Thermal testing of a new photovoltaic (PV) module for building integration encapsulated with glass fibre reinforced composite materials and comparison with conventional Photovoltaic

Rafaela A. Agathokleous and Soteris A. Kalogirou

Cyprus University of Technology, Limassol, Cyprus

Abstract

Photovoltaic (PV) panels usage is increased dramatically the last years. The PV panels for building integration however are not so popular yet. This is because the Building Integrated Photovoltaic (BIPV) Systems play an important role on the design of the building. There are architects and designers who like the idea of PV panels integrated on the envelope of a building but there are also those who believe that the colour and shape of the panels eliminate their creativity. BFIRST (Building Integrated Fibre Reinforced Solar Technology) project developed a new solar cells' encapsulation technology with glass fibre reinforced composite materials, and real size modules are manufactured. The idea behind this technology is to produce rigid photovoltaic panels with shapes that are not flat but they are also light-weight PV modules for building integration.

The aim of this study is to compare a 'BFIRST module' with a conventional module from the market, in terms of temperature under different amounts of solar radiation and inclination angles. Thus, two experimental apparatuses are constructed to represent building integration, forming an air gap between the PV and a second skin. The purpose of the air gap is to cool the PV panels and avoid the decrease of their efficiency due to overheating. In this study, the ventilation of the air gap is natural without any mechanical means to drive the air.

The tests are carried out in the Archimedes Solar Energy Laboratory (ASEL) at Cyprus University of Technology, Limassol, with the use of a large scale solar simulator. Although this is the first time the fibre reinforced encapsulation solar technology is tried, as the modules are produced only for research purposes, the tests show that this technology is very promising and worth to be developed. The maximum temperature recorded was very close with the temperature of the conventional PV panel. The temperature of the BFIRST PV panel under 450 W/m^2 constant solar radiation is 57.5ºC while the temperature of the conventional PV was 64ºC. For 800 W/m^2 constant solar radiation the temperature of the BFIRST PV panel was 73.4ºC and 73.6ºC for the conventional PV panel. An additional test for the BFIRST PV under higher solar radiation is carried out to record highest PV temperature attainable, and the maximum temperature of the panel under 1000 W/m^2 was 79ºC at the top side of the panel, which is satisfactory.

Keywords: BIPV, Solar Simulator, Thermal testing, BFIRST, Photovoltaic

1 Introduction

Photovoltaics (PVs) have faced an exponential recognition by people the last years and this trend will continue with the support of the feed in tariff policies in various countries, the EU directives for usage of renewable energy systems for energy production, and the need to mitigate emissions. Additionally, the usage of PVs will be supported by the fact that the manufacturing costs decrease and the cost of the energy produced from fossil fuels increases.

The situation for building integrated photovoltaics (BIPV) is however radically different from that of the general PV industry. Despite the impressive improvement on the PV modules in terms of shapes and colors, the current development for building integrated photovoltaic (BIPV) applications has still a large room for improvement.

In BIPV systems the photovoltaic (PV) panels are not just added on the building but they have a function on the envelope of the building. They replace conventional construction materials of the building's envelope such as windows, shading elements, louvres, roof tiles and façade materials. Thus, PV panels for building integration play an important role on the design of the building and they have to look aesthetically good but also to perform well. The designers and architects are divided to those who support the BIPV technology to their design and to those who believe that this technology eliminates their creativity and the aesthetic view of a building. As stated by Cerón et al. (2013), from architect's point of view the formal aspects of the materials are as important as the physical and functional integration. Thus, the PV sector and construction industry must work together with architects and join their experiences and knowledge in order to develop innovative elements to satisfy all related sectors and comply with all regulations.

The aim of this study is to introduce a new PV panel for building integration, manufactured based on a novel cell encapsulation technology with composite materials, and test it under artificial solar radiation from a solar simulator (SS) regarding its temperature and performance.

This new encapsulation technology is developed under the EU funded project named BFIRST (Building fibre-reinforced solar technology). The aim of the BFIRST project was the development and demonstration of a set of standardized, multifunctional photovoltaic building components based on a recently developed technology for solar cells encapsulation with glass fibre-reinforced composite materials. The objective out of this new technology is the development of lighter, more flexible in shape PV modules to ease their building integration. The resulting PV modules present advanced characteristics in terms of structural capacity, adaptability to non-planar geometries, protection, weight and reduction of manufacturing stages.

One of the developed PV modules named Ventilated Façade (VF) PV module is presented in this paper. Various tests are carried out with the VF PV module in order to evaluate its performance in operation. Most usual problem that the BIPV modules face is the overheating which lead to efficiency loss.

BIPV systems in façade or roof applications are most of the times integrated on the outer skin of the building's envelope replacing the outer construction material e.g., roof tiles. On the other hand, they can be integrated directly on the envelope of the building in the place of curtain walls, windows, louvres, shading elements etc.

In case of integration in a second skin (Figure 1), an air gap is left between the PV panel and the back skin of integration in order to let the air circulate and remove the excess heat generated from the hot surface of the PV panel. This technique prevents PV panel overheating and loss of efficiency and also building overheating and increase of the cooling loads in hot climates. The air gap can be ventilated naturally with fresh air circulation through the formed duct via openings on the bottom and top, or a fan is used to drive the air. In both ways, when fresh air enters the duct, it is heated up from the hot PV surface and exits the duct from an opening on the top of the duct. In BIPV/T (Building Integrated Photovoltaic/ Thermal) systems the heated air is driven into the building with the use of a fan, to provide space heating as shown in Figure 1.

