A Building Integrated Photovoltaic (BIPV) demonstration building in Belgium with new Fibre Reinforced Solar Technology PV modules: Analysis with Simulation and Monitoring data

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Abstract

New more flexible and lightweight photovoltaic (PV) modules based on a novel encapsulation technology with glass fibre reinforced composite materials are installed in a residential building in Mons, Belgium which is used as a demonstration building. The tested modules are named roofing shingles (RS) and they are installed on the south part of the building's roof with inclination angle 40º. The installation comprises of 54 RS modules of 32 monocrystalline Silicon cells each. The total installed power of the system is 7.01 kWp. The BIPV system installed on the Belgian demo site is monitored to observe its performance and optimise the installation in case of efficiency loss due to natural parameters e.g. overheating. Various equipment like temperature, humidity, radiation sensors, data loggers etc., are installed on the building for the monitoring. Prior to the installation, a simulation model in TRNSYS simulation software is carried out using weather data for Belgium from a Typical Meteorological Year (TMY) file, to predict the performance of the system as well as other various parameters such as the developed temperature on the PVs surface, air gap temperature etc. The aim of this study is to present the performance of the BIPV system on the demo site and compare the monitoring data with the simulation results. It is concluded that the results from the simulation agree with the monitoring results measured on site.

Keywords: Building integrated PV, Fibre Reinforced Solar Technology PV, simulation, monitoring.

1 Introduction

Photovoltaics (PV) usage in building integration increase in the last 10 years and this trend is expected to continue with the support of feed-in-tariff policies in some countries, the EU directives for renewable energy usage and energy from fossil fuels reduction and the on-going production costs reduction.

When the PV panels are integrated on a building's envelope and replace conventional construction materials of a building, then the PV system is called building integrated photovoltaic (BIPV) system. BIPV systems can be installed on a building's façade as well as on the roof. BIPV systems replace conventional construction materials from the building's envelope such as windows, shading elements, louvres, façade materials and roof tiles.

Most of the times, PV panels are being integrated to a second layer part of the building's construction. E.g. on the insulation of the roof. If they integrate directly to the second layer without air gap, the PV panel is heated and its efficiency drops. This also increase the temperature of the building and increases the cooling loads. Therefore, an air gap is formed between the PV panel and the building's layer which is responsible to allow air flow behind the PVs, to avoid overheating of the PVs and thus loss of their efficiency, as well as to drive the excess heat. Sometimes the excess heat can be used to provide space heating and thus the system is called Building Integrated Photovoltaic/Thermal (BIPV/T).

The air gap can be ventilated naturally or mechanically with the use of fan. Again, this depends on the climatic conditions and the building's needs. Sometimes natural ventilation may be adequate to move the excess heat of the system but in very hot climates, the use of fan to drive the air in the air gap may be more effective. However, natural ventilation has a number of advantages in comparison with the mechanically ventilated system such as the cost of the fan's operation, noise from the fan, special space for installation, difficult to maintain the fans after installation etc.

The size of the air gap in order to be effective depends on the amount of heat that is created due to the hot surface of the PV panel which depends on the location of the system and the weather conditions (ambient temperature and the amount of radiation), the inclination angle of the system, the height of the system, the existence of openings etc. According to Wang et al. (2006) BIPV has significant influence on the heat transfer through the building envelope because of the change of the thermal resistance by the various building elements. Brinkworth et al. (1997) found that a reduction up to 20 K can be obtained on the PV due to an air flow in a duct behind the PV component. That leads to significant increase in the electrical output and reduction of heat gain into the building.

Mirzaei et al. (2014) carried out a study for the role of cavity airflow on the performance of BIPV panels. It was concluded that the surface temperature of the PV panel is lower when there is an open cavity. Additionally, it is mentioned that the flow passing below the PV panel was almost twice than the flow above the PV. Apart from the flat panels, stepped ones are also tested. It is concluded that the stepped arrangement creates more turbulence in the air gap and thus has a significant advantage in cooling of the PVs than the flat arrangement.

Straight to the problem of PV overheating, Kaiser et al. (2014) performed an experimental study of cooling BIPV modules by forced convection in the air channel. The aim of the study was to investigate the influence of the air gap size and the forced ventilation on the cell temperature and consequently on the electrical efficiency of the PV module. The results presented showed that a critical aspect ratio close to 0.11 can be considered to minimize overheating of PVs. It is also concluded that the forced ventilation conditions (v=6 m/s) resulted to bigger power output increase than the natural ventilation cases (v=0.5 m/s).

The aim of this study is to present a new BIPV installation to a demonstration residential building in Mons Belgium, and analyse the monitoring data in terms of the PV temperature and the performance of the system. The BIPV installation finished on April 2016 and monitoring started on May 2016. The PV panels used, are based on a novel encapsulation technology with fibre reinforced materials developed within the BFIRST (Building integrated Fibre Reinforced Solar Technology) project. In addition to the monitoring data, a TRNSYS model is created, in order to estimate the performance of the system and the developed temperature of the PV modules through a year. The estimated results from the simulation are compared with the real monitoring data obtained for the BIPV system from June 2016 to October 2016. The TRNSYS simulation model is able to provide annual estimation of the thermal behaviour of the system and its performance, considering TMY (typical meteorological year) weather data for Brussels, Belgium which is the closest location with available TMY data near Mons.

