Evaluation of the implementation of a BIPV glass in office buildings in Spain

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Abstract

The evaluation of the impact of a transparent BIPV glass on an office building energy demands is presented for two climatic areas in Spain. The BIPV glass evaluated is a currently in development innovative technology consisting of a tandem structure of a photovoltaic active ultra-violet filter and organic infra-red photovoltaic cell. The evaluation is carried out with dynamic building simulation, using the experimental optical and electrical properties of the BIPV glass with new transparent BIPV model features. Conventional, acting as reference, and BIPV windows configurations are defined to fulfil the Spanish building code requirements. Then, the heating, cooling, and lighting energy demand, as well as the PV output are calculated, estimating the overall energy balance of the building. In terms of individual end uses, the consumption increases for heating and lighting, while decreasing for cooling. As a result, the total final energy increases in the heating dominated case and decreases in the cooling dominated. However, once accounting the PV generation the results show that the transparent BIPV glass presents an improvement of the overall energy balance by 47.2% and 17.2%, for warm and cold climatic regions in Spain, respectively.

Keywords: transparent BIPV, building simulation, emerging PV

1. Introduction

Reducing buildings' energy consumption and emissions is decisive to reduce the environmental impact and to make global economy sustainable. Currently, energy consumption in buildings represents about 40% energy and process-related carbon dioxide (CO_2) emissions (IEA, 2019), while its demand is forecasted to keep growing in the coming decades due to the floor growth increasing faster (2.5% per year) than the reduction in energy intensity (0.5-1%) since 2010 (IEA, 2020). Despite the implementation of energy efficiency measures, the service demand increase offset any improvement, resulting in an average annual energy demand increased by 1.8 % in the last years (IEA,2020; UN Environment, and International Agency, 2017). This challenges the goal to reduce greenhouse gases (GHG) emissions in order to meet a 1.5ºC world or below (IPCC, 2018).

Consequently, the EU implemented a legislative framework targeting buildings with the goal to achieve Europe energy and environmental goals, which included the *Energy Performance of Buildings Directive 2010/31/EU (The European Commission, 2010)* and the *Energy Efficiency Directive 2012/27/EU (The European Commission, 2021)*; both amended in 2018 and 2019, respectively. This stacks with European Green Deal presented in December 2019, which aims to make Europe the first climate-neutral continent by 2050 (The European Commission, 2019). As a result, all new building need to be net zero-energy buildings (NZEB) from December 2020, adding to December 2018 obligation for public building to be NZEB. Reaching this goal implies improvement of the energy efficiency, but it will only be achieved considering on-site renewable energy generation. Among these, PV presents the best opportunities for energy generation adapted to buildings design, specially through Building Integrated Photovoltaics (BIPV).

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BIPV are a promising solution for the buildings energy transition (Biyik et al., 2017). These technologies consist on replacing conventional building components or materials with PV active elements, keeping their aesthetical and structural functions. As crystalline silicon based cells are the most ubiquitous, due to their high performance, efficiency and availability, the most usual approaches are to replace opaque elements, either by PV modules attached to the envelope or with building elements with built-in PV cells. More recently, the emerging PV technologies as thin-film solar cells, allowed implementation in the transparent surfaces, either by cells cladding or with semi-transparent films (Jelle et al. 2012). In this sense, transparent BIPV are growing interest for implementation in building, particularly in windows, as these introduce advantages in solar gains control, daylighting, and aesthetical integration in buildings.

While transparent BIPV technologies are still dominated by Si based cells, mainly semi-transparent amorphous silicon cells, the interest on other technologies is growing. Recent development of thin film solar cells (TFSC), organic PV cells (OPV), perovskites, among others, offer new range of transparencies, shapes, cost-effectiveness and PV efficiency options (Husain et al., 2018). These features promise a great future for new architectural applications as PV windows. In order to select the adequate technology for implementing into a building, its impact on the thermal and lighting loads, as well as the electricity output and occupant comfort must be evaluated. Hence, a detailed dynamic building simulation is needed to accurately model the optical, thermal, and electrical performance of the PV glazing in conjunction with the whole building.

This study is carried within the framework of Tech4win project (Tech4win, 2019), whose objective is to develop a tandem structure of PV active UV filter and organic IR PV cell. The goal of the current study is to evaluate the performance of the last development of the BIPV tandem structure and to compare it to conventional windows in office buildings in Spain.

2. Methodology

The building simulations are run with TRNSYS18 Type 56 multi-zone building. A modified version of the Complex Fenestration System (CFS) model (Romani et al. 2021) is used. The following sections present the approach for BIPV, as well as the parameters used in the simulations evaluation.

