Evaluation of performance at experimental buildings and real demonstration sites in BFIRST project: Theoretical and practical aspects for BIPV monitoring system

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Abstract: Monitoring is one of the main activity of BFIRST, Building-integrated FIbre-Reinforced Solar Technology, project, a 5 years funded European project, project reference number 29601, that started in April 2102 and deals with the design, development and demonstration of a portfolio of innovative photovoltaic products for building integration, based on cell encapsulation within fibre-reinforced composite materials. Automatic data acquisition systems are generally required for monitoring, performance evaluation and exchanging data of PV systems. Standard IEC 61724:1998 "Photovoltaic system performance monitoring –Guidelines for measurement, data exchange and analysis" provides a guideline that shall be followed in these cases. As far as Building Integrated Photovoltaics (BIPV) are considered, besides electrical parameters there is in addition the need to monitor the specific building performances. That is because a BIPV module operates as a multi-functional building construction material; it generates energy and serves as part of the building envelope. Since the building related performances are not included in the aforementioned IEC standard, a general guideline for monitoring was prepared within the project that has been used within the project at two levels: one at experimental sites mainly related to experimental single module testing and the other at demosite with real PV size plants.

1. Introduction

Monitoring activity is an essential part for every Photovoltaic plant and Automatic data acquisition systems are generally used for monitoring, performance evaluation and exchanging data of PV systems, according to the Standard IEC 61724:1998 "Photovoltaic system performance monitoring –Guidelines for measurement, data exchange and analysis". But in the BFIRST project Building Integrated Photovoltaics (BIPV) are considered, so besides electrical parameters there is the need to monitor the specific building performances. That is because a BIPV module operates as a multi-functional building construction material; it generates energy and serves as part of the building envelope. In support of this, Standard EN 50583-1&2 "Photovoltaics in buildings" considers the following five specific functions for BIPV products: 1) Mechanical rigidity and structural integrity, 2) Primary weather impact protection (rain, snow, wind and hail), 3) Energy economy (such as shading, daylighting, thermal insulation), 4) Fire protection and 5) Noise protection.

Since the building related performances are not included in the aforementioned IEC standard, a general guideline was prepared within the project, which contains recommended procedure for:

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a) monitoring the basic electrical characteristics of BFIRST photovoltaic (PV) modules (as separate units or as an integral part of a whole PV array) such as the output and/or input power, voltage and current values in respect to non-electrical parameters such as irradiance at PV modules plane, as well as ambient and modules temperatures;

b) monitoring of parameters related to the outdoor and indoor microclimate that can be used as a reference for experimental test sites or for climatic environmental characterization. These data are necessary in order to characterize the thermal and optical behavior of BIPV module;

c) exchanging and analysis of monitored data.

This has been the theoretical aspect of the activity. In practice two levels of monitoring activities have been adopted within the project:

1) experimental test sites: one in Portici (Southern Italy) and one in Pikermi (Greece)

2) demo sites with real size products: a retrofitted office in Zamudio (Spain), a newly built residence in Mons (Belgium) and a retrofitted residence in Pikermi (Greece).

The monitoring activity has been started very recently, by August 2016.

2. Bfirst project

BFIRST project is a project funded by the European Union. It started on and it is due to finish on 30th of April, 2017. The project aims to the design, development and demonstration of a portfolio of innovative photovoltaic products for building integration, based on cell encapsulation within fibre-reinforced composite materials. From a technological point of view the process to use composite material manufacturing and cell encapsulation is very innovative and the advantage is that it takes place in a single-step process and the produced modules are monolithic, lightweight structures, in contrast with currently available glass-based multilayer modules. Moreover a high versatility regarding complex geometries, transmittance levels, colors and surface finishing can be achieved from different materials (resins, fibres, additives) and processes (pre-preg, infusion, etc.). Laboratory test-sites and three demo-sites has been set in order to provide a complete characterization which could helps designers, installers and final users making an optimal profit of the possibilities of the products. In this aspect the monitoring activity has played a very important role.

3. Guideline preparation

4. Monitoring activity

The monitoring process, although regulated by specific Standard, allow very large possibility for the user or the installer for installing a monitoring system, since the numbers of the equipment, their quality could be very costly depending on the level of uncertainty that is required. So the activity started with the publishing of a general guideline that could be considered the reference for the project, at least. That was the theoretical aspect of the monitoring. Then each of the 4 partner involved in the monitoring work package was asked to produce an adaptation according to their technical need and obviously budget. So 4 different adapted guidelines were then published. Once again in order to easy the comparison of data so different a procedure to give a best way to match the data coming from each sites was agreed. Details in Pellegrino and al. in references.