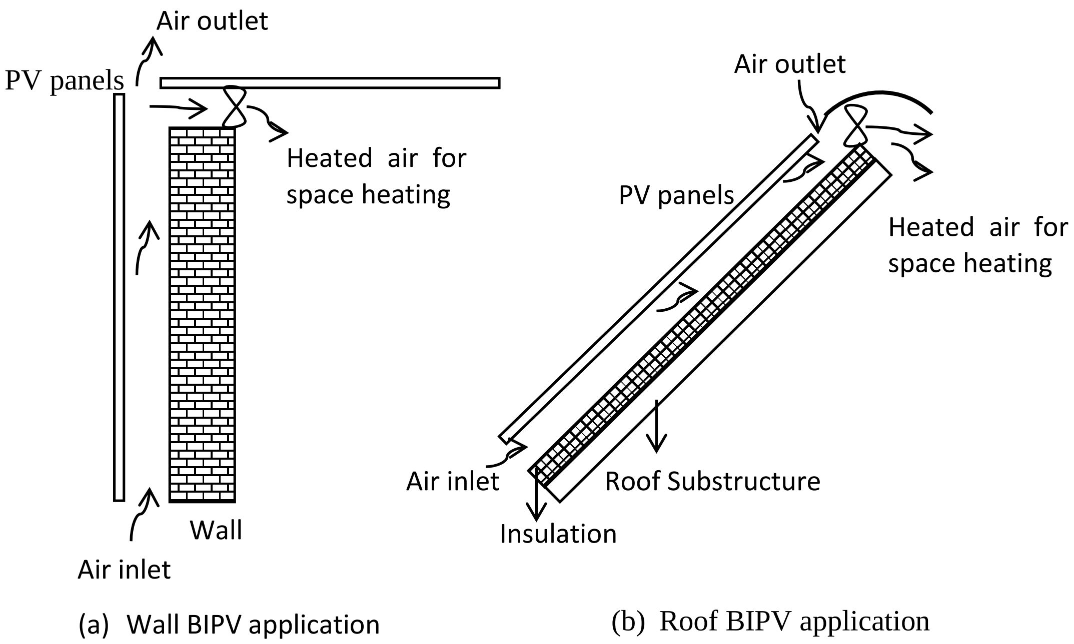


Figure 1. BIPV and BIPV/T systems for façade and roof applications.

The overheating of the BIPV systems and the loss of their efficiency is investigated by numerous researchers the last years, experimentally or with simulations. However, as mentioned by Agathokleous and Kalogirou (2016) most of the studies investigate the systems with forced ventilation of the air duct either because it is believed that it is more effective or because of the complexity of the natural convection on the naturally ventilated systems. It was concluded also that most researchers conclude that an air gap width between 0.10 - 0.15 m is enough to provide PV cooling and remove the excess heat from the duct. According to Brinkworth and Sandberg (2006), the depth of the air channel and the hydraulic diameter of its cross section is the most important variables to be fixed in the design of a PV façade. Brinkworth et al. (1997) found that a reduction of the PV temperature up to 20 K can be achieved if air flow occurs in the duct behind the PV.

Sanjuan et al. (2011) investigated the energy performance of a ventilated façade with open joints between the slabs, in comparison with a conventional sealed cavity façade. It was concluded that the open joints between the slabs improve the air circulation and reduce the energy needs of the building.

Gan (2009) developed a CFD model to investigate the effect of air gap between the PV modules and the building's envelope, on the performance of the BIPV system. It was concluded that for single module installation the air gap should be between 0.14 m and 0.16 m to reduce the mean PV temperature. However, the simulations were carried out considering bright sunshine conditions without wind. In real conditions with the existence of wind, the temperature will decrease more. In the experimental study of Kaiser et al. (2014) for forced ventilated BIPV system, it was concluded that a critical aspect ratio (depth/length of the duct) close to 0.11 can minimize PV overheating.

Therefore, in this study, a VF PV module is tested in a laboratory with a large scale solar simulator (SS) at the Cyprus University of Technology, Limassol, Cyprus. A custom made BIPV apparatus is used to represent integration to a second skin with air gap of 0.1 m and various tests have been carried out in different solar radiation intensities. An experimental set up is developed to record the temperature of the system in various points in order to investigate the thermal behavior of the system. Additional to the VF PV module, a conventional PV is tested under the same conditions for comparison. In this study, the ventilation of the air gap is considered natural without any mechanical means to drive the air. This has a number of advantages in comparison with the mechanically ventilated system such as the energy cost for the fan's operation, noise from the fan, space availability of the building facade for the fan/s installation, difficulty to maintain the fans after installation etc.

2 Experimental Methodology

As mentioned before, the VF PV panel is tested at different amounts of solar radiation of 450 W/m^2 and 800 W/m^2. During the experimental procedures, BIPV system is tested regarding the temperature distribution of the various parts of the system; PV, air gap and back wall. Additionally, a conventional PV panel is also tested with the same methodology. This is done in order to compare the thermal behavior of the new PV module against conventional PV panels from the market. The comparison is not based on the electrical performance of the two panels because they have different characteristics as shown in Table 1.

Table 1. Ventilated façade PV module and conventional PV module main characteristics.

Conventional Photovoltaic			
Area:	1640 x 992 x 45 mm	I_{sc}(A):	8.61
Power (W):	250	V_{oc}(V):	37.41
I_{mpp}(A):	8.16	Efficiency at STC:	15.46 %
V_{mpp} (V):	30.83	Temp. Coefficient:	-0.45%/°C
NOCT:	47±2ºC	No of cells:	6 x 10, 3 strings in a row
Weight:	18.3 kg	Frame:	Aluminium
Opacity:	0%	Plug in connections:	MC4
Cell size:	156 mm x 156 mm	Cells:	Polycrystalline Si
BFIRST Ventilated Facade Photovoltaic Panel			
Area:	1600 x 800 x 4mm	Efficiency at STC:	18.6%
Power (W):	162	No of cells:	36
Weight:	7.3 kg	Opacity:	85-90%
Frame:	Frameless	Plug in connections:	MC4
Cell size:	156 mm x 156 mm	Cells:	Monocrystalline Si

The two modules are not comparable in terms of their performance and power because they are made from different type of cells and they have different size, and thus the comparison in this study is only based on the temperature distribution on the two panels regarding the different materials used for their manufacture.

Therefore, experiments are mostly focused on the thermal behavior of the two BIPV systems and thus more emphasis is given on the temperature at various points of the systems when exposed to specific constant solar radiation for certain amount of time. Although all panels have a specific temperature coefficient to estimate the loss of open circuit voltage when temperature increases, most tests from the manufacturers are done instantaneously with incident light with duration only a fraction of a second.

This study presents transient, time dependent solar radiation flux tests by exposing the panels in constant solar radiation for a specific period of time, in order to record their temperature during the experimental procedure. All tests are performed at the Archimedes Solar Energy Laboratory (ASEL) with the use of a large scale solar simulator (SS).

