BUILDING INTEGRATED PHOTOVOLTAICS (BIPV) VS. BUILDING ATTACHED PHOTOVOLTAICS (BAPV): BALANCE BETWEEN ENERGY PRODUCTION AND ARCHITECTURAL DESIGN

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The European Performance Building Directive (Directive 2010/31 EU) on energy efficiency presents an efficient, rational and sustainable use of energy which involves the use of renewable resources and conceives buildings not only as energy consumers, but also as energy generators. In this area, photovoltaic technology is used largely on buildings due to its versatility and continuous development. However, installed systems prioritize energy generation while ignoring aesthetic considerations and thus often creating a negative visual impact. These concepts have been developed in numerous publications popularizing the terms “Building Integrated Photovoltaics” (BIPV) and “Building Attached Photovoltaics” (BAPV), where the main difference is that BIPV has a dual functionality: replacing the conventional elements of construction and generating energy. An analysis of the building integration potential considering both the energy generation and the aesthetic architectural harmony of photovoltaic systems is presented in this article. The balance between optimization of electricity generation and the integration into the building is quantified in several case studies. The thermal insulation potential based on the use of photovoltaic panels as cladding and roofing material and its subsequent potential for energy saving is also considered.

Keywords: "Building Integrated Photovoltaics (BIPV); Building Attached Photovoltaics (BAPV); Solar energy; Photovoltaic electricity generation; Architectural design"

ENERGÍA SOLAR FOTOVOLTAICA INTEGRADA EN EDIFICIOS FRENTE A INSTALACIONES SOLARES FOTOVOLTAICAS EN SUPERPOSICIÓN: BALANCE ENTRE PRODUCCIÓN ENERGÉTICA Y DISEÑO ARQUITECTÓNICO

La Directiva Europea de eficiencia energética de edificios (2010/31UE) plantea un uso eficiente, racional y sostenible de la energía que implica el uso de fuentes renovables concibiendo los edificios no solo como consumidores de energía, sino también generadores de la misma. Dentro de este ámbito, la tecnología fotovoltaica se emplea en gran parte de edificios debido a su versatilidad y continuo desarrollo. Sin embargo, los sistemas instalados priman la generación energética ignorando consideraciones estéticas que a menudo crean un impacto visual negativo. Estos conceptos se han ido desarrollando en numerosas publicaciones popularizando los términos BIPV (por sus siglas en inglés “Building Integrated Photovoltaics”) y BAPV (“Building attached/applied/added Photovoltaics”), donde la principal diferencia es la doble funcionalidad de los sistemas integrados: sustitución de un elemento convencional de construcción y generación energética. Se presenta en este artículo un análisis del potencial de la integración arquitectónica junto con la generación energética y la armonía estética de sistemas fotovoltaicos. El balance entre optimización de la generación eléctrica y la integración en el edificio se cuantificará en varios casos de estudio. El potencial del aislamiento térmico basado en el uso de paneles fotovoltaicos como material de revestimiento y cubiertas y su consiguiente ahorro energético.

Palabras clave: "Integración arquitectónica de energía solar fotovoltaica; Instalaciones solares en superposición; Energía solar; Generación eléctrica fotovoltaica; Diseñó arquitectónico"

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1. Introduction

Ground mounted photovoltaic (PV) arrays are moving toward smaller and integrated systems producing electricity on site and involving several technical, environmental and social benefits, such as reduction of transportation and distributed losses, improvement the quality and reliability of power supply in peak-hours, reduction of environmental impacts and supply energy on off-grid systems (Caamaño-Martín et al., 2008; Roa-Escalante et al., 2015)

This new vision of PV systems is in line with the European Union directives which prioritize the development of renewable energy resources in order to reduce the greenhouse gas emissions (GHG) and the energy dependence of the EU. The European Building Performance Directive (European Parliament and Council, 2010) on energy buildings efficiency reveals that buildings are responsible for 40% the energy consumption in the European Union and the forecasts for the coming years are a growth sector. Therefore, it encourages the use of renewable energy and an efficient and rational use of energy. It begins to consider buildings not only as energy consumers, but also as energy generators.

