j.solener.2010.06.013.
[31] Y. Chen, K. Galal, A.K. Athienitis, Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab, Sol. Energy 84 (2010) 1908–1919, http://dx.doi.org/10.1016/j.solener.2010.06.012.
[32] B. Agrawal, G.N. Tiwari, Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions, Appl. Energy 87 (2010) 417–426, http://dx.doi.org/10.1016/j.apenergy.2009.06.011.
[33] B. Agrawal, G.N. Tiwari, An energy and exergy analysis of building integrated photovoltaic thermal systems, Energy Sources Part A 33 (2011) 649–664, http://dx.doi.org/10.1080/15567030903226280.
[34] K. Vats, G.N. Tiwari, Performance evaluation of a building integrated semitransparent photovoltaic thermal system for roof and faade, Energy Build. 45 (2012) 211–218, http://dx.doi.org/10.1016/j.enbuild.2011.11.008.
[35] B.K. Koyunbaba, Z. Yilmaz, K. Ulgen, An approach for energy modeling of a building integrated photovoltaic (BIPV) Trombe wall system, Energy Build. 67 (2013) 680–688, http://dx.doi.org/10.1016/j.enbuild.2011.06.031.
[36] B. Kundakci Koyunbaba, Z. Yilmaz, The comparison of Trombe wall systems with single glass, double glass and PV panels, Renewable Energy 45 (2012) 111–118, http://dx.doi.org/10.1016/j.renene.2012.02.026.
[37] C. Peng, Y. Huang, Z. Wu, Building-integrated photovoltaics (BIPV) in architectural design in China, Energy Build. 43 (2011) 3592–3598, http://dx.doi.org/10.1016/j.enbuild.2011.09.032.
[38] J. Urbanetz, C.D. Zomer, R. Rüther, Compromises between form and function in grid-connected, building-integrated photovoltaics (BIPV) at low-latitude sites, Build. Environ. 46 (2011) 2107–2113, http://dx.doi.org/10.1016/j.buildenv.2011.04.024.
[39] O. Zogou, H. Stapountzis, Experimental validation of an improved concept of building integrated photovoltaic panels, Renewable Energy 36 (2011) 3488–3498, http://dx.doi.org/10.1016/j.renene.2011.05.034.
[40] J.H. Yoon, J. Song, S.J. Lee, Practical application of building integrated photovoltaic (BIPV) system using transparent amorphous silicon thin-film PV module, Sol. Energy 85 (2011) 723–733, http://dx.doi.org/10.1016/j.solener.2010.12.026.
[41] Santos Í.P. Dos, R. Rüther, The potential of building-integrated (BIPV) and building-applied photovoltaics (BAPV) in single-family, urban residences at low latitudes in Brazil, Energy Build. 50 (2012) 290–297, http://dx.doi.org/10.1016/j.enbuild.2012.03.052.
[42] G. Ban-Weiss, C. Wray, W. Delp, P. Ly, H. Akbari, R. Levinson, Electricity production and cooling energy savings from installation of a building-integrated photovoltaic roof on an office building, Energy Build. 56 (2013) 210–220, http://dx.doi.org/10.1016/j.enbuild.2012.06.032.
[43] J.J. Bloem, Evaluation of a PV-integrated building application in a well-controlled outdoor test environment, Build. Environ. 43 (2008) 205–216, http://dx.doi.org/10.1016/j.buildenv.2006.10.041.
[44] C. Lodi, P. Bacher, J. Cipriano, H. Madsen, Modelling the heat dynamics of a monitored Test Reference Environment for Building Integrated Photovoltaic systems using stochastic differential equations, Energy Build. 50 (2012) 273–281, http://dx.doi.org/10.1016/j.enbuild.2012.03.046.
[45] N. Friling, M.J. Jiménez, H. Bloem, H. Madsen, Modelling the heat dynamics of building integrated and ventilated photovoltaic modules, Energy Build. 41 (2009) 1051–1057, http://dx.doi.org/10.1016/j.enbuild.2009.05.018.