The two PV panels are tested as building integrated systems in vertical position to represent façade integration, because VF module is designed for façade applications. Two experimental apparatuses are built in the laboratory, as shown in Figure 2, one for each module. Each apparatus consists of a PV panel, wooden back side to represent the outer skin of the building for integration and two plexiglass sides left and right of 10 cm width. Thus, an air duct 10 cm wide is created between the PV panel and the back wooden surface. The ventilation of the air gap is natural since no fan is used to circulate the air from the inlet to the outlet.

BFIRST PV BIPV Conventional PV BIPV

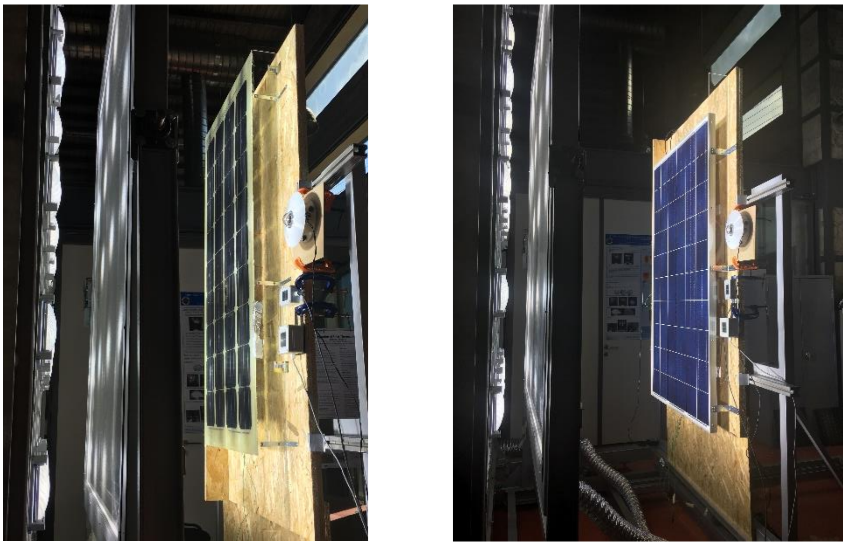


Figure 2. The two BIPV apparatuses, one for the BFIRST Ventilated Façade PV module and one for the conventional PV module.

The air gap width is set to 0.10 m as agreed from most researchers from the literature (Agathokleous and Kalogirou, 2016). Two openings are created one at the bottom side of the apparatus and one at the top, for the air inlet and outlet. This is shown better in the schematic representation of Figure 3.

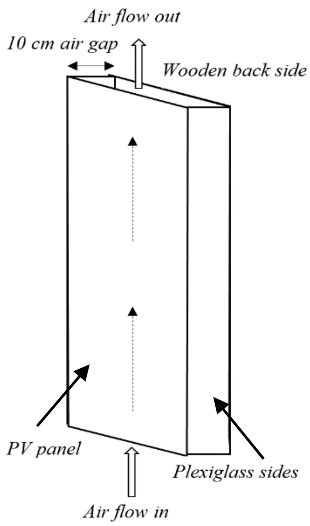


Figure 3. Schematic representation of the BIPV apparatus and the air inlet and outlet from the air gap created between the PV panel and the wooden back side of the apparatus.

The experimental set up is shown in Figure 4. Various thermocouples and data loggers are used to measure the temperature at various points on the BIPV system; on the PV panel, the air in the duct and the back wooden board. A pyranometer is also used to measure the incident solar radiation from the solar simulator. The measurements from the pyranometer are stored in a data logger. The thermocouples are also connected to data loggers. Additionally, a thermal camera is used to capture the temperature distribution on the system's components. The air velocity in the middle of the air duct is also measured, with the use of a hot wire anemometer. The air ventilation was natural and thus the developed air velocity was only based on buoyancy due to the temperature differences.

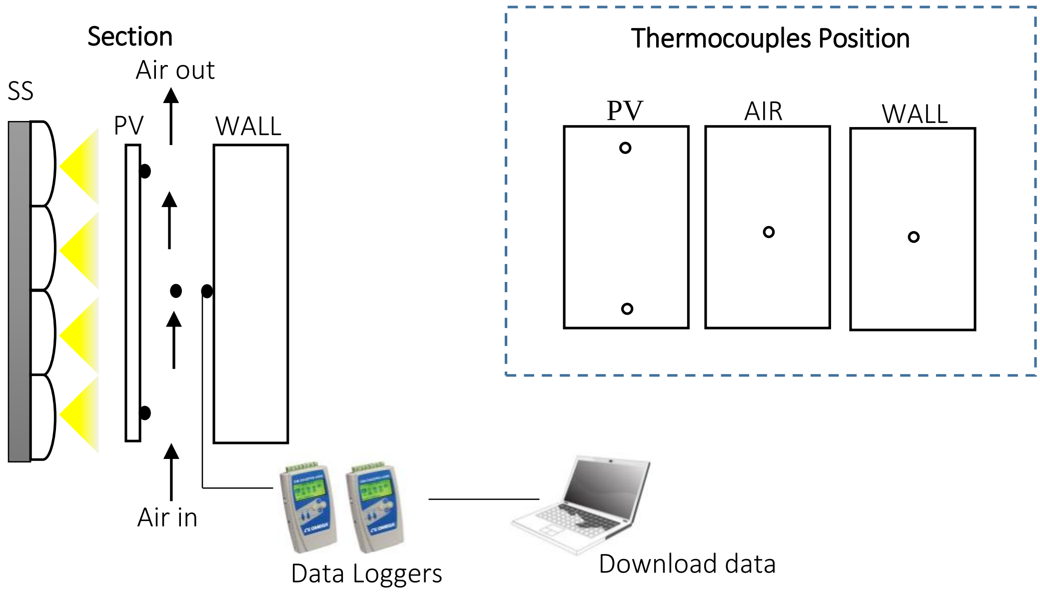


Figure 4. The experimental set up and the position of the thermocouples measuring the temperature on the surface of the PV panel, of the air in the duct, and the surface of the back wooden skin.

Table 2 shows the characteristics of the devices used to measure solar radiation, temperature and air velocity.

Table 2.Characteristics of the equipment used for the experiments.