PV integration technology is a challenge for both architects and engineers. Studies from Luque and Hegedus (2003) and Probst (2008), discuss the position of architecture on the PV facades, the ways of application and the types of PV cells that are preferable in terms of the aesthetics. According to 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, 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.

These are all the issues considered in the BFIRST project, and the aim was to develop and demonstrate flexible and lightweight photovoltaic modules but also efficient modules. One of the products of the project called Roofing Shingle (RS) is presented in this study. RS modules are installed on the roof of the demonstration building in Mons, in the place of roof tiles.

2 Roofing Shingle (RS) PV module & Demonstration Building

As mentioned earlier, the manufacturing of the RS module is based on a recently developed technology for solar cells encapsulation within glass fibre-reinforced composite materials. By means of this new technology, cell encapsulation within composite materials takes place in a single step, yielding a self-supporting, monolithic and lightweight photovoltaic module. Curved and complex geometries can be obtained, opening a wide range of new BIPV products with enhanced building integration possibilities.

Moreover, by using a composite material, in which the cells and their connections are completely embedded, the need to use additional materials as a base or covering is eliminated. Protective coating materials can also be added, either onto the mould during the manufacturing process, or afterwards, once the component has been released from the mould.

The resulting PV modules present advanced characteristics in terms of structural capacity, transparency, adaptability to non-planar geometries, protection, weight and reduction of stages in the manufacturing process, as well as issues concerning transport, manipulation, assembly, safety and security.

The Roofing shingle (RS) unit was designed to be easily handled thanks to a low weight and a reasonable size. The RS element is a frameless rectangular monocrystalline silicon solar panel with characteristic saw tooth shaped profile as shown in Figure 1.

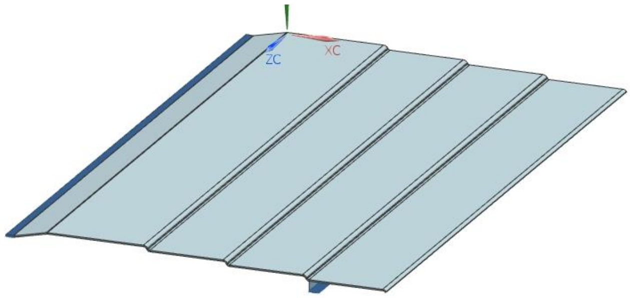

Figure 1. The Roofing Shingle (RS) PV module with saw tooth shaped profile.

The RS PV module has dimensions 905 x 1395 x 59 mm and weights 7.3 kg. From the manufacturing process, it is an opaque module which is later painted black to reproduce the colour of the natural slate of the roof. Table 1 shows some characteristics of the RS module.

Table 1. Characteristics of the Roofing Shingle PV modules.

Dimensions	905 x 1395 x 59 mm	**Cell type**	Monocrystalline Si
Weight	7.3 kg	**Cells Efficiency**	18.9%
Power	123 Wp	**Module Efficiency**	11.5%
Number of cells per module	32		

The demonstration building is a new residential building located in Mons, Belgium. The orientation of the building is 10° from south to west as shown in Figure 2. The roof BIPV system is installed on the south roof of the building with 40º slope. The south roof of the building has two parts, shown with orange and blue in Figure 2. Considering the size of the RS modules and the size of the main part of the roof (orange) and secondary part (blue), it was decided to install 57 RS modules as shown in Figure 3. Table 2 shows the characteristics of the PV system in the demonstration site. The northern side of the roof is covered with normal tiles. The residential house is connected to the electric grid using a 3 x 230 V connection of 12.7 kVA (30 A).

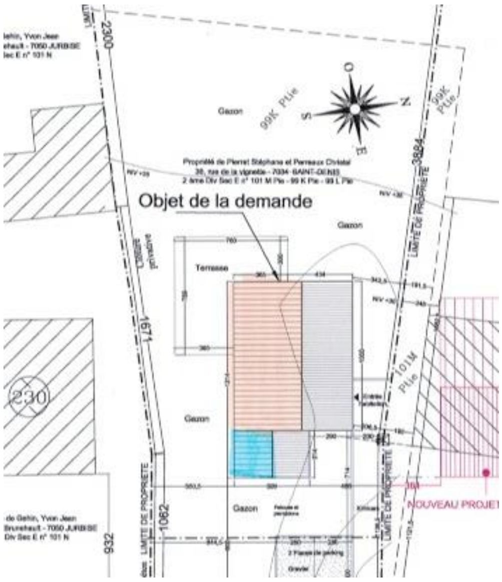

Figure 2.The demonstration site in Mons, Belgium, showing the two parts of the roof for BIPV installation.

Figure 3. The 57 RS modules on the roof of the demonstration building.

Table 2. Characteristics of the PV system installation.

