INTEGRATION OF INNOVATIVE BIPV SOLUTIONS ON MICRO CHP PLANTS

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ABSTRACT

According to the International Energy Agency, buildings are responsible for 32% of the world's energy consumption. Taking into account that almost 70% of the world population projected to live in urban areas by 2050, the main challenge is to convert the building for "energy consumers" to become "energy producers". To that end, the maximization of RES penetration into the building infrastructure is of high importance. Compared to other renewable and sustainable energy generation technologies, solar technology is rapidly-growing due to the fact that the solar energy is abundant and thus extended research has been carried out on this topic targeting mainly in the new BIPV technology for enhancing solar panels integration in the building opaque surfaces.

However, as also stated in the literature, one of the main parameters that affect the performance of a solar panel is the cell temperature, pointing out the need of cooling technics. In that direction and especially in building-integrated PV applications, the heat dissipating from the PV panels can be utilized to improve the overall energy conversion of such BIPV applications. It is stated that PV panels could benefit from cell temperature reduction and increase their electrical power by at least 3%, reaching an overall energy conversion efficiency of more than 40%.

This paper describes the operational performance results and the affected parameters of a 15 KW$_p$ grid-connected BIPV system applied on the roof of the building that hosts the School of Mining and Metallurgical Engineering of NTUA at Zografou Campus in Athens, Greece after a complete year of monitoring and based on IEC 61724 Standard. The evaluation of the results showed up to 20% reduction on electrical performance ration due to temperature effect, which can be overcome by applying a hybrid photovoltaic-thermal (PV-T) solution, which can result on an overall efficiencies of 70% or higher, depending on the conditions.

On this direction the technological solutions of H2020 PVadapt research project are presented in which a novel a Heat Mat / PV module component will be developed, aiming to a PV output increase and longevity through maintaining operating temperature at 25°C. The Heat Mat will be a system with dual function: firstly, when attached to the back panel of a photovoltaic module it will harvest the thermal energy of the solar cells, leading to the reduction of PV temperature that will increase performance and length of life. This research will result in maximizing the penetration of new BIPV/T and micro-CHP technologies leading to more efficient and low-cost holistic systems with shorter payback periods.

INTRODUCTION

In the last two decades, the energy consumption has been increased by approximately 58% (Enerdata, 2018). Both residential and commercial sectors are responsible for the consumption of 40% of U.S. and Europe total energy. Moreover, buildings are responsible for 36% of GHG emissions (E.C. 2016). For a more sustainable future, due to global warming and the exhaustion of fossil resources, research is conducted in order to create energy production systems more efficient and environmentally friendly (J. Twidell and T. Weir 2015). Today 55% of the world's population lives in urban areas, a proportion that is expected to increase to almost 70% by 2050 (Kiss et al. 2015).

It is more than obvious that a sustainable future cannot be achieved without transforming the urban environment by applying powerful energy production technologies based on renewables. Currently, more that 18% of the global energy consumption is delivered from renewable energy sources. To that end, modern BIPV and BIPV/T technologies consist the core for urban sustainability. Photovoltaic solar thermal hybrid system considered as CHP systems since they produce both electricity and heat from one energy source (solar) (Kolanowski 2011). A distributed generation using renewable energy can be a solution in order to reduce greenhouse gas emissions and to increase the supply security (Pepermans et al. 2005).

One of the main challenges is the development of solutions able to induce reduction of total energy consumption and to achieve the greatest possible integration of renewable energy systems into the building envelope. The use of renewable energy sources as part of the building envelope could potentially provide a promising solution, transforming buildings from "energy consumers" to "energy producers". For the PV technology in particular, the introduction of a PV panel that is not just the mean for producing energy but also a building element with enhanced properties, can become a smart, multifunctional and cost effective solution not only for new constructions but also for the retrofitting of old, even traditional buildings.