Pyranometer: Eppley Radiometer PSP			
Spectral Range:	295-2800 nm	Oper. Temperature:	-50°C to 80°C
Output:	0-10 mV analog	Temp. Response:	0.5% (-30°C to 50°C)
Response time:	95%, 5 s	Tilt Response:	0.5%
Data Loggers: Daq Pro 8-channel Data Logger, Omega			
Thermocouples: K- type		**Voltage**	
Range:	-250°C to 1200°C	Range:	0 to 10 V
Accuracy:	±0.5°C	Accuracy:	±0.5 %
Resolution:	0.1°C (1 μV)	Resolution:	200 μV
Accuracy:	-250 to 1200°C ±0.5 %	Input impedance:	125 KΩ
Solar Simulator			
Radiation:	0 - 1200 W/m^2	Type of lamps:	Halogen
No of lamps:	20	Power of lamps:	575 W each
Frame size:	2.15 m x 1.65 m	Inclination angle:	0-90°
Testing base size:	2 m x 1.5 m		
Hot Wire Anemometer: HD 2303.0 Delta Ohm, Probe: AP471S2, Pt100			
Type of meas.	Air speed, flow rate, air temp.	Speed Resolution:	0.01 m/s
Speed Range:	0.1 to 5 m/s	Temp. Resolution:	0.1°C
Temp. Range:	0 to 80°C	Cable length:	~2 m

The following experiments were carried out to compare the two panels in terms of temperature, and the results are presented in the next chapter:

- VF PV at Radiation 450 W/m^2
- VF PV at Radiation 800 W/m^2
- Comparison VF PV with conventional PV at 450 W/m^2

- Comparison VF PV with conventional PV at 800 W/m^2

In addition to the tests of radiation 450 and 800 W/m^2, the VF PV is also tested at radiation of 1000 W/m^2 in order to increase its temperature more and observe any changes in its appearance or a significant increase in its temperature that could reduce its efficiency dramatically.

3 Results

Each experiment had duration of 3 hours with the SS set to constant solar radiation. This is done to make sure that the temperature of the system attained its maximum value and remained at that steady state condition for more than two hours. The recording of the temperature of the various points on the system start few minutes before the SS was turned on and ended few minutes after the SS was turned off. Thus, all the graphs showing the temperature of the various points of the system present the temperature gradient during all the experimental procedure for each experiment for about 200 - 220 minutes.

3.1 BFIRST PV – Radiation 450 W/m^2 and 800 W/m^2

From the experiments, it was observed that the bottom of the PV panel was in lower temperature than the top because of the air inlet in the bottom of the BIPV apparatus. Fresh air enters the duct from the bottom side of the BIPV apparatus, behind the PV panel and cools the bottom side. While the air moves upwards, it is in contact with the heated PV panel's surface and becomes hotter and thus exits the duct at a higher temperature.

Figures 5 and 6 show the temperature recorded at the top (T_{pv_top}) and bottom (T_{pv_bottom}) of the PV when exposed to 450 W/m^2 and 800 W/m^2 solar radiation respectively, together with the ambient air temperature in the laboratory ($T_{ambient\_lab}$) during each experiment.

As can be observed in Figure 5, in constant radiation of 450 W/m^2 the maximum temperature of the PV panel at the top was 57.5 °C and 46 °C at the bottom. This means that the surface of the PV panel is not an isothermal surface. Although constant heat flux is applied in all its surface, the bottom and top sides of the panel have 11.5 °C temperature difference.

For 800 W/m^2 the maximum temperatures of the PV panel observed at the top and bottom were 73.4°C and 62°C respectively, as shown in Figure 6. As can be seen, in both cases the maximum value is stabilized after about 30-40 minutes and remained steady for the rest of the test.

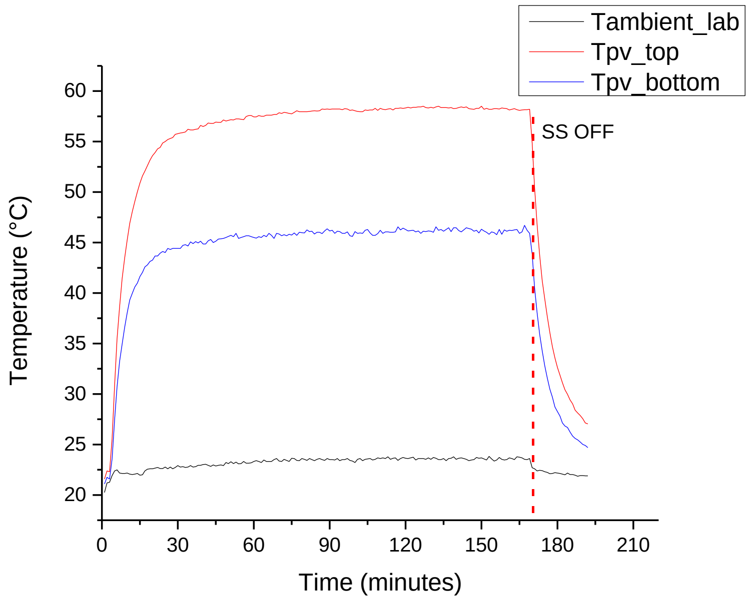


Figure 5.Measured temperature of the PV panel in the top and bottom sides for radiation 450 W/m² and the ambient temperature of the laboratory.