[46] J. Han, L. Lu, J. Peng, H. Yang, Performance of ventilated double-sided PV façade compared with conventional clear glass façade, Energy Build. 56 (2013) 204–209, http://dx.doi.org/10.1016/j.enbuild.2012.08.017.
[47] M. Drif, A. Mellit, J. Aguilera, P.J. Pérez, A comprehensive method for estimating energy losses due to shading of GC-BIPV systems using monitoring data, Sol. Energy 86 (2012) 2397–2404, http://dx.doi.org/10.1016/j.solener.2012.05.008.
[48] S. Wittkopf, S. Valliappan, L. Liu, K.S. Ang, S.C.J. Cheng, Analytical performance monitoring of a 142.5kWp grid-connected rooftop BIPV system in Singapore, Renewable Energy 47 (2012) 9–20, http://dx.doi.org/10.1016/j.renene.2012.03.034.
[49] P.R. Defaix, WGJHM Van Sark, E. Worrell, E. de Visser, Technical potential for photovoltaics on buildings in the EU-27, Sol. Energy 86 (2012) 2644–2653, http://dx.doi.org/10.1016/j.solener.2012.06.007.
[50] S.M. Bambrook, A.B. Sproul, Maximising the energy output of a PVT air system, Sol. Energy 86 (6) (2012) 1857–1871, http://dx.doi.org/10.1016/j.solener.2012.02.038.
[51] H. Wei, J. Liu, B. Yang, Cost-benefit comparison between Domestic Solar Water Heater (DSHW) and Building Integrated Photovoltaic (BIPV) systems for households in urban China, Appl. Energy 126 (2014) 47–55, http://dx.doi.org/10.1016/j.apenergy.2014.04.003.
[52] C.S.P. López, M. Sangiorgi, Comparison assessment of BIPV façade semi-transparent modules: Further insights on human comfort conditions, Energy Procedia 48 (2014) 1419–1428, http://dx.doi.org/10.1016/j.egypro.2014.02.160.
[53] T. Yang, A.K. Athienitis, Experimental investigation of a two-inlet air-based building integrated photovoltaic/thermal (BIPV/T) system, Appl. Energy 159 (2015) 70–79, http://dx.doi.org/10.1016/j.apenergy.2015.08.048.
[54] T. Yang, A.K. Athienitis, Performance evaluation of air-based building integrated photovolta-ic/thermal (BIPV/T) system with multiple inlets in a cold climate, Procedia Eng. 121 (2015) 2060–2067, http://dx.doi.org/10.1016/j.proeng.2015.09.207.
[55] E. Bigaila, E. Rounis, P. Luk, A. Athienitis, A study of a BIPV/T collector prototype for building façade applications, Energy Procedia 78 (2015) 1931–1936, http://dx.doi.org/10.1016/j.egypro.2015.11.374.
[56] D. Roeleveld, G. Hailu, A.S. Fung, D. Naylor, T. Yang, A.K. Athienitis, Validation of computational fluid dynamics (CFD) model of a building integrated photovoltaic/thermal (BIPV/T) system, Energy Procedia 78 (2015) 1901–1906, http://dx.doi.org/10.1016/j.egypro.2015.11.359.
[57] L. Maturi, R. Lollini, D. Moser, W. Sparber, Experimental investigation of a low cost passive strategy to improve the performance of Building Integrated Photovoltaic systems, Sol. Energy 111 (2015) 288–296, http://dx.doi.org/10.1016/j.solener.2014.11.001.
[58] E.A. Essah, A.R. Arguelles, N. Glover, Assessing the performance of a building integrated BP c-Si PV system, Renewable Energy 73 (2015) 36–45, http://dx.doi.org/10.1016/j.renene.2014.04.002.
[59] R. Eke, C. Demircan, Shading effect on the energy rating of two identical PV systems on a building façade, Sol. Energy 122 (2015) 48–57, http://dx.doi.org/10.1016/j.solener.2015.08.022.