In this aspect, The "Construct PV" FP7 European research project aspired to confront all the technical and architectural barriers of PV technology with a holistic approach of Building Integrated Photovoltaics (BIPV), by installing PVs for energy harvesting in the opaque surfaces of a building. The developed PV module introduces modern wire bonding and heterojunction technologies that lead to increase in active area and minimization of shading losses. As a result, the new PV panels achieve a higher efficiency of up to 7% when comparing with conventional solar panels (Peppas et al., 2017). For the evaluation of the new PV panel, a rooftop demo grid-connected BIPV system of 15 KWp has been installed in the roof of the building that hosts the School of Mining and Metallurgical Engineering of NTUA at Zografou Campus in Athens, Greece. The performance evaluation of the new PV modules has been done according to IEC 61724 Standard. Based on the results, it is more that evident that cell temperature significantly affects performance and the overall conversion efficiency of PV panels. More specifically, during summer, the cell temperature reached a maximum of 78^{o}C leading to a performance degradation of up to 15% (Peppas et al., 2018).

Thus, PV cell cooling techniques will not only increase PV's efficiency but also will exploit the thermal content that is generated. On this direction, solar-thermal collectors can be combined with photovoltaic (PV) modules to produce hybrid PV-thermal (PV-T) collectors. These can deliver both heat and electricity simultaneously from the same installed area and at a higher overall efficiency compared to individual solar-thermal and PV panels installed separately. Hybrid PV-T technology provides a particularly promising solution when roof space is limited or when heat and electricity are required at the same time.

DESCRIPTION OF THE BIPV INSTALLATION AND THE MONITORING SYSTEM

The rooftop demo site is a grid-connected system, thus, the renewable energy generated by the solar panels is fed, under proper conditions, to the local utility grid. A grid-connected BIPV system mainly consists of solar panels, inverters and all the necessary grid connection equipment.

Developed panel technical specifications and electrical layout

In the installed BIPV system, the majority of solar panels are the "Construct PV" panels **(Figure 1)**, which are prototypes developed within the framework of the research program: glass-glass panels coupled with bituminous back cover for waterproofing, having the ability to be used both as building and as roofing materials. Commercial thin-film panels are used only in one area of the demo-site (**Figure 2**, Area 8) due to specific shape requirements of the architectural design. Regarding the technical characteristics of the prototype photovoltaic panels, the new panels consist of monocrystalline solar cells, with rated power of 48 Wp, open circuit voltage (V_{oc}) of 6.5 V, short circuit current (I_{sc}) of 9.39 A and rated efficiency of 12.3%.

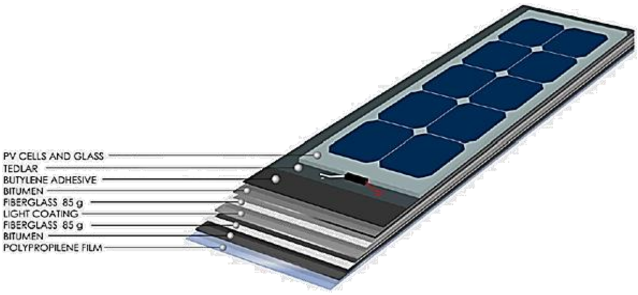
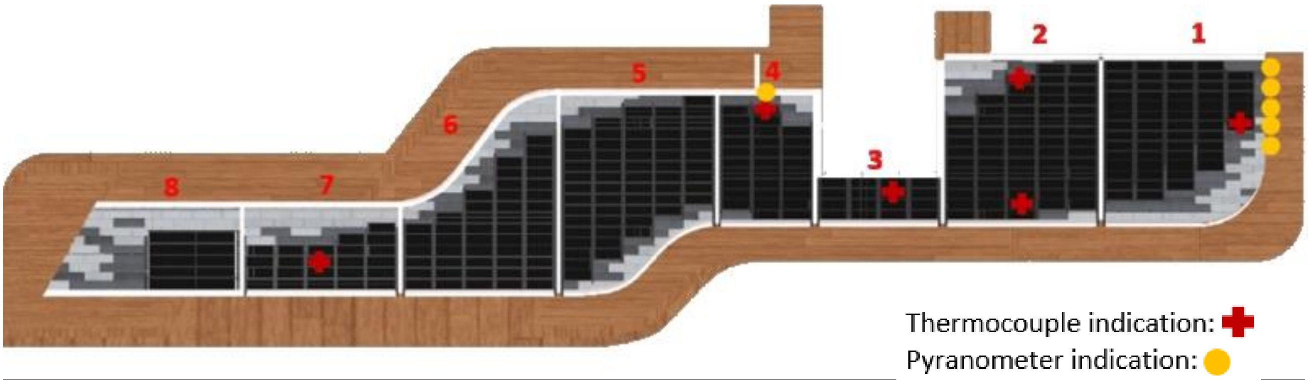


Figure 1. The "Construct PV" module.