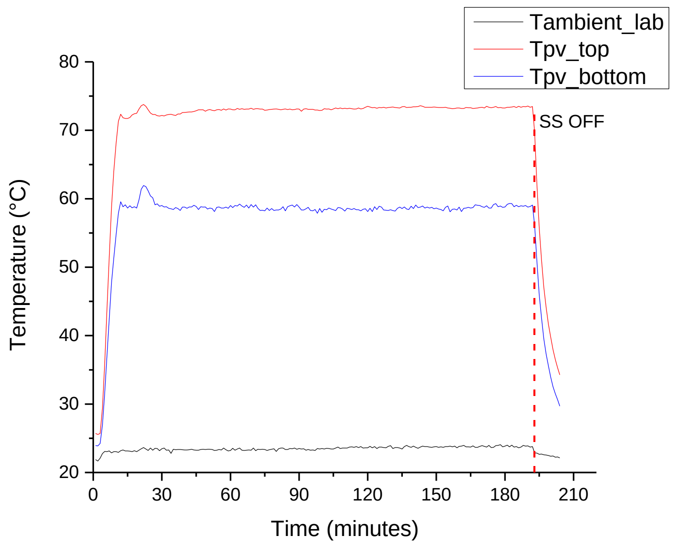
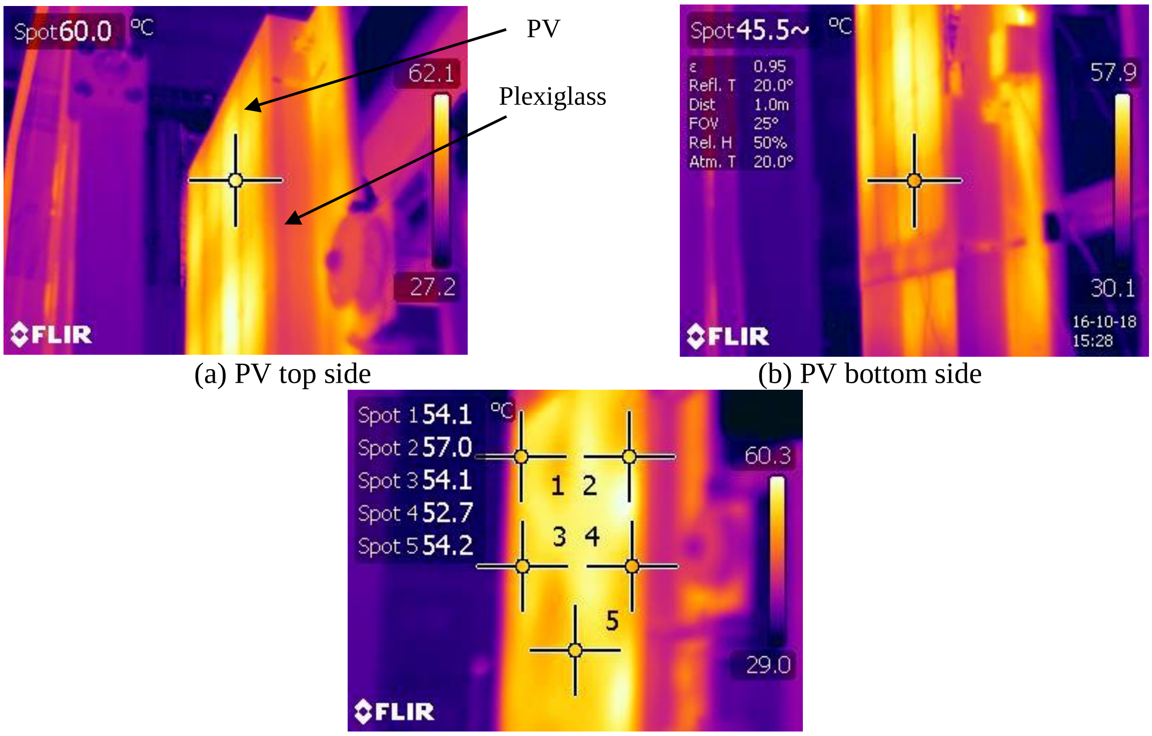


Figure 6. Measured temperature of the PV panel in the top and bottom sides for radiation 800 W/m² and the ambient temperature of the laboratory.

The temperature difference between the bottom side and the top is also validated from the thermography images taken from the thermal camera, shown in Figures 7 and 8 for the experiments with solar radiation 450 W/m^2 and 800 W/m^2 respectively.

As can be seen in Figure 7a and 7b the temperature of the top side of the PV panel is near 60°C and the bottom 45.5°C. Apart from showing that the top side is hotter than the bottom side, the values of the temperature recorded by the thermal camera do not differ too much from the measured values from the thermocouples presented in Figure 5. Figure 7c shows the temperature on various points on the PV surface.

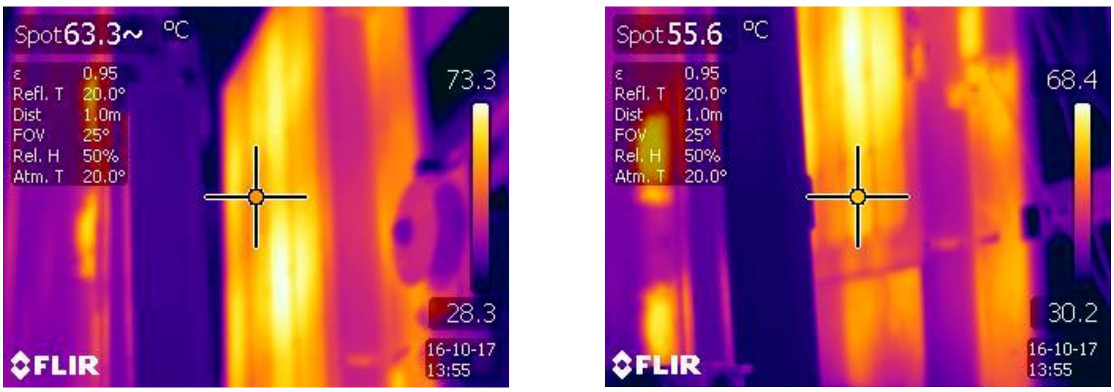


(a) PV top side (b) PV bottom side

(c) Various points on the PV surface

Figure 7. Images of the BFIRST VF PV panel from a thermal camera, during experiment in 450 W/m² solar radiation.

From Figure 8a and 8b for the experiment with 800 W/m² radiation, it can be observed that the temperature at the top side of the PV panel is higher than 70°C and at the bottom size is around 55°C. They do not meet exactly the values measured by the thermocouples because the time that the photos taken are random during the experiments, but they can validate the fact that the bottom side of the PV panel is cooler than the top side.



(a) PV top side (b) PV bottom side

Figure 8. Images of the BFIRST VF PV panel from a thermal camera, during experiment in 800 W/m² solar radiation.

Figures 9 and 10 show the average air velocity in the duct between the PV panel and the wooden back skin of the BIPV system for the experiments with 450 W/m² and 800 W/m² solar radiation. The velocity is measured in the middle of the air gap as shown earlier in Figure 4.

As already mentioned, the air flow was natural without mechanical means to circulate the air. Although no action was taken to the system openings to drive the air, the temperature difference of the PV panel created air flow from the bottom to the top with average air velocity of 0.35-0.4 m/s for the two radiation values used. This means that the air velocity in the air gap between the PV panel and the back wall is the same for the two experiments irrespective of the amount of incident radiation on the PV panel. However, it is interesting to see the air velocity after the SS was turned off. At this time, the system started to cool down and the air velocity decreases.