The current photovoltaic systems in buildings generally focuses on maximizing energy generation and ignores aesthetic considerations. The energy generation is conceived as a design parameter and the visual disturbance difficult the integration and harmonization with the urban environment (Scognamiglio, 2016).

Under this context, two solutions can be applicable: overlapping PV panels or architectural integrated PV components. These concepts have development in numerous publication popularizing the terms “Building Attached/Applied/Added Photovoltaics” (BAPV) and “Building Integrated Photovoltaics” (BIPV) (Cerón, Caamaño-Martín, & Neila, 2013; Petter-Jelle, Breivik, & Drolsum-Røkenes, 2012; Santos & Rüther, 2012).

In summary, PV systems in buildings can be classified into:

- Open rack mounted systems, where the main factor is maximizing energy generation, therefore PV panels face to the optimal azimuth and tilt angles. They are displayed in rows and the distance between them is as small as possible (to reduce available area) but keeping the distance to minimize the shading losses. These systems are only intended to generate electricity.
- Building Applied/Attached/Added Photovoltaics BAPV, are PV elements installed in overlap of the parallel panel to the skin of the building. In these systems, the energy performance is penalized by non-optimal orientation of the building envelope surfaces where PV is placed and it does not replace a building material.
- Building Integration Photovoltaics BIPV, consists of PV elements with dual functionality: replacing the conventional elements of construction and generating energy. They are architecturally integrated into the building design and serves as building envelope material and power generator at the same time.

In the case of the latter, BIPVs have a great potential compared with non-integrated systems. There are many case studies which investigate the thermal performance of PV elements and their impact on increasing or reducing the indoor temperature in a building (Cuce, Young, & Riffat, 2015; Young, Chen, & Chen, 2014). The potential thermal insulation based on the use of PV panels as cladding or roofing material may involve an important energy saving due to the higher overall heat transference coefficient (U-value) of the conventional construction materials and consequently the higher energy consumption demanded by the air conditioning system.

2. Objective and case study

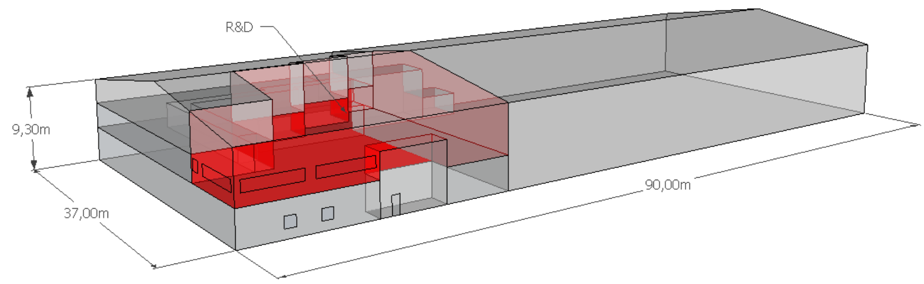
In this study, the power generation characteristics of different PV systems (open rack mounted, BAPV and BIPV) are analysed through a case study in an industrial building which is located in a suburban area in the south of Spain. Description of the building is shown in Table 1.

Table 1: Description of case study

Parameters	
Latitude	37°36' North
Longitude	1°45' West
Nº Floor	2
Total area	3954 m^2
External walls	Precast concrete panel
	16 cm
	U-value 3.5
Roof	Metal deck
	U-value 7.14
Glazing	Double glazed with aluminium frame
	6mm glass standard, 30 mm air gap and 6mm glass standard
	U-value 2.7
Roof area	3330 m^2
Roof pitch	9 deg.
Orientation	52 deg. South

Besides heating and cooling consumption is analysed in an exposed solar radiation area where BIPV system is placed in order to consider the energy saving (R&D room). Figure 1 shows architectural overview of the case study with the climate zone to assess in red colour and Table 2 shows distribution of climate zones.