Number of modules	57
Inclination angle	40º
Nominal power of the PV plant	7.01 kWp
Orientation	10º from South, to West

The shape of the modules required a special installation technique in order to simplify the installation. All 57 modules were installed in one day. From top to the bottom, the modules overlap to form one large continuous PV surface to cover all the roof's area (both main roof and secondary part of the roof). From left to right there are no joints in between the panels (Figure 4) and a hidden gutter is used to collect rainwater.

Figure 4.RS modules overlap, without connections in between the panels (left picture), and the gutter between the panels to collect the rain (right picture).

The roof is firstly covered with thermal insulation and a wooden structure on where the aluminium profiles to fix the PVs is installed. Thus, an air gap between the PV modules and the substructure is formed in order to cool the PVs and avoid loss of efficiency due to overheating. The air gap is naturally ventilated without the use of fan to drive the air behind the PVs, as shown in Figure 5. In this case, monitoring of the temperature of the PV surface and the power production, will help us to understand if natural ventilation is adequate to cool the PV surface or a fan to drive the hot air outside the duct is needed.

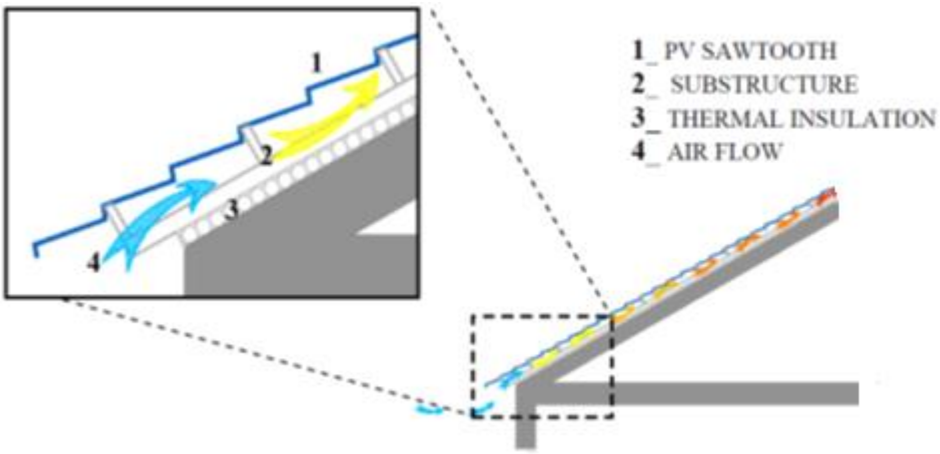

Figure 5. The roof structure showing the way of the air flow behind the PV panels.

3 TRNSYS Simulation Model

TRNSYS (Transient Systems Simulation) software is used to create a simulation model of a BIPV system, using weather data from a TMY (Typical Meteorological Year) file of Brussels, Belgium which is close to Mons where the demonstration building is located.

This kind of simulation is very useful prior to the installation in order to estimate and predict the performance of the system. In this case, simulation is carried out before installation and the estimated results regarding the temperature of the PV surface and the energy production are now compared with the monitoring results. Apart from the PV surface temperature and the energy production of the system, the developed model can estimate the mean temperature of the air in the duct between the PV panels and the roof's substructure, the temperature of the air in the outlet, the thermal efficiency of the system, the convective and radiative loses etc.

Type 566 from the Electrical Library of TRNSYS is used for the BIPV system, and Type 109 for weather data. A simulation is carried out for one year, with one hour time step, considering an inclined roof BIPV system at an angle of 40º and orientation of 10 degrees from south. The model needs as input the width and length of the BIPV system. In this application, the installation is made in two roof parts with different dimensions. Thus, two simulation runs were performed in order to estimate the total power production of the system. The heat transfer coefficients in the outer side of the PV modules as well as in the air gap, are estimated considering natural convection.

4 Monitoring process

The PV system set up on the building's roof finished on April 2016 and the monitoring started on May 2016. The sensors and rest of the monitoring equipment were installed during May and June 2016. Thus, most of the data were available from June or July.

As mentioned in section 2, the air duct between the PV panels and the substructure of the roof is naturally ventilated. This is to avoid the extra energy that is needed by the installed fan in the forced ventilated systems. One of the most important parameters to measure during monitoring is the temperature of the PV surface. By PV surface it is meant the big continuous PV surface of the roof covered by 57 modules. It is important to record the temperature of the PV surface during the year in order to observe if the PV panels overheat and lose efficiency. In this case, it means that the natural ventilation is not adequate to cool the PVs and a fan will be installed to drive fresh air in the duct. Ten temperature sensors were installed in various positions on the PV back surface, on the substructure, in the attic etc.

The equipment used for measuring the various parameters is shown below:

1. Irradiance sensor (Kipp and Zonen Smart Pyranometer SMP10)

2. Weather parameters (Temperature, wind, wind direction, irradiance) – QUADRA Weather Station
3. Relative humidity sensor
4. External temperature sensors – PT1000 sensors
5. Energy meters
6. Indoor temperature sensors – PT1000 sensors
7. Server for data acquisition
8. Continuous and automatic storage of data into a DB server on the Amazon Cloud

An overview of the complete monitoring equipment is presented in Figure 6, showing the outdoor and indoor sensors, and the procedure for connections to save data to the web server storage.