The total dimensions of each "Construct PV" panel are 950 mm (Length) x 420 mm (Width) x 10 mm (Thickness), resulting in an active area of 884 mm (Length) x 365 mm (Width). The panels developed can be used as structural building components creating a finishing top roof layer fulfilling water tightness requirements. It has to be noted that the installation procedure identified resulted in an ease and short-time process from non high experienced personnel, leading to severe reduction of installation costs.

As one of the main technological ConstructPV objectives was to simulate the majority of roof inclinations throughout Europe as well as to demonstrate the effective combination between system's performance and architectural integration, Therefore, the inclinations and the configuration of the BIPV system have been chosen accordingly, taking also into consideration technical aspects such as seismic and wind loads as well as legislative aspects such as national guidelines and protocols.

The total nominal rating of the PV plant is 15 KWp and is comprised of 303 PV panels (298 new panels and 5 commercial thin-film photovoltaic shingles) with bituminous base, achieving an active area of almost 97.5 m^2 as presented in **Figure 2**.



Module type	Area 8	Area 7	Area 6	Area 5	Area 4	Area 3	Area 2	Area 1
Number of "Construct PV" panels	-	23	48	59	30	16	64	58
Number of commercial panels	5	-	-	-	-	-	-	-
Inclination (degrees)	curved	13	16	19	25	22	25	30
Area power capacity (KW)	0.34	1.1	2.3	2.83	1.44	0.77	3.1	2.8

Figure 2. NTUA BIPV system topology and positions of monitoring infrastructure.

Two types of commercial inverters are used in the installed BIPV system: The 1-phase SMA SB 2.5-1 VL-40 inverter for the Areas 3 to 8 and the 3-phase inverter for Areas 1 and 2. The inverters convert the DC current to AC current and provide the renewable energy production to the local utility grid through automatically synchronization to the voltage and frequency of the utility grid.

PERFORMANCE EVALUATION

The performance evaluation analysis of the demo BIPV system is performed in accordance to the International Energy Agency Photovoltaic Power System (IEA PVPS) program and follows the guidelines of IEC standard 61724 for the calculation of daily global irradiation, array/final/reference yields, array/system efficiencies, and performance ratio. NTUA has identified all the necessary monitoring parameters and monitoring procedures to be applied for the performance evaluation of the BIPV system according to the above standard (**Table 1)**. These parameters include a variety of data, ranging from meteorological – such as ambient temperature, irradiance, wind speed, etc. – up to electrical and other BIPV-related data – such as module temperature, electrical characteristics, energy yield, etc. (Wittkopf et al., 2012).

Table 1. Performance Evaluation Parameters according to IEC 61724

Parameter	Symbol	Equation
Array Yield (*)	Y_A	$Y_A = (E_A/P_0)$
System Energy Yield (**)	Y_F	$Y_F = (E_f/P_0)$
Reference Yield (***)	Yr	$Yr = (H/G_0)$
Performance Ratio of Array (****)	PR_A	$PR_A = (Y_A/Yr)$

(*) Y_A: the daily array energy output E_A (DC) per KW of installed PV array.

(**) Y_F: the daily net energy output E_F (AC) per kW of installed PV array.

(***)Y_r: the ratio of total daily in-plane irradiance by the modules to the reference in-plane irradiance.

(****) PR_A: the overall effect of losses on the array's rated output due to array temperature, incomplete utilization of the irradiation, and system component inefficiencies or failures and it is defined as the ratio of final yield to the reference yield.

Four independent monitoring systems (weather station, pyranometers, thermocouples, inverters) were integrated in a single intelligent online data analytic system designed and developed by NTUA. In total, more than 140 meteorological and electrical measuring points are real-time synchronized and logged with 5-min time step. On this study, selective periods within 2018 and 2019 are analyzed in order to evaluate the performance of the whole rooftop BIPV system.