[60] V. Timchenko, O.A.Tkachenko, C. Ménézo, Numerical and experimental investigation of natural convection in open-ended channels with application to building integrated photovoltaic (BIPV) Systems, 2015, 01002.

[61] P.A. Mirzaei, J. Carmeliet, Influence of the underneath cavity on buoyant-forced cooling of the integrated photovoltaic panels in building roof: A thermography study, Prog. Photovoltaics Res. Appl. (2015), http://dx.doi.org/10.1002/pip.2390.

[62] M. Ritzen, Z. Vroon, R. Rovers, C. Geurts, B. Blocken, Real Life Lab BIPV field testing in the Netherlands. In: 2015 IEEE 42nd Photovolt Spec Conf PVSC 2015, 2015, 3–7, doi:http://dx.doi.org/10.1109/PVSC.2015.7355634.

[63] F. Chen, H. Yin, Fabrication and laboratory-based performance testing of a building-integrated photovoltaic-thermal roofing panel, Appl. Energy 177 (2016) 271–284, http://dx.doi.org/10.1016/j.apenergy.2016.05.112.

[64] M. Ordenes, D.L. Marinoski, P. Braun, R. Rüther, The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil, Energy Build. 39 (2007) 629–642, http://dx.doi.org/10.1016/j.enbuild.2006.10.006.

[65] W. Tian, Y. Wang, J. Ren, L. Zhu, Effect of urban climate on building integrated photovoltaics performance, Energy Convers. Manage. 48 (2007) 1–8, http://dx.doi.org/10.1016/j.enconman.2006.05.015.

[66] R. Rüther, P. Braun, Energetic contribution potential of building-integrated photovoltaics on airports in warm climates, Sol. Energy 83 (2009) 1923–1931, http://dx.doi.org/10.1016/j.solener.2009.07.014.

[67] C.L. Cheng, C.S. Sanchez Jimenez, M.C. Lee, Research of BIPV optimal tilted angle, use of latitude concept for south orientated plans, Renewable Energy 34 (2009) 1644–1650, http://dx.doi.org/10.1016/j.renene.2008.10.025.

[68] L.M. Candanedo, A.K. Athienitis, J.A. Candanedo, W. O'Brien, Y.X. Chen, Transient and steady state models for open loop air based BIPV/T Systems, ASHRAE Trans. 116 (1) (2010) 13.

[69] S.H. Yoo, H. Manz, Available remodeling simulation for a BIPV as a shading device, Sol. Energy Mater. Sol. Cells 95 (2011) 394–397, http://dx.doi.org/10.1016/j.solmat.2010.02.015.

[70] J. Cronemberger, E. Caamaño-Martín, S.V. Sánchez, Assessing the solar irradiation potential for solar photovoltaic applications in buildings at low latitudes – Making the case for Brazil, Energy Build. 55 (2012) 264–272, http://dx.doi.org/10.1016/j.enbuild.2012.08.044.

[71] T. Hwang, S. Kang, J.T. Kim, Optimization of the building integrated photovoltaic system in office buildings – Focus on the orientation, inclined angle and installed area, Energy Build. 46 (2012) 92–104, http://dx.doi.org/10.1016/j.enbuild.2011.10.041.

[72] D. Bigot, F. Miranville, H. Boyer, M. Bojic, S. Guichard, A. Jean, Model optimization and validation with experimental data using the case study of a building equipped with photovoltaic panel on roof: Coupling of the building thermal simulation code ISOLAB with the generic optimization program GenOpt, Energy Build. (2013), http://dx.doi.org/10.1016/j.enbuild.2012.10.017.

[73] J. Perez-Alonso, M. Perez-Garcia, M. Pasamontes-Romera, A.J. Callejon-Ferre, Performance analysis and neural modelling of a greenhouse integrated photovoltaic system, Renewable Sustainable Energy Rev. 16 (2012) 4675–4685, http://dx.doi.org/10.1016/j.rser.2012.04.002.

[74] L. Lu, K.M. Law, Overall energy performance of semi-transparent single-glazed photovoltaic (PV) window for a typical office in Hong Kong, Renewable Energy 49 (2013) 250–254, http://dx.doi.org/10.1016/j.renene.2012.01.021.

[75] T. Yang, A.K. Athienitis, A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets, Sol. Energy 104 (2014) 82–92, http://dx.doi.org/10.1016/j.solener.2014.01.049.

[76] M. Radmehr, K. Willis, U.E. Kenechi, A framework for evaluating WTP for BIPV in residential housing design in developing countries: A case study of North Cyprus, Energy Policy 70 (2014) 207–216, http://dx.doi.org/10.1016/j.enpol.2014.03.041.

[77] R.S. Kamel, A.S. Fung, Modeling, simulation and feasibility analysis of residential BIPV/T+ASHP system in cold climate Canada, Energy Build. 82 (2014) 758–770, http://dx.doi.org/10.1016/j.enbuild.2014.07.081.

[78] A.J. Veldhuis, Reinders AHME, Shadow analysis for BIPV and PIPV systems in a virtual environment, 2015. In: IEEE 42nd Photovolt Spec Conf PVSC 2015, 2015, 1–5, doi: http://dx.doi.org/10.1109/PVSC.2015.7355635.