2.1. BIPV model

The CFS implemented in TRNSYS (Hiller and Schöttl, 2014) allows the calculation of the optical and thermal behaviour of a window composed of up to six panes including external and internal shading systems. It uses ISO 15099 (ISO 15099, 2003) energy balance and bidirectional scattering distribution function (BSDF) for optical calculations. The modified version of the CFS introduces a new input allowing to introduce the PV generation into the window panes energy balance, Fig. 1. It can be assigned to the specific pane containing the PV cell. The energy is distributed equally between the two nodes (front and back) of the glazing pane.

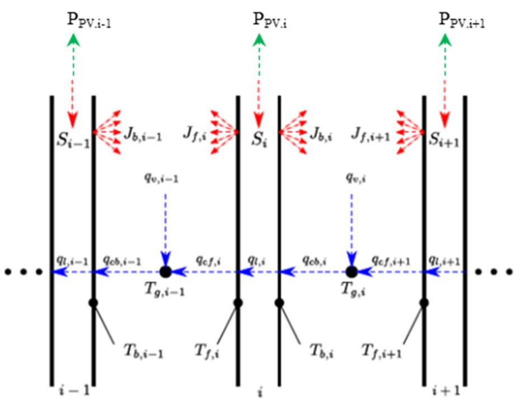


Fig. 1 ISO 15099 window energy balance modified to include PV generation (Romaní et al., 2021).

In the current study, the output of the cell is calculated using equation 1 (Evans and Florschuetz, 1977). The inputs are obtained from CFS model outputs. The cell temperature is the average temperature of the corresponding window pane. The radiation available in the pane is calculated with the radiation outputs according equation 2.

$$\dot{P}_{PV.i} = \eta_{ref}\left[1 + \beta_T\left(T_i - T_{ref}\right)\right]G_{\tau\alpha} \quad \text{(eq. 1)}$$

$$G_{\tau\alpha.i} = G_t - G_r - \sum_0^{i-1} \dot{S}_n \quad \text{(eq. 2)}$$

Where $\dot{P}_{PV.i}$ PV output at "i" window pane [W·m^{-2}]; η_{ref} PV cell nominal efficiency [-]; β_T: Temperature coefficient [%·K^{-1}]; T_i temperature of the window pane [ºC]; T_{ref} reference temperature of PV cell nominal efficiency calculation, 25 ºC; $G_{\tau\alpha}$ transmitted and absorbed solar radiation at the window pane "i" [W·m^{-2}]; G_t global solar radiation incident to the window [W·m^{-2}]; G_r reflected solar radiation [W·m^{-2}]; and $\dot{S}_n$ absorbed solar radiation at the previous window pane "n" [W·m^{-2}].

Illuminance conditions and lighting control are modelled using Type 56 integrated Daysim approach. Note this method does not use the CFS capabilities from the add-on. However, as the current study does not consider shading system no significant discrepancies are expected.

2.2. Evaluation parameters

As any window, transparent BIPV window affect the heating, cooling, and lighting loads of the building, while also adding the electricity production. The characteristics of the PV glass influence the whole window configuration, resulting in optical and thermal properties that may differ from the conventional windows solutions implemented in a specific case. Moreover, maximization of the PV generation limits the solar protection (shading) elements to be implemented on the external side of the façade. Therefore, the implementation of transparent BIPV window need to optimize the design accounting all the possible impacts on the building energy demand.

The energy performance is calculated using the final energy for cooling, heating, lighting, ventilation, and PV generation, with the overall performance being assessed by the energy balance index (EBI) as presented in equation 3. The final energy is considered electricity for all end uses, assuming heating and cooling is supplied by a reversible heat pump.

$$EBI = HFE + CFE + LFE + VFE - PV \quad \text{(eq. 3)}$$

Where EBI: Energy balance index [kWh]; HFE: Heating final energy [kWh]; CFE: Cooling final energy [kWh]; LFE: Lighting final energy [kWh]; VFE: Ventilation final energy [kWh]; and PV: Photovoltaic generation [kWh].

Regarding the lighting performance, the evaluation parameters are the daylight autonomy (DA), the continuous daylight autonomy (CDA), and the hours with too high illuminance. The DA measures the fraction of occupancy hours in which the daylight illuminance in the reference point is above the minimum required illuminance (500 lux). CDA works as DA but also giving credit for the hours in which the illuminance is below the required value. Finally, illuminance above 2000 lux is considered to cause too bright environments which might lead to visual discomfort as well as glare risk.

3. Case of study

The case study consists in evaluating a sample office room in two different climatic zones in Spain. The envelope and windows characteristics are adapted to Spanish building code (Ministerio de Fomento, 2019) requirements for the selected climatic zones.