Photovoltaic Array Performance (PR_A)

Figure 3 illustrates the monthly variation of the array performance ratio in relation to the BIPV system's different inclinations. The overall performance ratio per month for the whole installation is about 0.80 indicating a high performance and efficiency of the BIPV system. More specifically, Area 3, which also has the most suitable inclination for Greece (CRES, 2009), reaches a maximum of 0.87 during January 2018, whereas the minimum value of 0.736 appears during July 2018 for Area 2. As can be concluded, a BIPV system performs better during winter period rather than summer period, indicating the fact the temperature is a major factor of system's performance.

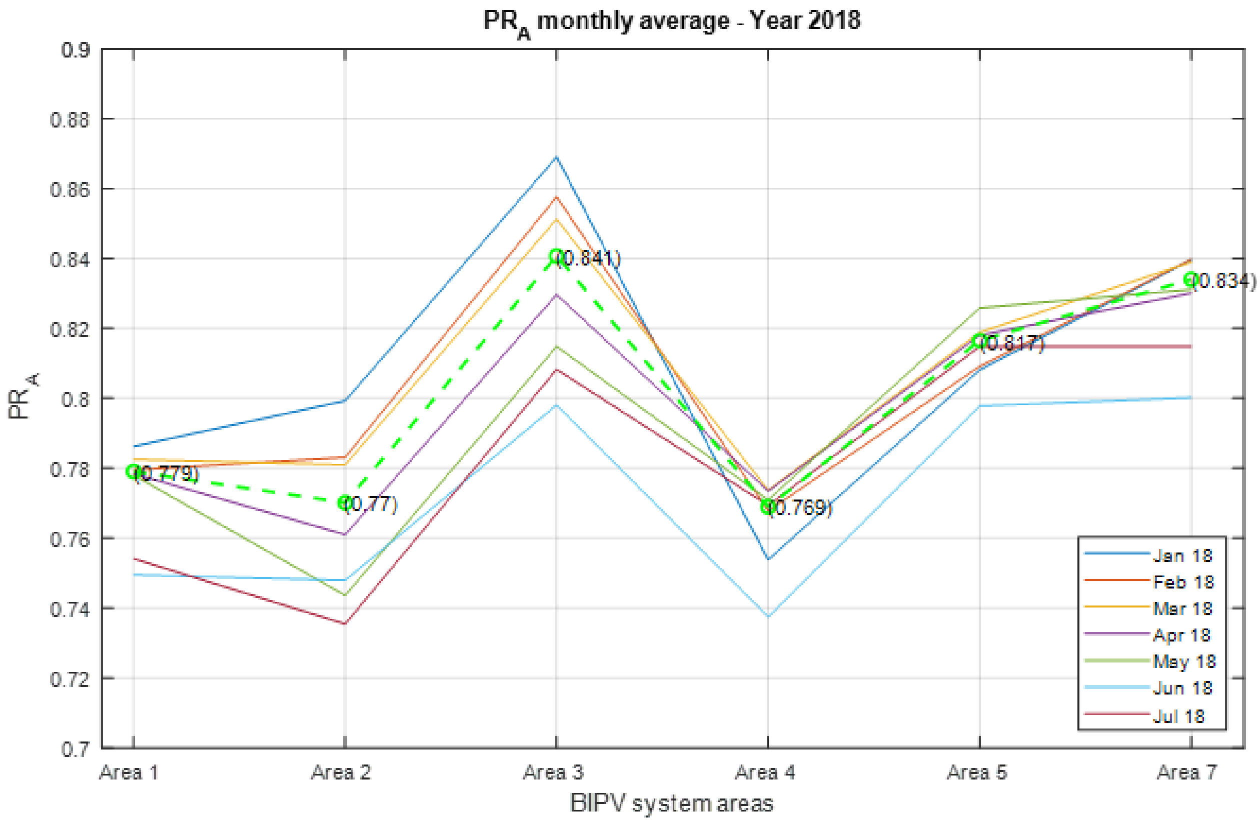


Figure 3. Monthly average PR of the different areas of the BIPV installation.