[79] E. Vuong, R.S. Kamel, A.S. Fung, Modelling and simulation of BIPV/T in EnergyPlus and TRNSYS, Energy Procedia 78 (2015) 1883–1888, http://dx.doi.org/10.1016/j.egypro.2015.11.354.

[80] H.-R. Kim, F.E. Boafo, J.-H. Kim, J.-T. Kim, Investigating the effect of roof configurations on the performance of BIPV system, Energy Procedia 78 (2015) 1974–1979, http://dx.doi.org/10.1016/j.egypro.2015.11.387.

[81] E.D. Rounis, E. Bigaila, P. Luk, A. Athienitis, T. Stathopoulos, Multiple-inlet BIPV/T Modeling: Wind Effects and Fan Induced Suction, Energy Procedia 78 (2015) 1950–1955, http://dx.doi.org/10.1016/j.egypro.2015.11.379.

[82] G. Hailu, P. Dash, A.S. Fung, Performance evaluation of an air source heat pump coupled with a building-integrated photovoltaic/thermal (BIPV/T) system under cold climatic conditions, Energy Procedia 78 (2015) 1913–1918, http://dx.doi.org/10.1016/j.egypro.2015.11.370.

[83] H. Li, C. Cao, G. Feng, R. Zhang, K. Huang, A BIPV/T system design based on simulation and its application in integrated heating system, Procedia Eng. 121 (2015) 1590–1596, http://dx.doi.org/10.1016/j.proeng.2015.09.184.

[84] D. Knera, E. Szczepańska-Rosiak, D. Heim, Potential of PV façade for supplementary lighting in winter, Energy Procedia 78 (2015) 2651–2656, http://dx.doi.org/10.1016/j.egypro.2015.11.338.

[85] T. Salem, E. Kinab, Analysis of building-integrated photovoltaic systems: a case study of commercial buildings under mediterranean climate, Procedia Eng. 118 (2015) 538–545, http://dx.doi.org/10.1016/j.proeng.2015.08.473.

[86] R.S. Kamel, A.S. Fung, Modelling and characterization of transparent building integrated PV/T collector, Energy Procedia 78 (2015) 1871–1876, http://dx.doi.org/10.1016/j.egypro.2015.11.349.

[87] L.F. Mulcué-Nieto, L. Mora-López, Methodology to establish the permitted maximum losses due to shading and orientation in photovoltaic applications in buildings, Appl. Energy 137 (2015) 37–45, http://dx.doi.org/10.1016/j.apenergy.2014.09.088.

[88] M.S. Elsayed, Optimizing thermal performance of building-integrated photovoltaics for upgrading informal urbanization, Energy Build. 116 (2016) 232–248, http://dx.doi.org/10.1016/j.enbuild.2016.01.004.

[89] L. Sun, W. Hu, Y. Yuan, X. Cao, B. Lei, Dynamic performance of the shading-type building-integrated photovoltaic claddings, Procedia Eng. 121 (2015) 930–937, http://dx.doi.org/10.1016/j.proeng.2015.09.053.

[90] P.A. Mirzaei, R. Zhang, Validation of a climatic CFD model to predict the surface temperature of building integrated photovoltaics, Energy Procedia 78 (2015) 1865–1870, http://dx.doi.org/10.1016/j.egypro.2015.11.348.

[91] E.A. Akata, A. Martial, D. Njomo, B. Agrawal, Thermal energy optimization of building integrated semi-transparent photovoltaic thermal systems, Int. J. Renewable Energy Dev. 4 (2015) 113–123, http://dx.doi.org/10.14710/ijred.4.2.113-123.

[92] L. Bueno, M. Ibliha, B. Vizcarra, G.M. Chaudhry, M.K. Siddiki, Feasibility analysis of a solar photovoltaic array integrated on façades of a commercial building, 2015, In: IEEE 42nd Photovolt Spec Conf, 2015, 1–4, doi:http://dx.doi.org/10.1109/PVSC.2015.7355831.

[93] S. Saadon, L. Gaillard, S. Giroux-Julien, C. Ménézo, Simulation study of a naturally-ventilated building integrated photovoltaic/thermal (BIPV/T) envelope, Renewable Energy 87 (2016) 517–531, http://dx.doi.org/10.1016/j.renene.2015.10.016.

[94] A. Buonomano, F. Calise, A. Palombo, M. Vicidomini, BIPVT systems for residential applications: An energy and economic analysis for European climates, Appl. Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2016.02.145.