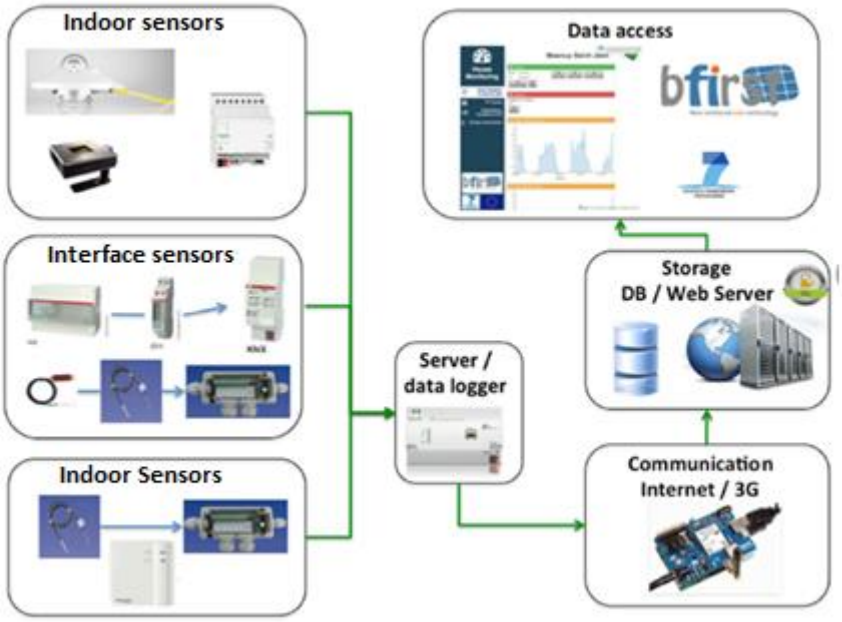

Figure 6.The monitoring equipment and the monitoring setup, installed on the demonstration building in Mons, Belgium.

5 Results

This section presents the results obtained from the TRNSYS simulations in the first part, and the monitoring data in the second part. TRNSYS modeling can give results for one full year, while monitoring data are available from June 2016 and analyzed until October 2016. As already mentioned, the monitoring of the building started on May 2016 but not all the sensors are activated the same time.

It was not possible to compare the estimated and monitored data for one year because only 5 months of monitoring data are available so far. Thus, the data are compared only for the last months. It was not expected to predict the exact values for energy production of the system or the exact values of temperature on the PV surface from the simulation because of the different weather data used (TMY Vs actual), but the simulation would help us to see an overall image of the system's performance for one complete year.

5.1 Results from Simulation

The solar radiation and ambient temperature data from the TMY file for Brussels, Belgium for one year are shown in Figure 7 and Figure 8 respectively. The x-axis shows the hour of the year as given by the TMY file, and the red lines show the month period more clearly.

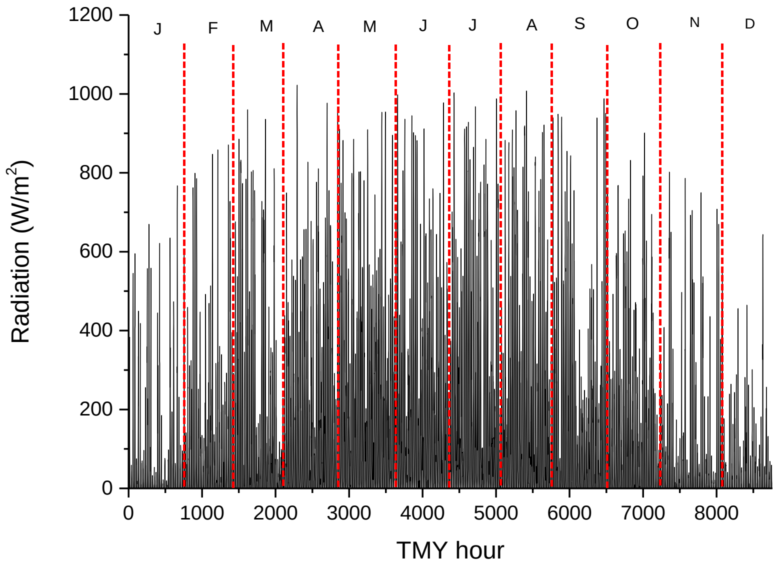

Figure 7. Solar radiation from the TMY file of Brussels, Belgium.

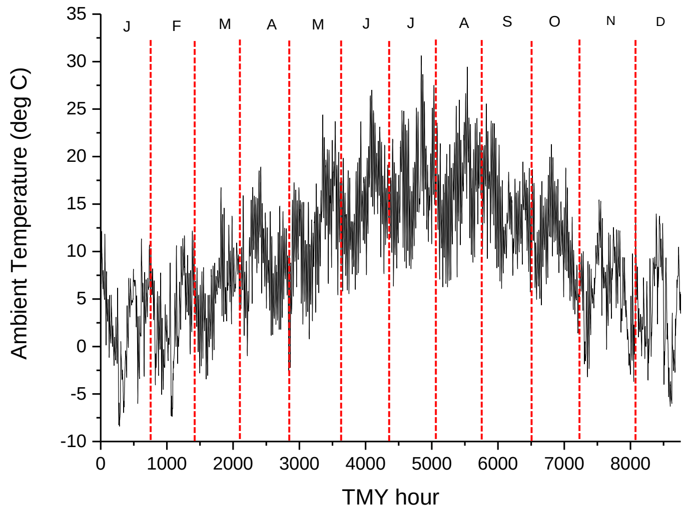

Figure 8. Ambient Temperature for Brussels, Belgium from TMY file.