3.1. Climatic conditions

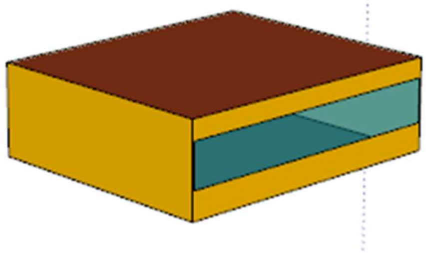
Two different climatic zones are selected for the case study, using Almeria as reference city for a warm climate and Leon as reference for a cold climate. Each corresponding to climates of types "A" and "E", respectively, according Spanish building code. The characteristic of each climate are summarized in Tab. 1.

Tab. 1: Climate characteristics.

Reference city	Almeria	León
Spanish building code classification	A4	E1
Köppen Geiger	BWk	Csb
Average temperature	18.4 ºC	12.3 ºC
Annual solar incident radiation on horizontal surface	1825.2 kWh/m^2	1605.1 kWh/m^2

3.2. Building characteristics

The study uses a reference room facing South with a single façade exposed to outdoors, whose geometric characteristics are summarized in Fig. 2. The same construction solutions are used in all the cases, adjusting the insulation to fit the thermal transmittance (U-value) requirement in each climate, as summarized in Tab. 2, Tab. 3, Tab. 4, and Tab. 5. Only the external wall and the roof needed adjusting the insulation, the parameters that differs between each case are highlighted.



Parameter	Value
Length	11.21 m
Depth	9.58 m
Height	3.47 m
Floor surface	107.39 m^2
Façade surface	33.24 m^2
Window surface	18.48 m^2
Window to Wall Ratio (WWR)	47.5%

Fig. 2. Reference room characteristics.

Tab. 2. Façade wall characteristics.

Façade wall composition and properties		Almería	León
Composition	Lacquered aluminium	0.002 m	0.002 m
	Rock wool	**0.050 m**	**0.120 m**
	Galvanized steel	0.002 m	0.002 m
Total thickness		0.054 m	0.124 m
U-value		**0.687 W·m^{-2}·K^{-1}**	**0.307 W·m^{-2}·K^{-1}**

Tab. 3. Roof characteristics.

Roof composition and properties		Almería	León
Composition	Sand gravel	0.100 m	0.100 m
	Cellular concrete	0.125 m	0.125 m
	Cork	**0.005 m**	**0.006 m**
	Reinforced concrete slab	0.350 m	0.350 m
	Aluminium ceiling	0.005 m	0.005 m
Total thickness		**0.585 m**	**0.586 m**
U-value		**0.483 W·m^{-2}·K^{-1}**	**0.327 W·m^{-2}·K^{-1}**

Tab. 4. Floor characteristics.

Floor composition and properties		Almería	León
Composition	Ceramic tile	0.020 m	
	Cement mortar	0.020 m	
	Sand	0.020 m	
	Reinforced concrete slab	0.035 m	
	Aluminium	0.005 m	
Total thickness		0.415 m	
U-value		2.4 W·m^{-2}·K^{-1}	

Tab. 5. Inner walls characteristics.

Inner walls composition and properties		Almería	León
Composition	Gypsum	0.030 m	

	Rock wool	0.070 m
	Gypsum	0.030 m
Total thickness		0.130 m
U-value		0.440 W·m^{-2}·K^{-1}

The building operates under a generic office schedule, presented in Fig. 3. The sensible heat gains and radiative fraction is summarized in Tab. 6. People and equipment gains are proportional to the occupancy profile, while lighting gains depend on the lighting control. The air renovation rates are 1.1 ACH for ventilation and 0.32 ACH for infiltration. Heating operates with a set-point of 21ºC and a set-back of 17ºC during non-occupancy hours. Cooling operates with a set-point of 26ºC.

In terms of electricity consumption, the heating and cooling is supplied by a reversible heat pump (HP) with a COP of 3.5 and a EER 2.2. The equipment and lighting electricity specific power is presented in Tab. 6 . The lighting is controlled under a continuous daylighting strategy, in which the lights are continuously dimmed up to 500 lux of daylighting. The reference sensor is place at the centre of the room at 0.85 m from the floor. Finally, ventilation electricity consumption is calculated with a linear correlation of 2 kW per m^3·s^{-1}.

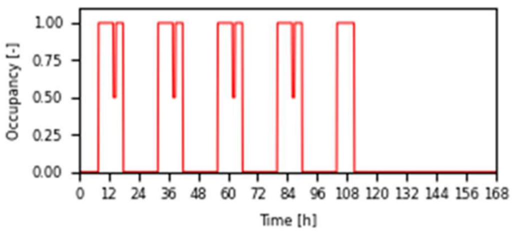


Fig. 3. Occupancy schedule.

Tab. 6. Internal heat gains and associated specific power.