[95] David S. Ginley, David Cahen (Eds.), Fundamentals of Materials for Energy and Environmental Sustainability, Cambridge University Press, 2012, pp. 229–235.

[96] Aswani Yella, Hsuan-Wei Lee, Hoi Nok Tsao, Chenyi Yi, Aravind Kumar Chandiran, Md. Khaja Nazeeruddin, Eric Wei-Guang Diau, Chen-Yu Yeh, Shaik M Zakeeruddin, Michael Grätzel, Science, 2011, 334, 629–634.

[97] M. Spath, J. van Rossmalen, P. Sommeling, N. van der Burg, H. Smit, D. Mahieu, et al. Dye sensitised solar cells from laboratory scale to pre-pilot stage, Photovolt Energy Conversion, 2003 In: Proc 3rd World Conf 2003;1:196–9 Vol. 1.

[98] K. Branker, M.J.M. Pathak, J.M. Pearce, A review of solar photovoltaic levelized cost of electricity, Renewable Sustainable Energy Rev. 15 (2011) 4470–4482, http://dx.doi.org/10.1016/j.rser.2011.07.104.

[99] K. Branker, M.J.M. Pathak, J.M. Pearce, Renewable Sustainable Energy Rev. 15 (2011) 4470–4482.

[100] K. Kalyanasundaram (Ed.), Dye-sensitized Solar Cells, EPFL Press, 2010, pp. 271–277.

[101] http://www.robaid.com/tech/epfls-new-convention-center-west-facade-features-dye-solar-cells.htm (Access date: 6th Apr, 2016).

[102] http://www.smartcitygraz.at/wordpress/wp-content/uploads/2014/05/folder_EN_einzelseiten.pdf (Access date: 6th Apr, 2016).

[103] K. Vats, V. Tomar, G.N. Tiwari, Effect of packing factor on the performance of a building integrated semitransparent photovoltaic thermal (BISPVT) system with air duct, Energy Build. 53 (2012) 159–165, http://dx.doi.org/10.1016/j.enbuild.2012.07.004.

[104] M. Fathi, A. Aissat, M. Ayad, Design of building integrated photovoltaic (BIPV) and integration of photons converters, Energy Procedia 18 (2012) 377–383, http://dx.doi.org/10.1016/j.egypro.2012.05.049.

[105] L. Maturi, G. Belluardo, D. Moser, M. Del Buono, BiPV system performance and efficiency drops: Overview on PV module temperature conditions of different module types, Energy Procedia 48 (2014) 1311–1319, http://dx.doi.org/10.1016/j.egypro.2014.02.148.

[106] J. Kang, C. Cho, J.-Y. Lee, Design of asymmetrically textured structure for efficient light trapping in building-integrated photovoltaics, Org. Electron. 26 (2015) 61–65, http://dx.doi.org/10.1016/j.orgel.2015.07.021.

[107] S. Yeop Myong, Jeon S. Won, Design of esthetic color for thin-film silicon semi-transparent photovoltaic modules, Sol. Energy Mater. Sol. Cells 143 (2015) 442–449, http://dx.doi.org/10.1016/j.solmat.2015.07.042.

[108] C. Cornaro, S. Bartocci, D. Musella, C. Strati, A. Lanuti, S. Mastroianni, et al., Comparative analysis of the outdoor performance of a dye solar cell mini-panel for building integrated photovoltaics applications, Prog. Photovoltaics Res. Appl. (2015), http://dx.doi.org/10.1002/pip.2426.

[109] J. Escarre, H.Y. Li, L. Sansonnens, F. Galliano, G. Cattaneo, P. Heinstein et al. When PV modules are becoming real building elements: White solar module, a revolution for BIPV, 2015m In: IEEE 42nd Photovolt Spec Conf PVSC 2015, 2015, 1–2, doi:http://dx.doi.org/10.1109/PVSC.2015.7355630.

[110] A. Virtuani, D. Strepparava, Modeling the performance of amorphous and crystalline silicon photovoltaic modules for different types of building integration conditions, 2015, In: IEEE 42nd Photovolt Spec Conf 2015, 1–3. doi:http://dx.doi.org/10.1109/PVSC.2015.7355636.