Effect of PV Cell Temperature

The important role of the operating temperature in relation to the electrical efficiency of a PV module found to be a critical parameter that affects negatively the performance of the module. More specific the correlation of PR_A and cell temperature in Area 3 of the BIPV system for selected solar radiations 585 W/m^2 and 916 W/m^2 is presented in **Figure 4.** The optimum performance for cell temperature at 25°C (Fuentes et al., 2018) reached 0.95, when a minimum value of 0.80 at 70°C cell temperature was observed (maximum operating temperature measured was 79.6°C), which proves the exploitation potential of Solar-thermal collectors.

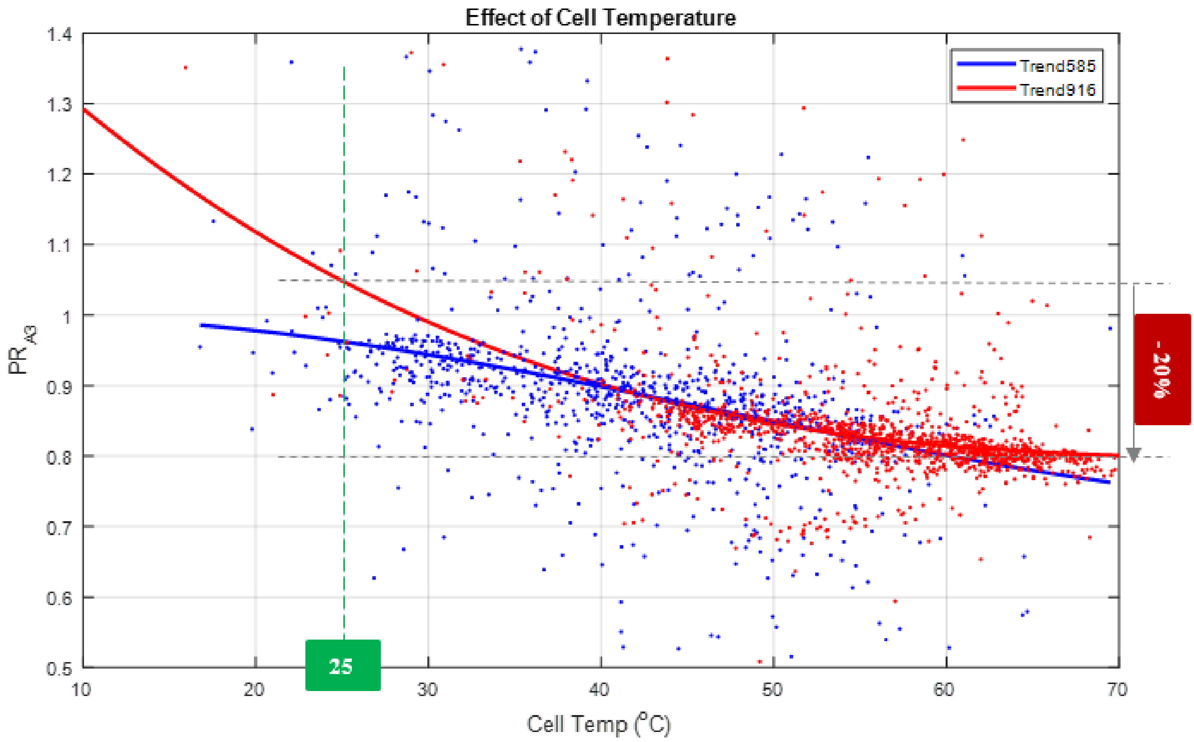


Figure 4. Effect of Cell Temperature.

The degradation rate of the demo rooftop BIPV installation is presented in **Figure 5,** which showed a mean 4% decrease of the PR_A values in all areas.