4.1 **Experimental sites**

Two experimental sites for early characterization were selected: one in Portici, in the Southern of Italy, and the other one in Pikermi, in Greece.

4.2 **Demosites**

DEMOSITES

Three demosites for real plant were selected: one in Mons, Belgium, the second in Pikermi, in Spain, and the third in Pikermi, Greece. Table I presents the main demosites characteristics.

Table I. Demosites characteristics

Site	Type	Tilt (°)	Azimuth (°)	Nominal power (kW)	Total area (m^2)
Zamudio	Skylight	33	0	1.89	33.5
	Al Ventilated facade	90	-90	2.42	20
Mons	Roof shingles left	40	5	3.44	30.8
	Roof shingles right			3.57	31.5
Pikermi	Shading elements				
	Balcony				
	Ventilated facade				

For all the demosites a table, table II, contains information about global radiation on horizontal and diffuse component, if any, and on the plane of the array.

Table II. Radiation parameters values

Site	Type	Mean daily global radiation in the horizontal plane ($Wh \cdot m^{-2}$)	Mean daily diffuse radiation ($Wh \cdot m^{-2}$)	Mean daily global radiation in the plane of the array ($Wh \cdot m^{-2}$)
Zamudio	Skylight	NA	NA	5479
	Al Ventilated facade			2958
Mons	Roof shingles left	NA	NA	5076
	Roof shingles right			
Pikermi	Shading elements	NA	NA	NA
	Balcony			Na
	Ventilated facade			NA

Table III shows data about air temperatures. For each month the Maximum value, the average and the standard deviation for the daily maximum temperature was reported (column with heading Max monthly air T), and the maximum the average and the standard deviation for the air temperature.

Table III. Air temperature values

Site	Type	Max monthly air Max, mean and st.dev (°C)	Monthly air Max, mean and st.dev (°C)
Zamudio	Skylight	38.84 27.77 4.45	38.84 20.66 4.88
	Al Ventilated facade		
Mons	Roof shingles left	NA	32.24 17.78 4.46
	Roof shingles right		
Pikermi	Shading elements	NA	NA
	Balcony		
	Ventilated facade		

Table IV shows data about rain and some statistics for velocity. These values are important for characterizing the climate

Table IV. Climatic values

Site	Type	Precipitation ($mm \cdot m^{-2}$)	Average Velocity speed Mean, Max ($m \cdot s^{-1}$) and direction Mean, St.dev (°)	
Zamudio	Skylight	10.60	1.48 3.07	127.81 19.22
	Al Ventilated facade			
Mons	Roof shingles left	NA	1.63	266.06
	Roof shingles right			
Pikermi	Shading elements	NA	NA	
	Balcony			
	Ventilated facade			

Next table, Table V shows data about module temperatures. For each month the Maximum value, the average and the standard deviation for the daily maximum module temperature was reported (column with heading Max monthly module temperature, and the maximum the average and the standard deviation for the module temperature. These values are important for characterizing the thermal losses.

Table V. Module temperature values

Site	Type	Max monthly Module temperature Max, mean and st.dev (°C)	Monthly module temperature at day Max, mean and st.dev (°C)
Zamudio	Skylight	66.34 54.73 6.33	66.34 36.72 12.42
	Al Ventilated facade	NA	NA
Mons	Roof shingles left	NA	67.28
	Roof shingles right		61.20
Pikermi	Shading elements	NA	NA
	Balcony		
	Ventilated facade		

Last table, Table VI, reports the yield at DC side and AC side.

Table VI. Yields

Site	Type	Monthly energy DC producion (Wh)	Monthly energy AC production (Wh)
Zamudio	Skylight	287598	489062
	Al Ventilated facade	210632	
Mons	Roof shingles left	432959	417100
	Roof shingles right	448178	431080
Pikermi	Shading elements	NA	NA
	Balcony		
	Ventilated facade		

5. Monitoring results

5.2 Experimental sites

5.2.1 Portici

Portici site is close to the Mediterranean sea and is a location characterized by a maritime climate. Monitoring in Portici has been starting since May 2016 and it was performed only for the shingle roof module. After 9 months of continuous exposure no particular damage, such yellowing, delamination or other visual defects were observed. The smears that appear in figures 1-3 were already present at the moment of the exposure, and they were due to some not optimized manufacturing process and represent a kind of delaminaton.