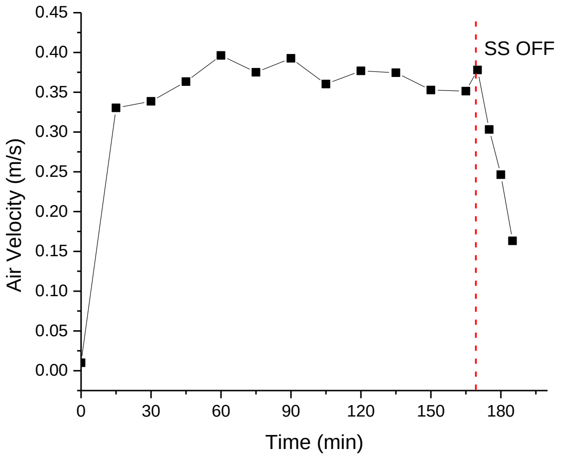


Figure 9.Air velocity in the air duct behind BFIRST VF PV for radiation 450 W/m^2.

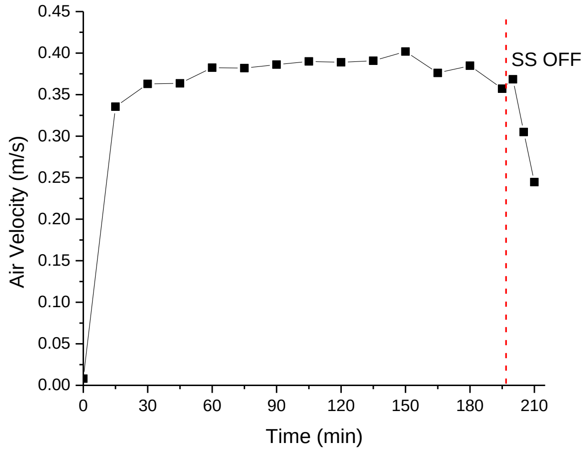


Figure 10. Air velocity in the air duct behind BFIRST VF PV for radiation 800 W/m^2.

Figures 11 and 12 show the temperature of the wooden back skin (T_{w_back}) of the BIPV apparatus, as well as the temperature of the air in the air duct (T_{air_gap}), during the two experiments with radiation of 450 W/m^2 and 800 W/m^2 respectivly.

As can be observed in Figure 11 for the experiment with radiation of 450 W/m^2, the air in the duct was initially at the beginning of the experiment close to the ambient air temperature around 21°C and reached 28.9°C until the end of the experiment. The same trend is also observed for the temperature of the wooden back side of the apparatus which started in 20.5°C and reached maximum 28.4°C later.

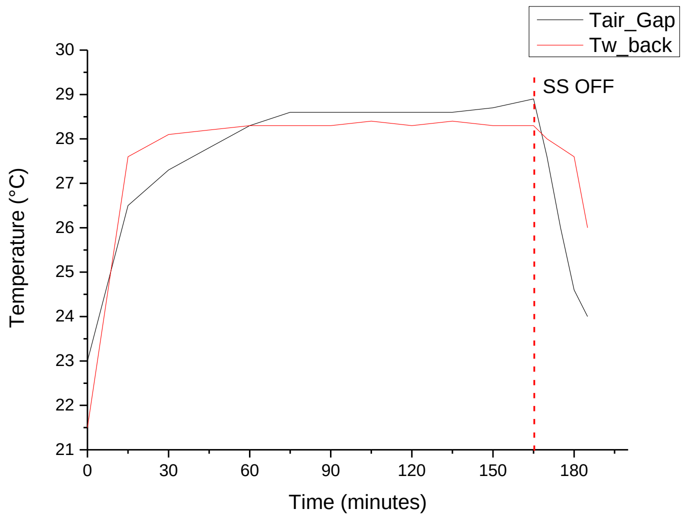


Figure 11.The temperature of the air in the middle of the air duct of the BIPV system and the temperature of the wooden back side of the apparatus for radiation 450 W/m^2.

Figure 12 for the experiment with radiation 800 W/m^2, shows also that the temperature of the air in the duct as well as the temperature of the wooden back side of the apparatus (T_{w_back}) have the same trend and they have very similar temperatures. In both cases the air temperature is slightly higher than the wooden back side temperature.

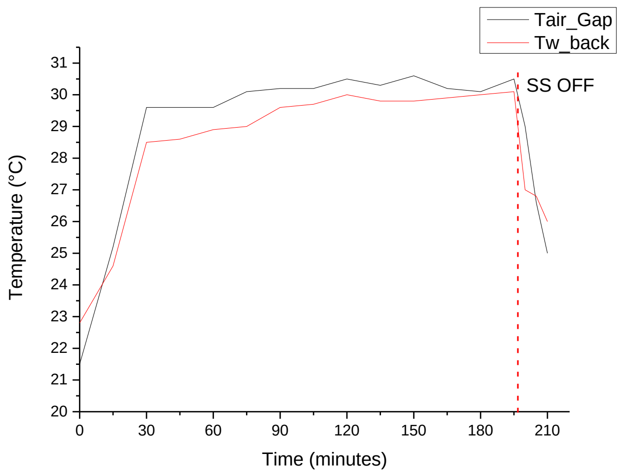


Figure 12. The temperature of the air in the middle of the air duct of the BIPV system and the temperature of the wooden back side of the apparatus for radiation 800 W/m^2.

3.2 Comparison BFIRST Ventilated Facade PV & Conventional PV

As mentioned earlier, a conventional PV panel is also tested with the same experimental procedure as the BFIRST PV, for solar radiations of 450W/m^2 and 800 W/m^2. BFIRST VF PV module is not yet in the market because it is developed for research purposes within the EU project BFIRST. However, the scope of this comparison between the BFIRST module and a conventional PV module is to see whether the BFIRST module with this new manufacturing method using different materials from the conventional modules for coating and cells encapsulation, could be suitable for mass manufacturing. The comparison is regarding the temperature of the PVs because this is one of the most important parameters that affects the performance of a PV module. Usually PV manufacturers give the temperature coefficient value which describes the percentage drop in the PV's efficiency per degree of Celsius above 25°C which is the testing reference temperature. Accordingly, measuring the maximum temperature that a

PV panel can reach during experiments, gives a corrected value of the panel electrical efficiency as well as the degree of its drop.

The comparison of the temperature of the two PVs is shown in Figures 13 and 14. As shown in previous graphs, the temperature at the top side of the PV panel was higher and thus this is selected to be compared for the two panels in this section. Figure 13 shows the temperature of the top side of the PV panels for radiation 450 W/m^2 and Figure 14 for 800 W/m^2.