Figure 1: Case study, 3D perspective



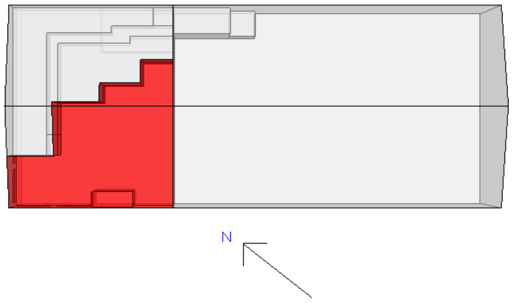


Table 2: Case study: climate zones

Floor	Purpose	Area (m^2)
Basement	Hall	21.8
Basement	Offices	108.3
First floor	Research	544.6
First floor	Conferences room	95.07
First floor	Offices	210.6

The purpose of this research is to estimate the potential of BIPV systems in a region with high irradiance levels, to analyze changes in cooling or heating loads by the modification in thermal properties of building envelope materials and to identify strategies for improving the BIPV application of photovoltaic systems.

2. Methodology

Three PV systems are proposed to analyse the viability of BIPV from the point of view of energy generation: open rack mounted, BAPV and BIPV. PV panels are applied to the best oriented roof area in open rack mounted and BAPV systems at the same time, also the best oriented façade of the second floor together the same area of roof is taken into account in BIPV design. Polycrystalline silicon technology is used in non-integrated systems and a commercial BIPV product (Polysolar, n.d.) with a thermal transmittance of 1.1 W/m^2K, solar heat gains coefficient (g-value) of 0.42 and similar power generation for BIPV system. Table 3 shows the electrical characteristics and dimensions of the considered PV panels.

Table 3: Electrical characteristic at standard test condition (STC) and dimensions of PV panels used in this case study

	Rack Mounted & BAPV	BIPV
PV technology	Polycrystalline silicon	Amorphous silicon
Model	Poly 110 Wp 72 cells	Poly Solar PS-D-130
Pnom (W)	110	130
Isc (A)	3.4	2.22
Voc (V)	43.4	92
Impp (A)	3.16	1.86
Vmpp (V)	34.8	71
FF	0.75	0.65

PCE (%)	12.24%	9.09%
Temperature coefficient in Voc (%/ºC)	-0.44	-0.33
Length (mm)	1335	1100
Width (mm)	673	1300
Thickness (mm)	25	2
Weight (kg)	10.5	24

Building energy performance simulation Ecotect Analysis (Carlos & Corvacho, 2011) is used to observe the influence of BIPV module installation in the building skin and Photovoltaic Geographical Information System (PVGIS) is used to determinate the PV production (Šúri et al., 2007; The European Commission's science and knowledge service, n.d.).

2. Results and discussion

Figure 2 shows the schematic diagram in each PV system considered and Table 4 shows the specification of PV system.

Figure 2: Schematic diagram a) open rack mounted b) BAPV c) BIPV

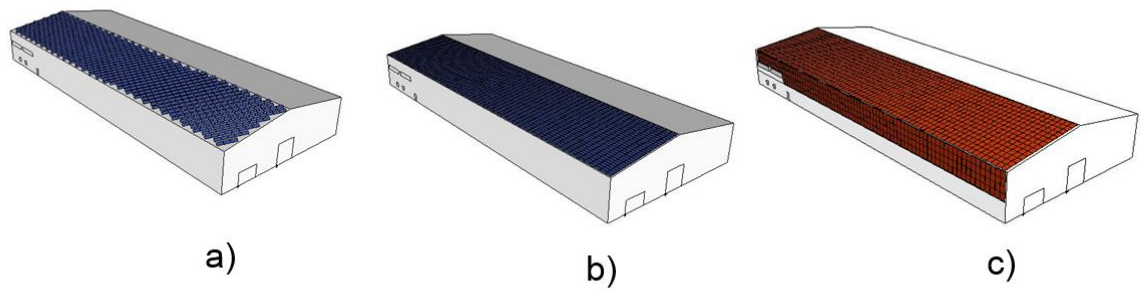


Table 4: Specification of PV system

System	Open rack Mounted	BAPV	BIPV	
Location PV panels	Roof	Roof	Roof	Facade
Nominal power of the PV system (kWp)	85.91	193.05	141.96	37.44
Number of PV panels	781	1755	1092	288
Inclination of modules (deg.)	34	9	9	90
Orientation (azimuth) of modules (deg.)	0	52	52	52