This information, together with other like relative humidity, wind velocity, wind direction, atmospheric pressure, solar azimuth angle etc., are used as inputs to the Type 566, in order to estimate the temperature of the PV system during a year, the mean fluid temperature behind the PV panels, and the energy production of the system.

Figure 9 shows the average temperature on the PV surface (continuous surface covered by 57 PV panels) during one year. Red lines and letters on the top separate each month of the year. As can be observed, higher temperatures are shown from May to September, reaching up to 66ºC in some days.

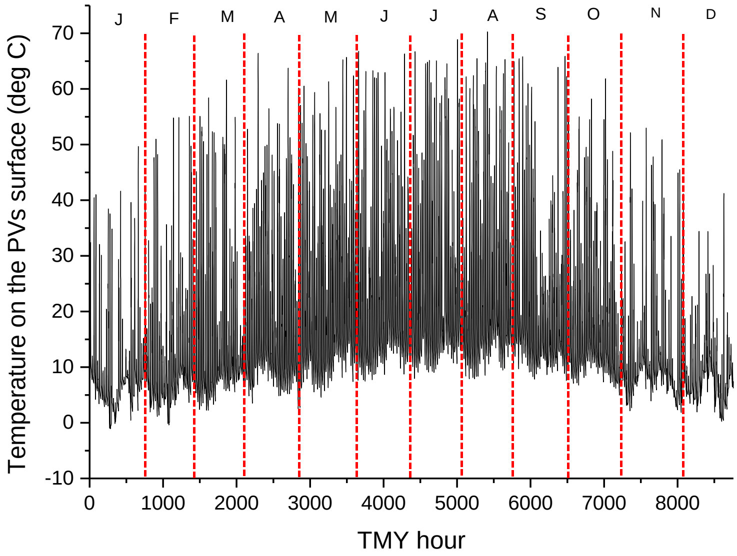

Figure 9. The estimated temperature on the surface of the PV panels during a year, from TRNSYS simulation.

As shown earlier in Figure 5 an air gap is formed between the RS modules and the roof's substructure, and it is naturally ventilated. The air inlet temperature in the TRNSYS model is set to be equal with the ambient temperature. The convective heat transfer coefficients on both sides of the PV modules are estimated considering natural convection.

Although the air enters the formed duct in ambient temperature, the temperature of the air at the outlet is expected to be much higher. The air passes through the duct and heat up due to the direct contact with the hot PV modules surface. The simulation showed that the temperature of the air at the exit of the duct was approximately 10°C higher than in the inlet.

In the real site, it is expected that the bottom side of the PV system will be cooler than the top side because of the continuous ambient air inlet from the bottom.

The mean air temperature in the duct estimated from TRNSYS simulation is shown in Figure 10. The air in the duct is hotter in the summer months reaching a maximum of 50ºC. This may affect the temperature in the attic, during the summer period, so the temperature of the back side of the air gap on the roof's substructure is also estimated from the simulation. The results showed that during the year, the temperature variation of the substructure was up to 5ºC, which is not too big to affect the cooling loads of the building.

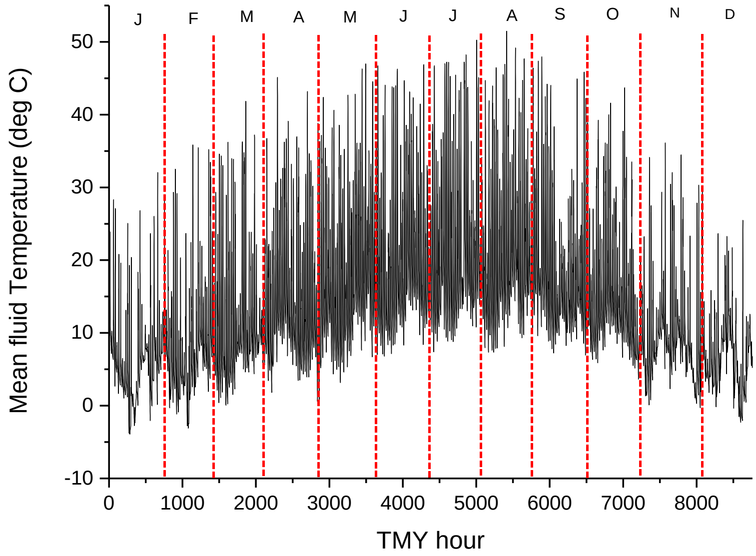

Figure 10. The air mean temperature in the air gap between the PV modules and the substructure, from TRNSYS simulation.