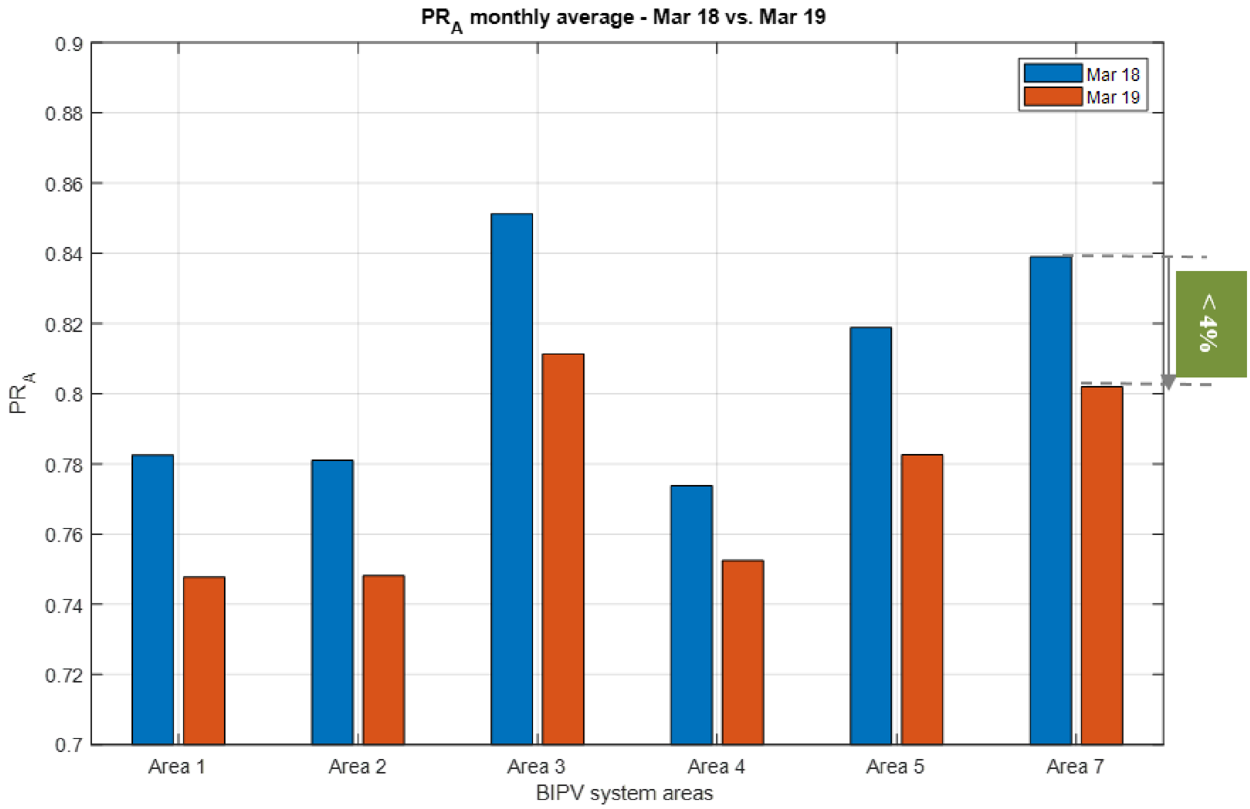


Figure 5. Degradation rate.

The overall energy flow of the Area 3 of the BIPV system in illustrated in **Figure 6**. presenting the electricity delivered in the AC side (81%) analyzing also the related losses within each production stage. The specific energy delivered to the grid for the aforementioned period was 1108.5 KWh/KWp, leading to an average monthly specific energy yield of 158.3 KWh/KWp. It is worth mentioned that according to bibliography the monthly specific energy production in Attica area is expected to be about 125 KWh/KWp (Protogeropoulos et al., 2010).