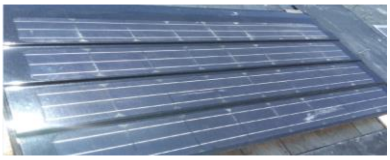

Fig.1. Pictures of the module before exposure

Fig.2. Picture of the module after 6 months of exposure

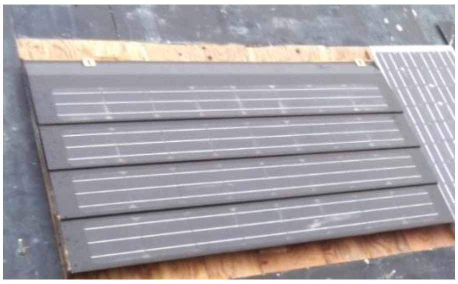

Fig.3. Picture of the module after 9 months of exposure

At different times the IV-curve at standard condition of the module has been taken and the electrical results are shown in table. Table VI shows that the electrical parameters in term of peak power, short circuit current, open voltage and fill factor haven't changed significantly, within the uncertainty of the laboratory measurements.

Table VI. Electrical parameters at different steps

Step	Date	Cumulative irradiation (kWh/m2)	Peak power (W)	Short Circuit Current (A)	Voltage (V)	Fill factor (%)
0	May the 9th	Starting	124.5	8.18	20.1	75.8
1	June the 15th	240.7	123.4	8.13	20.1	75.6
2	September the 5th	804.7	124.2	8.16	20.1	75.7
3	November the 2nd	1170.2	123.7	8.13	20.1	75.7
4	January the 24th 2017	NA	122.5	8.12	20.0	75.3

Table WII shows the module performance ratio. It is signifcant that since ther is only one module connected to a resistive load only the losses due to temperature effects and spectral mismatch are considered. Temperature modules monitoring indicates that the temperature of the modules is quite below the usual temperatures of traditional modules.

Table VII. Electrical parameters at different steps

Step	Irradiation (kWh/m2)	DC yield (kWh)	PR
June (since the 16th)	87.8	9.98	0.91
July (up to 26th)	164.5	18.6	0.91
September	157	17.81	0.91

5.2 Demosites

Due to the delay of the installations and that the incoming end of the project makes very short the period for the monitoring, according to the different state of development of the demosites, two periods were considered.

1) From August to November (first report)
2) From December to February (second report)

Mons started on May 2016 but data were made exportable only since August, Zamudio started on July 2016 and Pikermi has not yet begun, at the moment; figures 4-7 show the comparisons for all the available plants in the first monitoring period, since August to November 2016.

Monitoring comparison – Derived parameters		Monthly global in the plane of the array	Monthly net energy from array/peak power	Monthly net energy from the PV system/peak power	BoS efficiency	Array yield	Final PV system yield	Reference yield	Array capture losses	thermal losses	BoS losses	Array Performance ratio	Performance ratio	Mean array efficiency	Overall PV plant Efficiency
Unit		$H_{I,mth}$	$E_{A,mth,Pp}$	$E_{TUN,mth,Pp}$	η_{BoS}	YA	YF	YR	L_c	L_{th}	L_{BOS}	PR	PR	$\eta_{Amean,month}$	$\eta_{tot,month}$
		$kWh{\cdot}m^{-2}{\cdot}mth^{-1}$	kWh/kW	kWh/kW		$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$			%	%
Zamudio	Skylight	178.23	152.17	113.52	0.98	152.17	113.52	178.23	26.07	12.83	2.80	0.85	0.88	4.82	6.27
	Al-Ventilated facade	91.69	87.11			87.11		91.69	4.58		1.60	0.95		11.49	
Mons	Roof shingles left	144.36	125.73	121.00	0.96	125.73	121.00	144.36	18.63		4.61	0.87	0.84	9.74	9.43
	Roof shingles right		125.66		0.96	125.66			18.70		4.79	0.87		9.86	
Pikermi	Shading elements														
	Balcony														
	Ventilated facade														