In the case of the open rack mounted PV system the optimal slope latitude of location, 34º is considered and the distance between rows is chosen according to the solar height at solstice noon (Dec. 21). On the other hand, BAPV and BIPV system PV elements are oriented by envelope of building, which implies a low irradiation per square meter received by the modules and significantly affects the façade (inclination 90º and azimuth 52º) in BIPV system as shown in Figure 3. The ideal orientation of solar modules is south with a slope of 34º during the year while PV panels installed on surfaces with a slope of 9º and azimuth 52º have much higher solar gain in summer.

Figure 3: Global irradiation per square meter as a function of inclination and azimuth

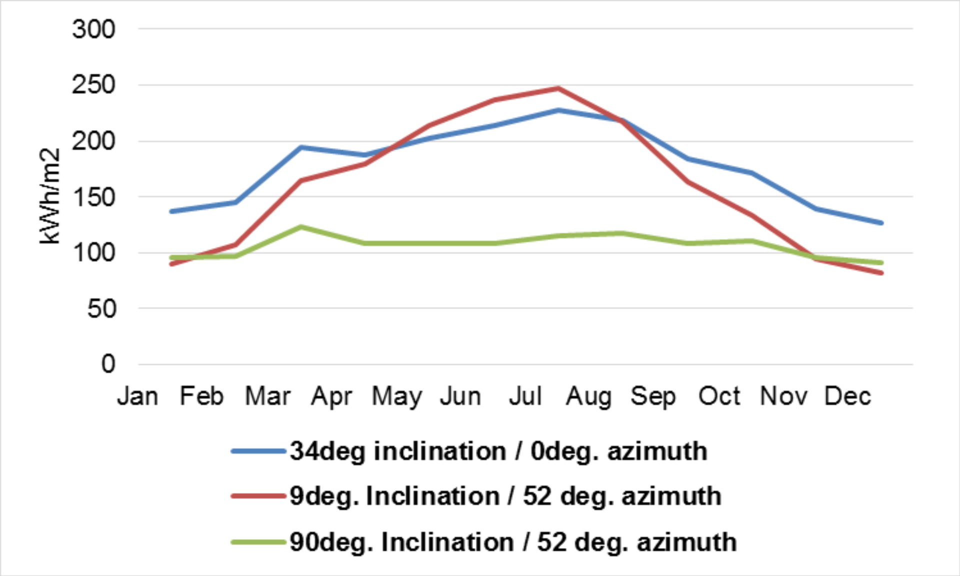
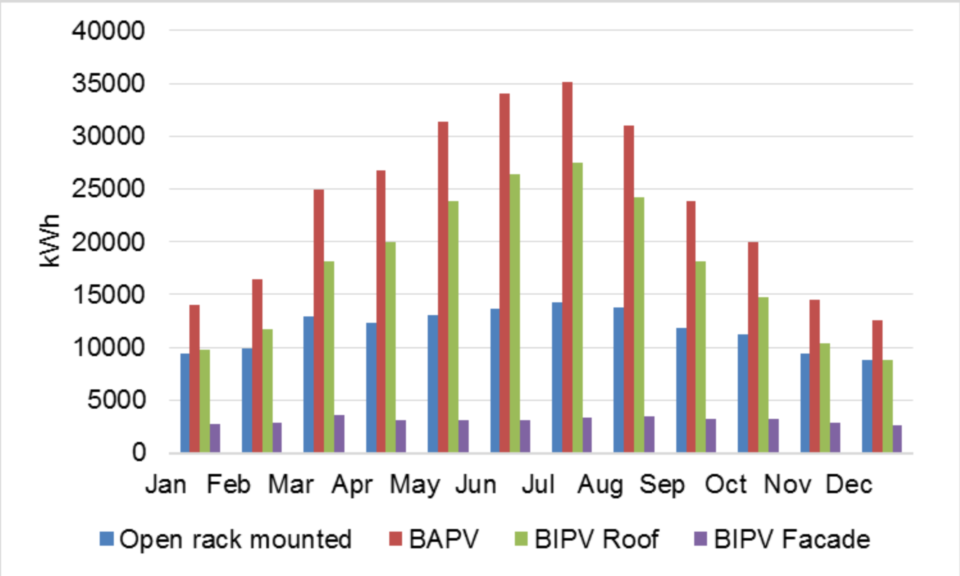