[111] H. Yu, Q. Wang, C. Lu, C. Wei, The research on a new type of BIPV modules constructed by thin-film photovoltaic panel(or module)/PU/color organic-coated steel plate, In: 2014 IEEE 40th Photovolt Spec Conf PVSC 2014 2014, 2724–2727, doi:http://dx.doi.org/10.1109/PVSC.2014.6925492.

[112] M. Mazzoni, S. Lai, F. Ratto, S. Centi, R. Pini, L. Zani, et al. Gold nanoparticles and organic dyes for BIPV-DSSCS, 4–7.

[113] C. Han, S. Park, Material Characterization and Process Optimization of Dye-sensitized Solar Cell Sealant, 2015, 14–7.

[114] Z. Zhen, X. Taoyun, S. Yanping, L. Wang, P. Jia, J. Yu, A method to test operating cell temperature for BIPV modules, IEEE J. Photovoltaics 6 (2016) 272–277, http://dx.doi.org/10.1109/JPHOTOV.2015.2501719.

[115] G.C. Bakos, M. Soursos, N.F. Tsagas, Technoeconomic assessment of a building-integrated PV system for electrical energy saving in residential sector, Energy Build. 35 (2003) 757–762, http://dx.doi.org/10.1016/S0378-7788(02)00229-3.

[116] M.J. Huang, P.C. Eames, B. Norton, Thermal regulation of building-integrated photovoltaics using phase change materials, Int. J. Heat Mass Transf. 47 (2004) 2715–2733, http://dx.doi.org/10.1016/j.ijheatmasstransfer.2003.11.015.

[117] R.H. Crawford, G.J. Treloar, R.J. Fuller, M. Bazilian, Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit, Renewable Sustainable Energy Rev. 10 (2006) 559–575, http://dx.doi.org/10.1016/j.rser.2004.11.005.

[118] A. Chel, G.N. Tiwari, A. Chandra, Simplified method of sizing and life cycle cost assessment of building integrated photovoltaic system, Energy Build. 41 (2009) 1172–1180, http://dx.doi.org/10.1016/j.enbuild.2009.06.004.

[119] L. Stamenic, M. Rajkovic, D. Klisic, Performance optimization of the BIPV powered electrolyser and fuel cells installation, Energy Build. 51 (2012) 39–47, http://dx.doi.org/10.1016/j.enbuild.2012.03.044.

[120] G. Zeng, M. Cao, Y. Chen, A multi-functional utility interface of BIPV systems based on cascade multilevel converter, Energy Procedia 17 (2012) 356–365, http://dx.doi.org/10.1016/j.egypro.2012.02.106.

[121] F. Ghani, M. Duke, J.K. Carson, Estimation of photovoltaic conversion efficiency of a building integrated photovoltaic/thermal (BIPV/T) collector array using an artificial neural network, Sol. Energy 86 (2012) 3378–3387, http://dx.doi.org/10.1016/j.solener.2012.09.001.

[122] B. Liu, S. Duan, Energy efficiency evaluation of building integrated photovoltaic systems with different power configurations, Simul. Model. Pract. Theory 29 (2012) 93–108, http://dx.doi.org/10.1016/j.simpat.2012.07.014.

[123] B. Liu, S. Duan, T. Cai, Modeling and coordinate control of photovoltaic DC building module based BIPV system, Sol. Energy 86 (2012) 482–488, http://dx.doi.org/10.1016/j.solener.2011.10.022.

[124] B. Celik, E. Karatepe, S. Silvestre, N. Gokmen, A. Chouder, Analysis of spatial fixed PV arrays configurations to maximize energy harvesting in BIPV applications, Renewable Energy 75 (2015) 534–540, http://dx.doi.org/10.1016/j.renene.2014.10.041.

[125] H. Fathabadi, Increasing energy efficiency of PV-converter-battery section of standalone building integrated photovoltaic systems, Energy Build. 101 (2015) 1–11, http://dx.doi.org/10.1016/j.enbuild.2015.04.024.

[126] H. Wang, S. Member, K. Meng, Z.Y. Dong, S. Member, Z. Xu, et al. A MILP Approach to Accommodate More Building Integrated Photovoltaic System in Distribution Network, 2015.

[127] M. Seyedmahmoudian, I. Kavalchuk, B. Horan, A.M.T. Oo, A. Stojcevski, Viable approaches for increasing the efficiency of buiding integrated photovoltaic systems. In: 2015 Australas Univ Power Eng Conf Challenges Futur Grids, AUPEC 2015 2015, doi:http://dx.doi.org/10.1109/AUPEC.2015.7324864.