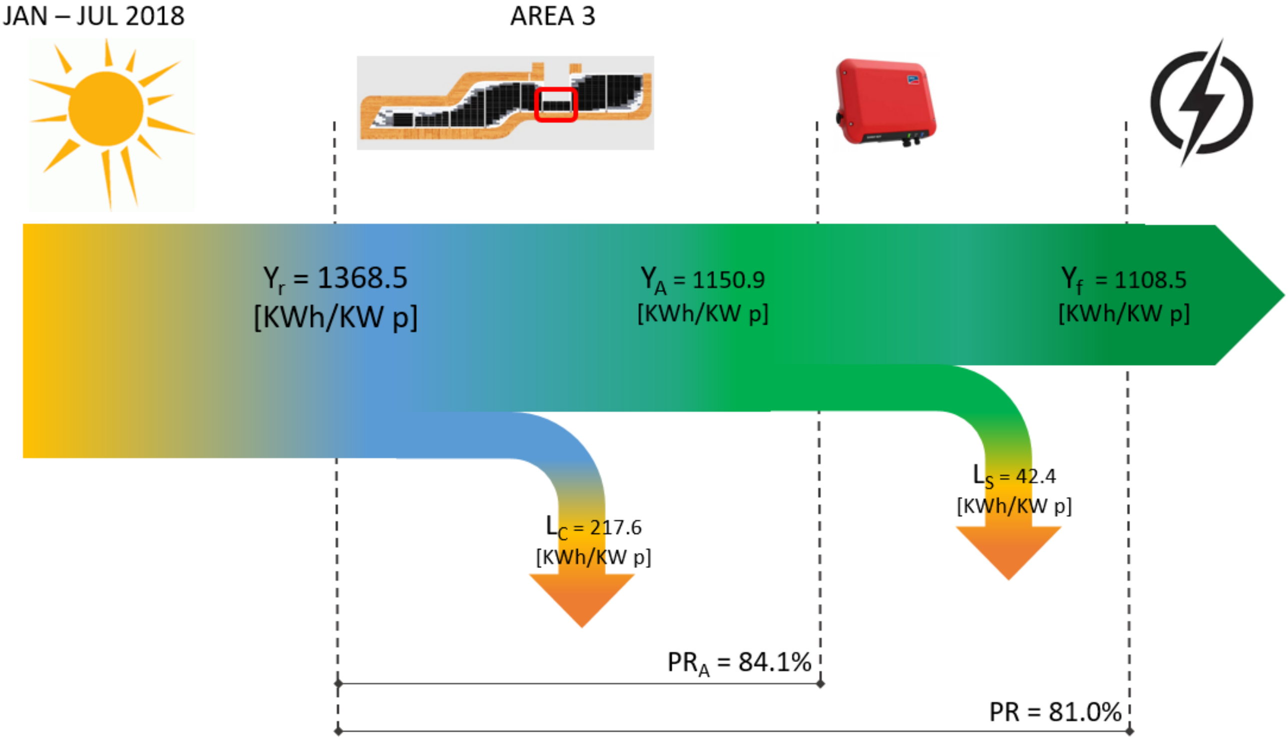


Figure 6. Energy flow of the BIPV system.

EXPLOITATION OF THERMAL ENERGY THROUGH PV-T SOLAR-COLLECTORS

As already presented, temperature can be considered as one of the major parameters that affect both the performance and the reliability of a BIPV system. In this framework, the H2020 PVadapt European research program will exploit a turn-key prefabricated and multifunctional BIPV system harvesting both thermal and electrical solar energy. On the technology proposed a Heat Mat (HM) element will be attached to the back cover of the PV panel and will recover the heat generated by the solar panels (**Figure 7**).