Figure 4 shows monthly energy production for each system. As it can be seen, the BAPV system generates more energy is due to the larger number of PV panels disposed and consequently to the higher peak power installed (although the weight of the 1755 PV panels which is 18427 kg could require a reinforcement of the roof structure) moreover, it is not affected by shadows between them. Open rack mounted system should take into account the minimisation of shading losses which are nevertheless unavoidable in early morning and late evening hours, although these losses are not significant (0.19%), the weight of this system is 8200 kg. Finally, the BIPV system replaces construction elements in roof and wall so it does not affect the structure but it is less efficient than silicon crystalline PV technology and although it has a greater surface to display PV panels, it cannot reach BAPV system installed capacity. The annual energy production for rack open mounted, BAPV and BIPV systems are 141000 kWh, 285000 kWh and 251100 kWh respectively.

Figure 4: Monthly electricity production



It is noteworthy that system loss is an important evaluation factor. Performance Ratio (PR) is the ratio between actual yield and target yield, and it is used to evaluate the energy production performance. It takes into account losses by Balance of System (BOS) components, thermal losses, operation and maintenance. Figure 5 shows PR due to temperature in two technologies considered: polycrystalline silicon and amorphous silicon. As it can be seen, thermal losses affects less to thin film PV technology although the nominal efficiency in crystalline silicon is better. Table 5 shows other losses considered to calculate the energy yield.