Apart from the temperature distribution on the various parts of the PV system and the structure, one of the most important reasons to carry out this kind of simulation prior to a PV installation is to predict the energy production from the system through a year. For the RS PV system, the estimated energy production from the system is shown in Figure 11 which for one year is estimated to be 7160 kWh.

The monthly estimated energy production is shown in Figure 12. It can be observed that the biggest energy production is estimated between May and August. However, in Figure 9 it was shown that from May to August the temperature of the PV surface was maximum. This means that the increased PV temperature up to 66ºC does not affect the performance of the building according to the simulation.

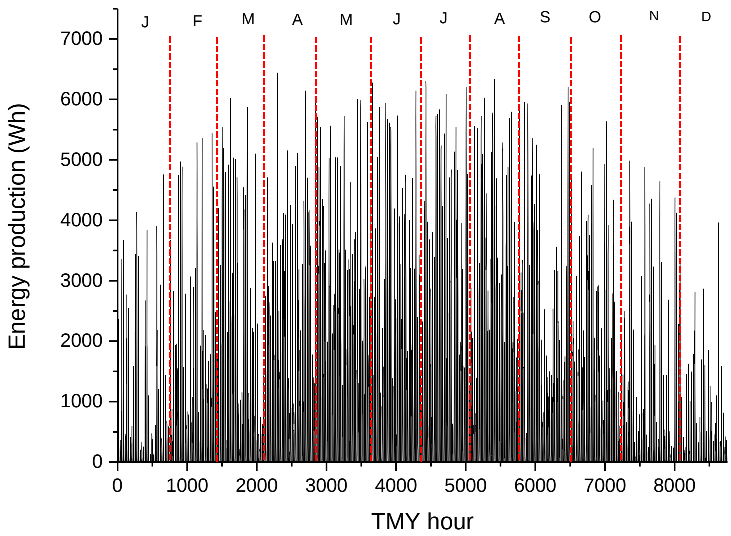

Figure 11. Estimated energy production of the RS PV System for one year from TRNSYS simulation.

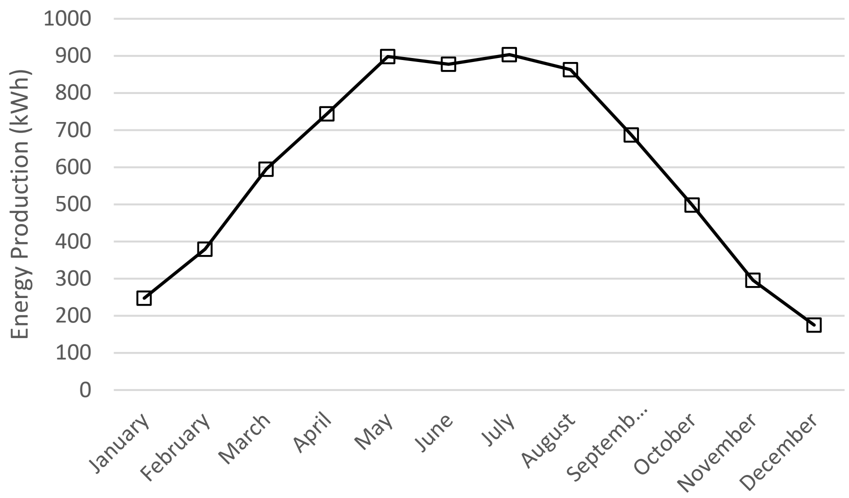

Figure 12.Estimated energy production of the RS PV System from TRNSYS Simulation.

5.2 Results from Monitoring

As mentioned before, the monitoring started on May 2016. However, not all the instruments started monitoring the same time and not all instruments were set to have the same duration between measurements. Thus, it was difficult to present the measured values in terms of real time for each month. Therefore, to unify the data it was decided to present them in terms of 'Measuring Time' or 'Hours of Measurement' which represent the measurement points recorded every day for the five months from June to October. It is important to mention that not all the graphs have the same values in the x-axis (time) because not all instruments were measuring in the same frequency. Each month is separated with red lines to show each month. This is made to present data in an understandable form.

Figure 13 and Figure 14 show the radiation measured from a pyranometer installed on the roof of the building, and the ambient temperature respectively. As can be observed from Figure 13, the measured solar radiation appears to be higher than the radiation from the TMY file used in TRNSYS shown in Figure 7, but on an average basis it is very similar. The measured ambient temperature agrees with the data in the TMY file used for simulation.

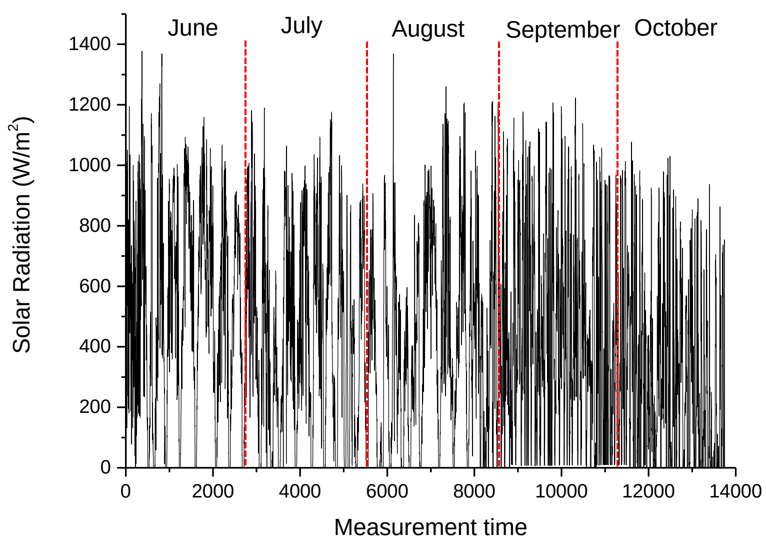

Figure 13. Solar radiation measured on site in the demonstration site in Mons, Belgium, from June to October.