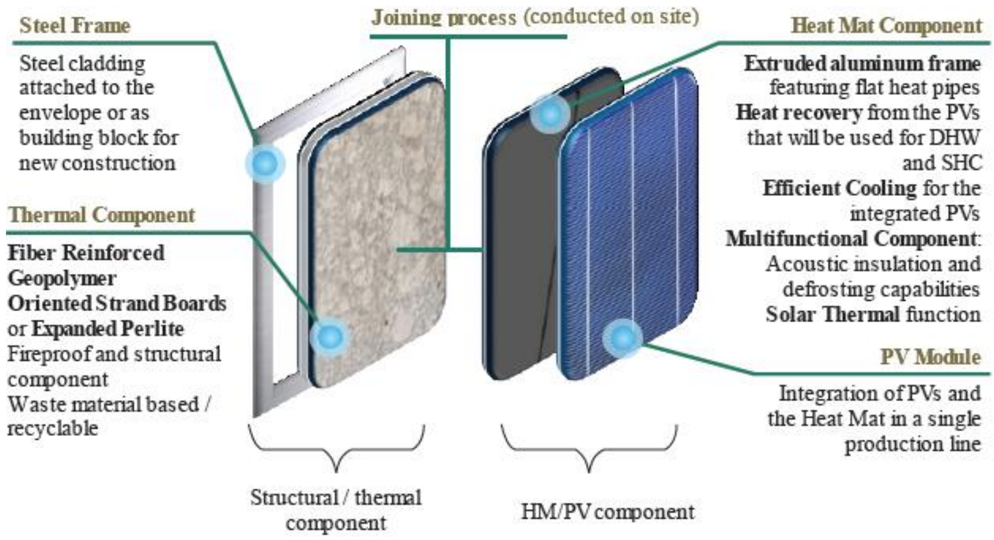


Figure 7. Multifunctional BIPV building block proposed by PVadapt project.

There are four main pillars comprising the activities of this specific project. The first pillar is the delivery of a PV/T component active energy component comprised of a sheet of flat heat pipes (Heat Mat-HM) in a PV module. The second is the delivery of a prefabricated structural panel with multiple passive functions (thermal, resilience, stability, waterproofing among others). The third is the delivery of a Smart Envelope System, achieving critical functions such as load prediction and shifting and predictive maintenance. The fourth is producing an environmentally and financially viable result.

However, combining functional building elements with solar energy technologies leads to the BIPV market comprising a wide array of products with corresponding variations in price range. PVadapt project focuses on providing a cost-effective, smart, sustainable BIPV, whereas the crucial factors leading to price reduction are related to:

i) Prefabrication of BIPV components, which can reduce not only on-site work and waste, but also the costs of the components, in conjunction with the selection of appropriate materials. Prefabrication will also lead to substantially faster installation times for refurbishment, and even more so for new construction.

ii) Modularity as a design philosophy, which can facilitate the work of architects and engineers and enable them to meet and exceed the expectations of the end-user. A modular BIPV component is designed to be customizable by design, to fit specific requirements without increasing costs. Likewise, a PV module can be similarly adapted to specific applications, often at lower costs through the replacement of components such as glass with metal foils.

iii) Circularity, which can also be a driver to reduce costs. PV waste in Europe alone is expected to increase up to 33,000 tons in 2020, to about 133,000 tons in 2030 and to 9.5 million tons in 2050. Closing the loop in solar energy life cycle would allow for repairing, reusing, refurbishing or recycling of components to produce new installations, reducing the costs and averting of PV and Construction and Demolition Waste (CDW).

iv) Smartness: Apart from improving energy efficiency and reducing energy costs, through smart-house systems the consumer has a clear picture of the energy profile of his building and can adjust his behaviour accordingly. It makes sense, that any innovation in BIPVs is coupled with smartness, benefiting the consumer on a micro scale and society on a macro scale.

CONCLUSIONS

Studies predict cities will house over 80% of population by 2050, with global energy use in building doubling or even tripling by then. Currently, cities account for over 70% of global energy used and 40-50% of worldwide GHG emissions. It is thus difficult to envision a sustainable future without transforming the urban environment using powerful renewable energy technologies. To that end, the utilization of BIPVs makes perfect sense in the urban environment. Building integration of photovoltaics replaces traditional elements (windows, cladding, roofs or accessories) with a functional component able to generate energy.

The data resulted by monitoring of a novel BIPV's installed at the demo-site located at NTUA (Zografos Campus) indicated the important role of the operating temperature in relation to the electrical efficiency of a PV module. Operating temperature affects negatively the performance of the module; more precisely, 70^{o}C cell temperature resulted in the reduction of the system's PR_A by 20% compared to the optimum operating cell temperature of 25^{o}C. It definitely proves the exploitation potential of solar-thermal collectors and the importance of innovative BIPV that will be delivered by PVadapt project. The BIPV system provided by PVadapt project represents an additional opportunity for increasing the global presence of the European BIPV industry, on the condition that BIPV costs are significantly reduced, providing high performance and reliability systems at prices below € 200/m^2 in terms of building components, or below € 2/Wp in the language of the energy industry. Furthermore, PVadapt BIPV is coupled with smartness, benefiting the consumer on a micro scale and society on a macro scale.

ACKNOWLEDGMENTS

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