[128] G. Keoleian, G. Lewis, Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the US, Renewable Energy 28 (2003) 271–293.

[129] C.L. Cheng, C.Y. Chan, C.L. Chen, Empirical approach to BIPV evaluation of solar irradiation for building applications, Renewable Energy 30 (2005) 1055–1074, http://dx.doi.org/10.1016/j.renene.2004.06.006.

[130] C. da Silva Jardim, R. Rüther, I.T. Salamoni, T. de Souza Viana, S.H. Rebechi, P.J. Knob, The strategic siting and the roofing area requirements of building-integrated photovoltaic solar energy generators in urban areas in Brazil, Energy Build. 40 (2008) 365–370, http://dx.doi.org/10.1016/j.enbuild.2007.02.035.

[131] N.W. Alnaser, R. Flanagan, W.E. Alnaser, Model for calculating the sustainable building index (SBI) in the kingdom of Bahrain, Energy Build. 40 (2008) 2037–2043, http://dx.doi.org/10.1016/j.enbuild.2008.05.015.

[132] B. Agrawal, G.N. Tiwari, Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems, Energy Build. 42 (2010) 1472–1481, http://dx.doi.org/10.1016/j.enbuild.2010.03.017.

[133] G.P. Hammond, H.A. Harajli, C.I. Jones, A.B. Winnett, Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations, Energy Policy 40 (2012) 219–230, http://dx.doi.org/10.1016/j.enpol.2011.09.048.

[134] F. Cucchiella, I. Dadamo, Estimation of the energetic and environmental impacts of a roof-mounted building-integrated photovoltaic systems, Renewable Sustainable Energy Rev. 16 (2012) 5245–5259, http://dx.doi.org/10.1016/j.rser.2012.04.034.

[135] T.D. Tsoutsos, S.K. Tournaki, Z.K. Gkouskos, E. Despotou, G. Masson, Training and certification of PV installers in Europe, Renewable Energy 49 (2013) 222–226, http://dx.doi.org/10.1016/j.renene.2012.01.027.

[136] Y.T. Chae, J. Kim, H. Park, B. Shin, Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells, Appl. Energy 129 (2014) 217–227, http://dx.doi.org/10.1016/j.apenergy.2014.04.106.

[137] P.K. Ng, N. Mithraratne, Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics, Renewable Sustainable Energy Rev. 31 (2014) 736–745, http://dx.doi.org/10.1016/j.rser.2013.12.044.

[138] R.J. Yang, Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): Hardware and software strategies, Autom. Constr. 51 (2015) 92–102, http://dx.doi.org/10.1016/j.autcon.2014.12.005.

[139] K.C. Goh, A.B.K. Yap, H.H. Goh, T.W. Seow, T.C. Toh, Awareness and Initiatives of Building Integrated Photovoltaic (BIPV) implementation in Malaysian Housing Industry, Procedia Eng. 118 (2015) 1052–1059, http://dx.doi.org/10.1016/j.proeng.2015.08.548.

[140] F. Cucchiella, I. D'Adamo, S.C. Lenny Koh, Environmental and economic analysis of building integrated photovoltaic systems in Italian regions, J. Cleaner Prod. 98 (2015) 241–252, http://dx.doi.org/10.1016/j.jclepro.2013.10.043.

[141] L. Belussi, M. Mariotto, I. Meroni, C. Zevi, S.D. Svaldi, LCA study and testing of a photovoltaic ceramic tile prototype, Renewable Energy 74 (2015) 263–270, http://dx.doi.org/10.1016/j.renene.2014.07.053.

[142] R.J. Yang, P.X.W. Zou, Building integrated photovoltaics (BIPV): Costs, benefits, risks, barriers and improvement strategy, Int. J. Constr. Manage. 16 (2016) 39–53, http://dx.doi.org/10.1080/15623599.2015.1117709.

[143] EU Commission, Energy Performance of Building Directive. Directive 2010/31/EU.

[144] EuroACe, EuroAce position on the EU Efficiency Plan 2011.

[145] http://www.leonardo-energy.org/ (Access date: 25th Feb, 2015).

[146] http://www.onyxsolar.com/index.html (Access date: 25th Feb, 2015).

[147] NREL Report, Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis of Installed Rooftop System Prices. www.nrel.gov/docs/fy12osti/53103.pdf (Access date: December 16, 2016).