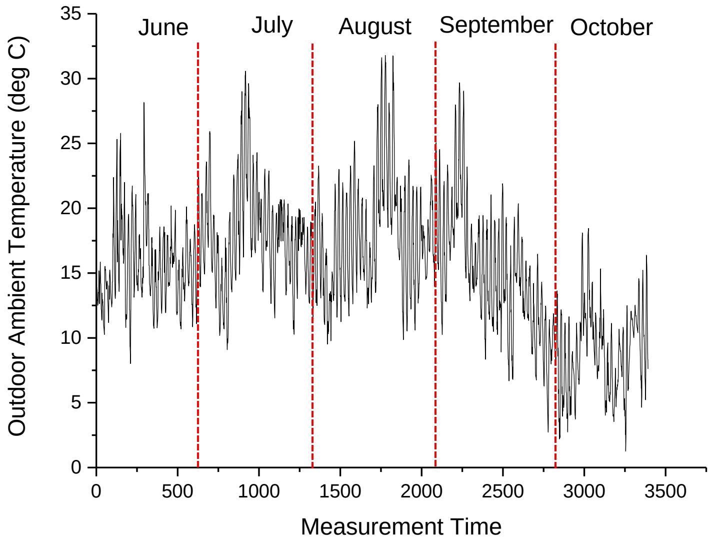

Figure 14. Ambient temperature measured on-site in Mons, from June to October.

The temperature of the RS modules was recorded in various points on the system. It is important to investigate the temperature in various points on the large roof area covered by PV panels, in order to avoid hot spots, overheating in specific panels etc.

An important observation from this set of data, was the difference of the temperature between the panels in the bottom row and the top row. The temperature at the PVs in the top row is higher than in the bottom row. This shows that the PVs in the bottom are cooler due to the inflow of the ambient air. The maximum temperature of the PVs at the bottom row and top row is 52ºC and 63ºC respectively. The average temperature of the PV surface is shown in Figure 15. The simulation results showed maximum PV surface temperature up to 66ºC which is close to the measured maximum temperature of 62ºC.

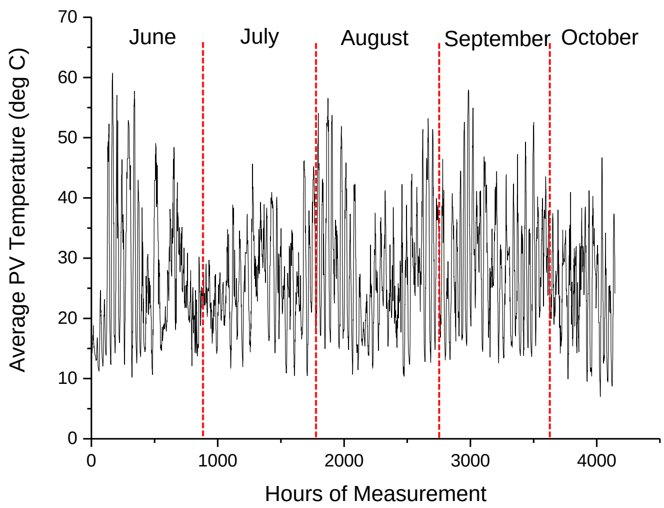

Figure 15. Averagete mperature of the RS PV panels from June to October.

The most important outcome of this study is the energy production of the system. Previously, the total estimated yearly energy production of the system estimated to be 7160 kWh. For the monitoring, the energy production started to be recorded from August. Thus, the measured energy production of the system from August to October is shown in Figure 16.

By comparing the estimated energy production from TRNSYS simulation with the measured energy production for the same months (August, September and October), it can be observed that the estimated energy production is very similar to the measured production. The estimated energy production from TRNSYS simulation from August to October is shown in Figure 17.

Although there is a difference in the trend of the two graphs, especially during September where in the TNRYS estimation, the energy production is at lower levels than the measured, the estimated total energy production for the three months and the measured are very close. As shown in Table 3, the total estimated energy production for the three months August to October is 2148 kWh and the measured energy production for the three months is 2255 kWh. The difference between the two values is only 4.8% and the reason for the deviation is the difference in solar irradiation between the TMY data and actual data.