As can be observed in both figures, the temperature developed on the conventional PV's surface is very similar to the temperature on the BFIRST PV. Accordingly, the new manufacturing technology of the BFIRST PV does not make the PV panel to be heated more than normal PV panels or in different trend. The temperature of the PV panel under 450 W/m^2 constant solar radiation is 57ºC while the temperature of the conventional PV was 64ºC. For 800 W/m^2 constant solar radiation the temperature of the BFIRST PV panel was 73.4ºC and 73.6ºC the conventional PV panel.

The two panels are compared only regarding the temperature on their surface and not regarding their performance because they have different size, different power and different type of cells. Thus such a comparison would not be correct. However, the comparison show that in terms of temperature on the PV surface, BFIRST PV keeps slightly lower surface temperature than a normal conventional PV.

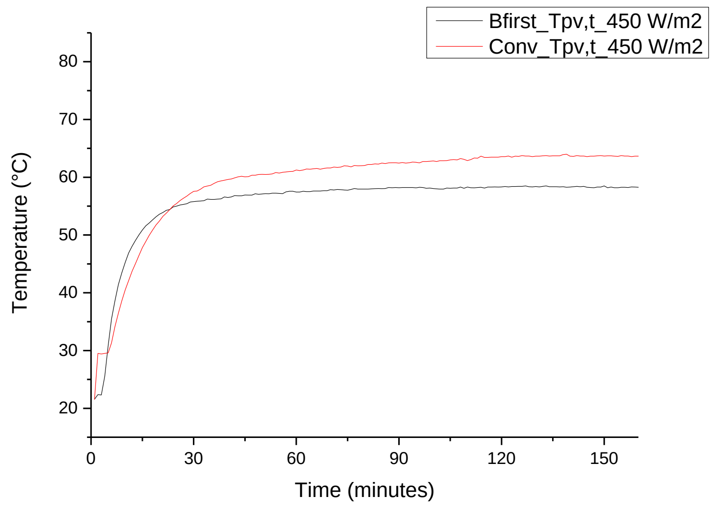


Figure 13. Temperature at the top side of the BFIRST PV and conventional PV at 450 W/m^2.

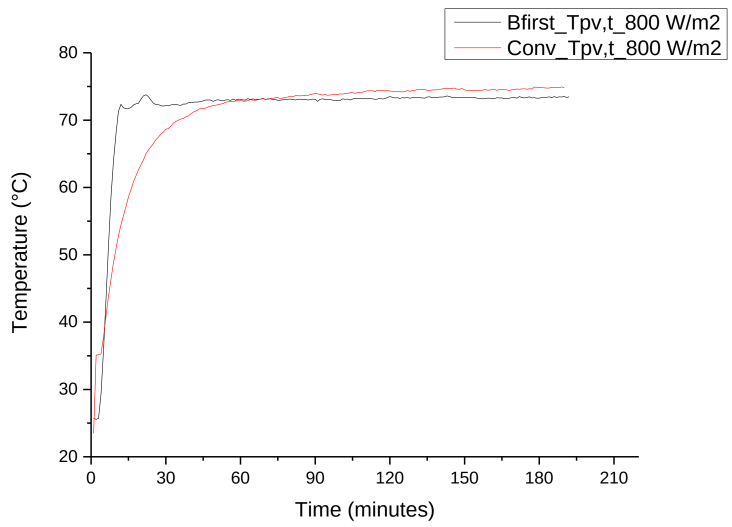


Figure 14. Temperature at the top side of the BFIRST PV and conventional PV at 800 W/m^2.

3.3 Higher radiation testing of BFIRST PV panel

The maximum temperature observed on the BFIRST PV surface from the two experiments is 73.4°C when exposed to 800 W/m^2.

In addition to the testing of the BFIRST PV in low radiation of 450 W/m^2 and high radiation of 800 W/m^2, it is decided to carry out one more test on the BFIRST PV with solar radiation of 1000 W/m^2 in order to measure the highest temperature that the panes can get. A significant temperature increase could affect the PV's efficiency dramatically. Another reason to carry out a test at higher radiation and increase more the PV's temperature, was to observe if higher temperature can cause changes in the coating material of the PV surface or deformation of the fibre due to high radiation. The same methodology with the previous experiments is followed.

As shown in Figure 15, for 1000 W/m^2 constant solar radiation the maximum temperature developed at the top and bottom sides of the PV panel are 79°C and 69°C respectively, which are much higher than in the experiments with 450 W/m^2 and 800 W/m^2 solar radiation, but as before the maximum value is stabilized after about 40 minutes and remained steady for the rest of the test.

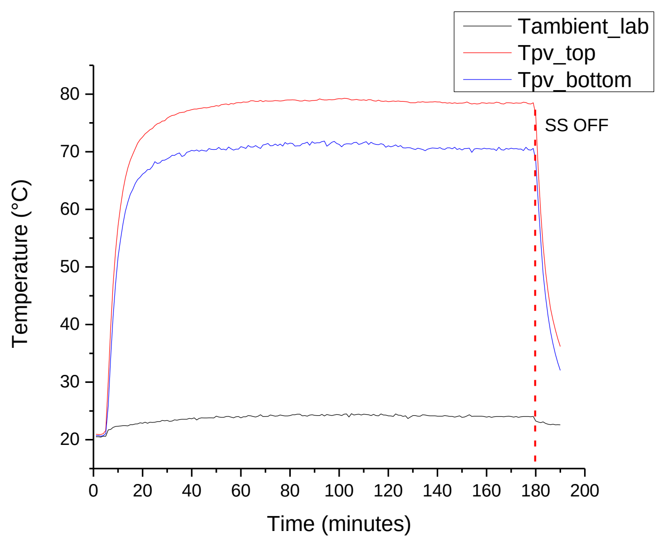


Figure 15. Measured temperature of the PV panel in the top and bottom sides for radiation 1000 W/m^2 and the ambient temperature of the laboratory.

Figure 16 show the average air velocity in the duct between the PV panel and the wooden back skin of the BIPV system for the experiment of 1000 W/m^2 solar radiation. The trend of the line showing the air velocity is the same with the previous experiments and the values of the velocity are also similar between 0.35-0.4 m/s irrespective to the higher solar radiation applied.