Figure 5: PR due to temperature

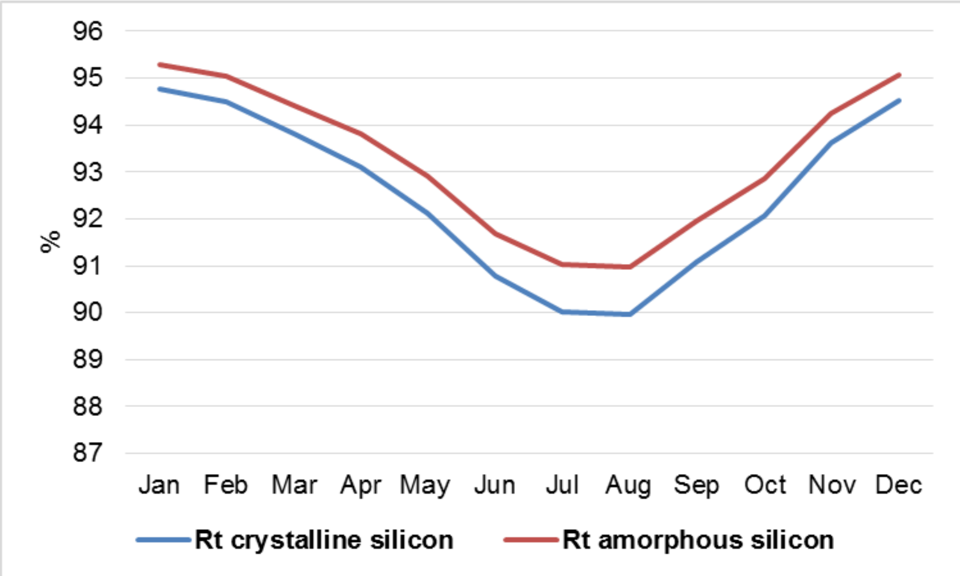


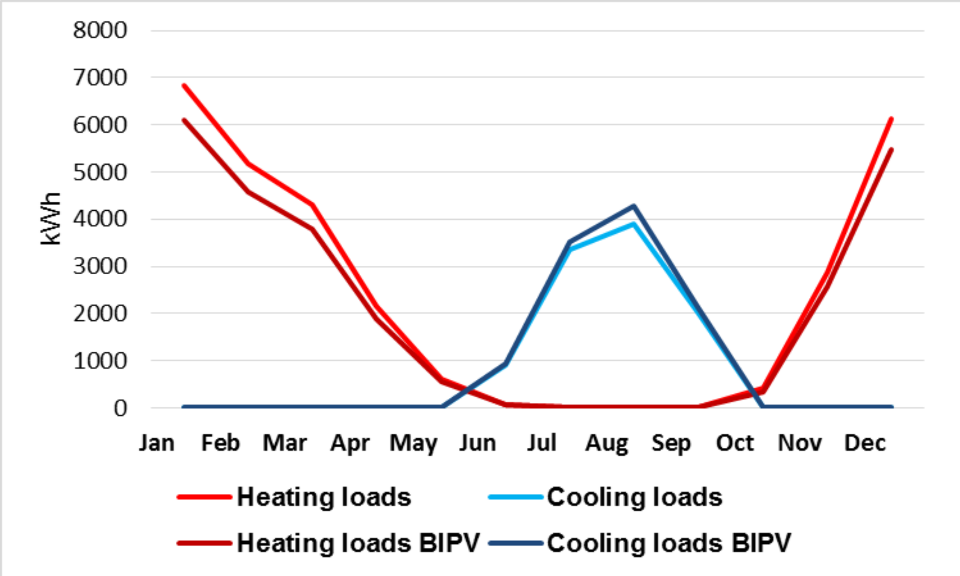
Table 5: Losses in simulation by PVGIS

Losses	Rack Mounted	BAPV	BIPV	
	Roof	Roof	Roof	Facade
Angular reflectance effects	2.6%	3.2%	3.2%	4.1%
Temperature and low irradiance	11.3%	10.6%	8.0%	8.0%
Other losses (cables, inverter etc.)	11.6%	11.4%	11.4%	11.4%
Combined PV system losses	25.5%	25.2%	22.6%	23.50%

Figure 6 shows the results of simulation software Ecotect Analysis, a comfortable indoor temperature was set between 20 ºC and 26 ºC, and the energy consumed by air conditioner (efficiency 95%) is calculated throughout an entire year in a time span from 7 A.M to 8 P.M. According to simulation results, the annual energy consumed by the air conditioner in BIPV system is 36203.78 kWh which is approximately 4.72% less than 38765.35 kWh for the study case with 16 cm pre-fabricated concrete façade. Although the overall result is positive, the installation of PV panels saves energy for heating in winter, but consumes energy for cooling in warm weather when compared with the same building without the PV panels, as can be seen in Figure 6; this is probably due to the g-value of BIPV element. Although it counts with a low thermal conductivity, the wall becomes a warm façade and needs more effort to be cooled in summer.

The total energy savings by reduction in air conditioning consumption in a year is 2562 kWh, which added to the 251100 kWh generated by the BIPV system amounts to a total of 253662 kWh.

Figure 6: Heating and cooling loads in the R&D room



5. Conclusions

Power generation and energy savings in cooling and heating loads were calculated for three PV systems in different configurations on an industrial building in the south of Spain. The main conclusions of the work are:

- BAPV and BIPV systems have more energy yield than open rack mounted system with optimal tilt and azimuth demonstrating that aesthetic considerations are not a barrier to the implementation of this systems from the point of view of electricity generation.
- BAPV system has the highest energy production and although a BIPV system has more surface to implement, the selection of a-Si thin film PV panel does not compete with a mature PV technology due to its lower power conversion efficiency.
- BIPV panels used in this study reduces heating loads in low ambient temperatures and increases cooling loads in warm climates due to PV panel g-value.
- The combination of power generation and energy savings by cooling and heating loads in BIPV systems is not enough to compete with the power generation by BAPV system.

In line with these conclusions, the future of BIPV systems will depend on the balance of thermal characteristics and power conversion efficiency of the PV panels. Including new materials, encapsulating the systems and the ability to manufacture custom sizes of the panels can be the key to consolidate the total integration of PV systems in buildings. This article is a first approach to determinate the potential benefits of BIPV systems; the scope of this study should be extended considering environmental and economic aspects.

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