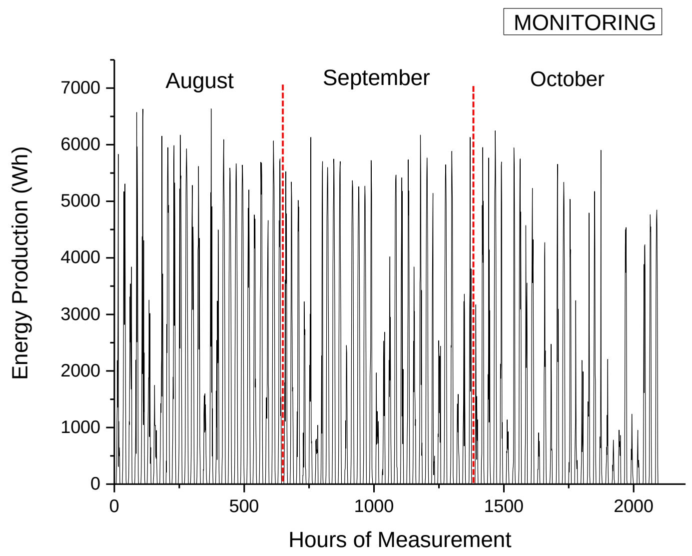

Figure 16. Measured energy production of the RS BIPV system from August to October.

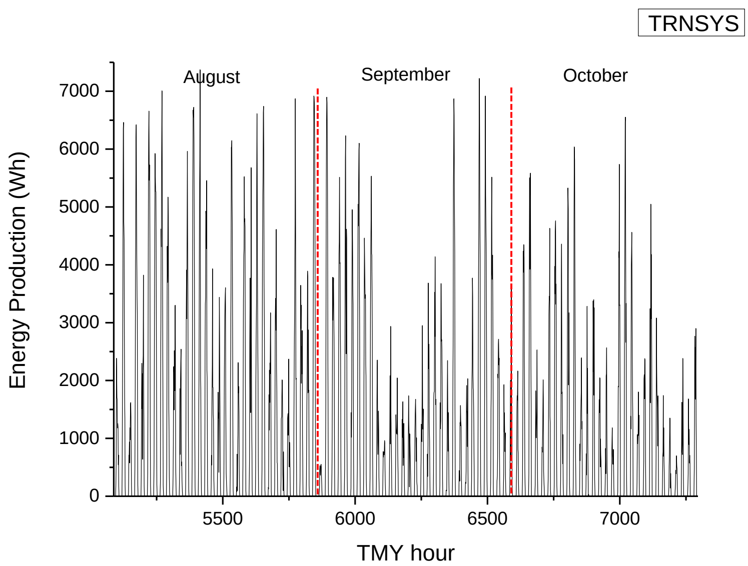

Figure 17.Estimated energy production from TRNSYS simulation from August to October.

Table 3. Energy production from August to October from real measurements and simulation.

	Production for August, September, October
From Monitoring	2255 kWh
From Simulation	2148 kWh

6 Conclusions

This study presented a new BIPV installation on a residential building in Mons, Belgium. The PV panels used are produced within the BFIRST Project with a new encapsulation method with fibre reinforced composite materials. The modules installed on the BIPV system in Mons are called Roofing Shingles and they replace the roof tiles of the southern roof of the building. In total 57 RS modules were installed on the roof of the building in April 2016. One month later, a number of sensors were installed on the demonstration site and the monitoring of the system started, recording the temperature of the system in various points, the weather conditions, the energy production, the climatic conditions in the building etc. The monitored data presented in this study start from June 2016 to October 2016, except from the energy production which started on August 2016.

Apart from the monitoring results, a TRNSYS simulation is also carried out in order to estimate the performance of the system during a whole year, using weather data from TMY file for Brussels, Belgium. The results obtained from the simulation are compared with the monitored data for the months that monitoring data were available.

The most important outcomes from this study are summarised below:

- The RS PV modules, although they are dramatically lighter than other PV modules for building integration in the market, they fit perfectly on the design of the building and they look like normal tiles.
- The lightweight panels can be installed easily than other heavy modules. All 57 modules were installed on the roof of the building in one day.
- The results from the TRNSYS simulation agree with the monitored results for PV surface temperature and the energy production. Thus, the energy production of the system in one year of operation is expected to be around 7160 kWh as estimated from the simulation.
- The PV panels in the bottom row are cooler than the panels at the top row because of the air inlet at the bottom. In the bottom, the maximum measured temperature from August to October was 52°C at the bottom and 62°C at the top.
- Energy production does not present any drop during the period with high PV temperature. The increase in the surface temperature of the top row of PVs, up to 63°C did not affect the overall energy production of the system.
- The air gap with natural ventilation is adequate to keep the temperature of the PV panels below 62°C even in August where the ambient temperature and the solar radiation were at maximum.
- The energy production estimated from TRNSYS simulation for the months August to October was only 4.8% lower than the real energy production measured on site mainly due to differences in TMY radiation data compared to actual measured data.

Acknowledgements

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Nomenclature and Abbreviations

BFIRST	Building integrated Fibre Reinforced Solar Technology
BIPV	Building Integrated Photovoltaic

BIPV/T	Building Integrated Photovoltaic/Thermal
EU	European Union
PV	Photovoltaic
RS	Roofing Shingle
TMY	Typical Meteorological Year
TRNSYS	Transient Systems Simulation

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