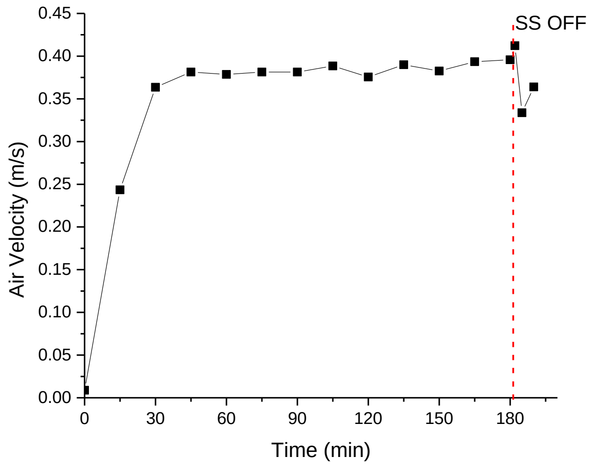


Figure 16. Air velocity in the air duct behind BFIRST VF PV for radiation 1000 W/m^2.

Figure 17 shows the temperature of the wooden back skin (T_{w_back}) of the BIPV apparatus, as well as the temperature of the air in the air duct (T_{air_gap}), during the experiment of radiation 1000 W/m^2.

As can be observed, the air in the duct was initially at the beginning of the experiment close to the ambient air temperature around 23°C and reached 30.2°C until the end of the experiment. The same trend is also observed for the temperature of the wooden back side of the apparatus which started in 19°C and reached maximum 30.3°C later.

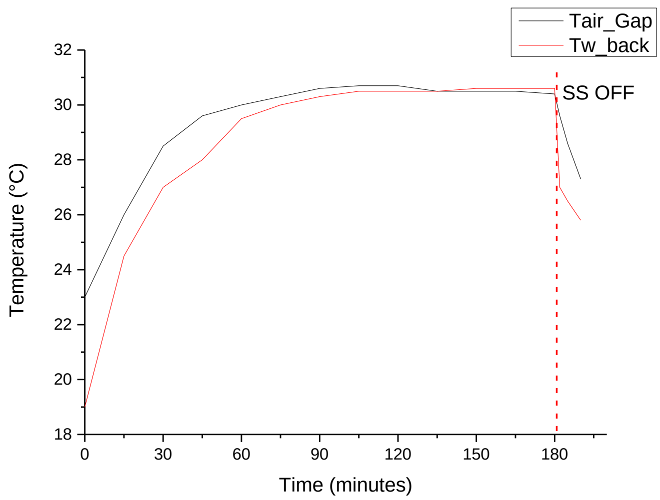


Figure 17. The temperature of the air in the middle of the air duct of the BIPV system and the temperature of the wooden back side of the apparatus for radiation 1000 W/m^2.

4 Conclusions

BFIRST project achieved the main scope to produce aesthetically good, shape flexible and most important lightweight PV modules for building integration. This paper presented one of the products developed in BFIRST project, named Ventilated Façade (VF). VF modules are manufactured based on a new encapsulation method with composite fibre reinforced materials. BFIRST VF PV modules are developed only for research purposes so far, and the aim of this study was to test the new VF module under different amounts of solar radiation in order to record its temperature which is the main parameter that affects the efficiency of the PV modules. A conventional PV panel is tested under the same conditions and same radiation for comparison. The two PVs are tested for three hours under constant solar radiation of 450 W/m^2 and 800 W/m^2.

An additional test with radiation of 1000 W/m^2 is also carried out on the BFIRST PV, to increase more its temperature and reach the maximum possible. It is useful to ensure that the maximum temperature will not cause appearance changes to the panel like discoloration, fibre deformation or coating failure.

The conclusions that can be drawn from this study are:

- Top surface of the PVs in BIPV applications with air gap and openings in the top and bottom, is hotter than bottom surface because the air inlet from the bottom provides PV cooling. In real applications in high buildings, this is expected to be more obvious due to the bigger height of the system. Thus, the air that moves through the air gap with an upward trend, is heated more as it moves to the air gap.
- Buoyancy forces maintain natural air flow circulation at the air gap with air velocity from 0.35 m/s to 0.40 m/s. In the experimental procedure, it is shown that this velocity is adequate to keep PV module's temperature below 80ºC. When the BFIRST PV module was exposed in constant 1000 W/m^2 solar radiation, the maximum temperature measured on its surface was 79ºC.
- The temperature of the BFIRST PV panel under 450 W/m^2 constant solar radiation is 57.5ºC while the temperature of the conventional PV was 64ºC. For 800 W/m^2 constant solar radiation the temperature of the BFIRST PV panel was 73.4ºC and 73.6ºC the conventional PV panel.

Acknowledgements

The work is carried out under the research program Building-integrated fibre-reinforced solar technology (BFirst), funded by the EU Seventh Framework Programme FP7/2007-2013, under grant agreement n° 296016.

Nomenclature and Abbreviations

BFIRST:	Building Fibre Reinforced Solar Technology
BIPV:	Building Integrated Photovoltaic
BIPV/T:	Building Integrated Photovoltaic/Thermal
EU:	European Union
PV:	Photovoltaic
SS:	Solar Simulator

References

Agathokleous, R.A., Kalogirou, S.A., (2016). Double skin facades (DSF) and building integrated photovoltaics (BIPV): A review of configurations and heat transfer characteristics. Renew. Energy 89, 743–756.

Brinkworth, B.., Cross, B.., Marshall, R.., Yang, H., (1997). Thermal regulation of photovoltaic cladding. Sol. Energy 61, 169–178.

Brinkworth, B.J., Sandberg, M., (2006). Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays. Sol. Energy 80, 89–103.

Cerón, I., Caamaño-Martín, E., Neila, F.J., (2013). "State-of-the-art" of building integrated photovoltaic products. Renew. Energy 58, 127–133.

Gan, G., (2009). Effect of air gap on the performance of building-integrated photovoltaics. Energy 34, 913–921.

Kaiser, A.S., Zamora, B., Mazón, R., García, J.R., Vera, F., (2014). Experimental study of cooling BIPV modules by forced convection in the air channel. Appl. Energy 135, 88–97.

Sanjuan, C., Suárez, M.J., González, M., Pistono, J., Blanco, E., (2011). Energy performance of an open-joint ventilated façade compared with a conventional sealed cavity façade. Sol. Energy 85, 1851–1863.