Fig. 4. August monitoring comparison

Monitoring comparison – Derived parameters		Monthly global in the plane of the array	Monthly net energy from array/peak power	Monthly net energy from the PV system/peak power	BoS efficiency	Array yield	Final PV system yield	Reference yield	Array capture losses	thermal losses	BoS losses	Array Performance ratio	Performance ratio	Mean array efficiency	Overall PV plant Efficiency
Unit		$H_{I,mth}$	$E_{A,mth,Pp}$	$E_{TUN,mth,Pp}$	η_{BoS}	YA	YF	YR	L_c	L_{th}	L_{BOS}	PR	PR	$\eta_{Amean,month}$	$\eta_{tot,month}$
		$kWh{\cdot}m^{-2}{\cdot}mth^{-1}$	kWh/kW	kWh/kW		$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$			%	%
Zamudio	Skylight														
	Al Ventilated facade														
Mons	Roof shingles left	132.12	114.61	110.36	0.96	114.61	110.36	132.12	17.51		4.20	0.87	0.84	9.70	9.40
	Roof shingles righ		114.62		0.96	114.62			17.50		4.30	0.87		9.82	
Pikermi	Shading elements														
	Balcony														
	facade														

Fig. 5. September monitoring comparison

Monitoring comparison

Derived parameters		Monthly global in the plane of the array	Monthly net energy from array/peak power	Monthly net energy from the PV system/peak power	BoS efficiency	Array yield	Final PV system yield	Reference yield	Array capture losses	thermal losses	BoS losses	Array Performance ratio	Performance ratio	Mean array efficiency	Overall PV plant Efficiency
Unit		$H_{I,mth}$	$E_{A,mth,Pp}$	$E_{TUN,mth,Pp}$	η_{BoS}	YA	YF	YR	L_c	L_{th}	L_{BOS}	PR	PR	$\eta_{Amean,month}$	$\eta_{tot,month}$
		$kWh \cdot m^{-2} \cdot mth^{-1}$	kWh/kW	kWh/kW		$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$			%	%
Zamudio	Skylight														
	Al Ventilated facade														
Mons	Roof shingles left	89.58	78.26	75.78	0.97	78.26	75.78	89.58	11.32		2.74	0.87	0.85	9.77	9.52
	Roof shingles righ		79.10		0.96	79.10			10.48		3.07	0.88		10.00	
Pikermi	Shading elements														
	Balcony														
	facade														

Fig. 6. October monitoring comparison

Monitoring comparison

Derived parameters		Monthly global in the plane of the array	Monthly net energy from array/peak power	Monthly net energy from the PV system/peak power	BoS efficiency	Array yield	Final PV system yield	Reference yield	Array capture losses	thermal losses	BoS losses	Array Performance ratio	Performance ratio	Mean array efficiency	Overall PV plant Efficiency
Unit		$H_{I,mth}$	$E_{A,mth,Pp}$	$E_{TUN,mth,Pp}$	ηBoS	YA	YF	YR	Lc	Lth	LBOS	PR	PR	$\eta_{Amean,month}$	$\eta_{tot,month}$
		$kWh \cdot m^{-2} \cdot mth^{-1}$	kWh/kW	kWh/kW		$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$	$h.mth^{-1}$			%	%
Ingrid	Skylight														
	Al Ventilated facade														
Mons	Roof shingles left	52.95	41.47	39.78	0.96	41.47	39.78	52.95	11.48		1.64	0.78	0.75	8.76	8.45
	Roof shingles righ		41.58		0.96	41.58			11.37		1.85	0.79		8.89	
Pikermi	Shading elements														
	Balcony														
	facade														

Fig. 7. November monitoring comparison

6. Conclusions

Data of the first monitoring period are not yet completed, due to some unpredicted difficulties to effectively run the monitoring systems at different locations and for the different delay times of the various installations, so most of the tables are with empty cells or not available data. Uncertainties of the measurements should be carefully evaluated, since in some case values of parameters are not congruent. In any case the main conclusions at the moment are:

1) Monitoring at experimental sites and demosites show very good values of the performance ratio of the plant (module or array) PR, especially for the warmer months, respect to the values founded in literature, for example in F. degli Uberti, 2010 . One of the reason could be the lower operating temperatures of these kind of modules respect the traditional ones.
2) Thermal losses are limited
3) BoS efficiency is high
4) No visual damages appear to heavily affect the modules, due to the their exposure.

7. References:

Standard IEC 61724:1998 "Photovoltaic system performance monitoring –Guidelines for measurement, data exchange and analysis".

Standard EN 50583-1&2 "Photovoltaics in buildings"

M.Pellegrino, A. Sanz, A.Kyritsis, E.Mathas, S.Tselepis, S. Pierret, Monitoring procedures and annexes, Not published public BFIRST document

F. degli Uberti , R. Faranda, S. Leva, E. Ogliari, PERFORMANCE RATIO OF A PV POWER PLANT: DIFFERENT PANEL TECHNOLOGIES COMPARISON, Proceedings of the Solar Energy Tech 2010 ISBN 978-1-4467-3765-1