Gain type	Sensible heat gain	Radiative fraction	Specific power
People	6 W·m^{-2}	0.2	-
Equipment	4.5 W·m^{-2}	0.5	5.63 W·m^{-2}
Light	4.11 W·m^{-2}	0.42	7.28 W·m^{-2}

3.3. BIPV window characteristics

Regarding the windows, the conventional solutions in Spain consist of double glazing with air-chamber, including low-emissivity glass in the colder climates. The BIPV solutions use the same structure but removing the outermost clear glass with the currently in development Tech4win transparent BIPV glass, which consists of a tandem structure of a photovoltaic active UV filter and IR organic photovoltaic cell. Both cases consider a 15% frame of insulated PVC with thermal break.

The conventional window is modelled using the glass data from the International Glazing Data Base (IGDB) (Lawrence Berkeley Laboratory, 2021a) included in WINDOW7 (Lawrence Berkeley Laboratory, 2021b). For the BIPV, the spectral properties were processed with OPTICS6 (Lawrence Berkeley Laboratory, 2013). Note that the BIPV glass has properties similar to a solar control glass, as shown in Fig. 4, although with lower visible transmittance and higher absorption in the UV and near infrared related to the PV cell properties.

The properties of the conventional and BIPV window for both scenarios is summarized in Tab. 7 and Tab. 8. The thermal transmittance (U-value) of both cases is similar, which fits with the Spanish building code prescriptive requirements (Ministerio de Fomento, 2019), 2.7 W·m^{-2}·K^{-1} and 1.8 W·m^{-2}·K^{-1} for Almería and León cases, respectively. However, the optical properties of the BIPV window, with higher absorption leads to a lower solar heat gain coefficient (SHGC) and visible transtmittance (τ_{vis}). The BIPV is modelled with a nominal efficiency of (η_{ref}) 5.54 % and a temperature coefficient of (β_T) of -0.25 %/K. This is the most up to date efficiency data obtained in Tech4win laboratory scale devices. Finally, the case study does not consider shading systems, neither external nor internal.

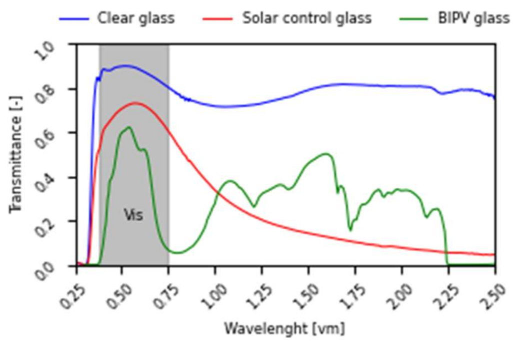


Fig. 4: Comparison of glass transmittance

Tab. 7: Window configuration for CTE climate "A" requirements (Almería)

Case	Glazing system	U ($W \cdot m^{-2} \cdot K^{-1}$)	SHGC (-)	τ_{vis} (-)
Conventional	8/12/8 (float glass / air / float glass)	2.553	0.587	0.544
BIPV	14/12/6 (BIPV glass / air / float glass)	2.550	0.352	0.276

Tab. 8: Window configuration for CTE climate "E" requirements (León)

Case	Glazing system	U ($W \cdot m^{-2} \cdot K^{-1}$)	SHGC (-)	τ_{vis} (-)
Conventional	8/12/8 (float glass / air / low-e glass)	1.653	0.492	0.526
BIPV	14/12/6 (BIPV glass / air / low-e glass)	1.652	0.285	0.271

4. Results

The behaviour of the office building in representative days of winter and summer is presented in Fig. 5 and Fig. 6 for Almería and León, respectively. In both cases the BIPV window maintains a lower temperature of the room (T_{room}) in summer and winter. The lower SHGC coupled with the PV effect on the BIPV window results in a reduced window temperature ($T_{wind\ int.}$) compared to the conventional one, reducing the convective and long-wave radiation heat gains to the room, as well as reducing the solar gains. This impact is higher in winter than in summer, as the heating load is driven by outdoor climatic conditions while the cooling load is mainly driven by internal gains. As a result, in the BIPV window case the heating load increases and the cooling load decreases. Moreover, the reduced window temperature and solar heat gains results into a lower radiant temperature (T_{rad}), up to 2ºC in winter and up to 1ºC in summer. The difference in radiant temperature will affect to the thermal comfort of occupants, although the analysis of this issue is beyond the scope of the current paper.

Regarding the lighting performance, the lower visible transmittance of the BIPV window reduces the natural daylight illuminance on the reference sensor. This helps in having fewer hours of excessive illuminance (>2000 lux), especially in the winter days when the sun elevation is lower. However, it also implies more time in which the daylight illuminance is below the set-point of 500 lux, then lighting is ON for more hours and with higher power required (Light control). In the southernmost climate of Almería with high sun elevation all year round, the BIPV window guarantees that daylight illuminance does not exceed 2000 lux at the reference sensor. In contrast, in Leon the low sun elevation in winter causes very high daylight illuminance values, especially in the morning and afternoon. Here the BIPV window helps in reducing the excessive illuminance, although high values still happen.

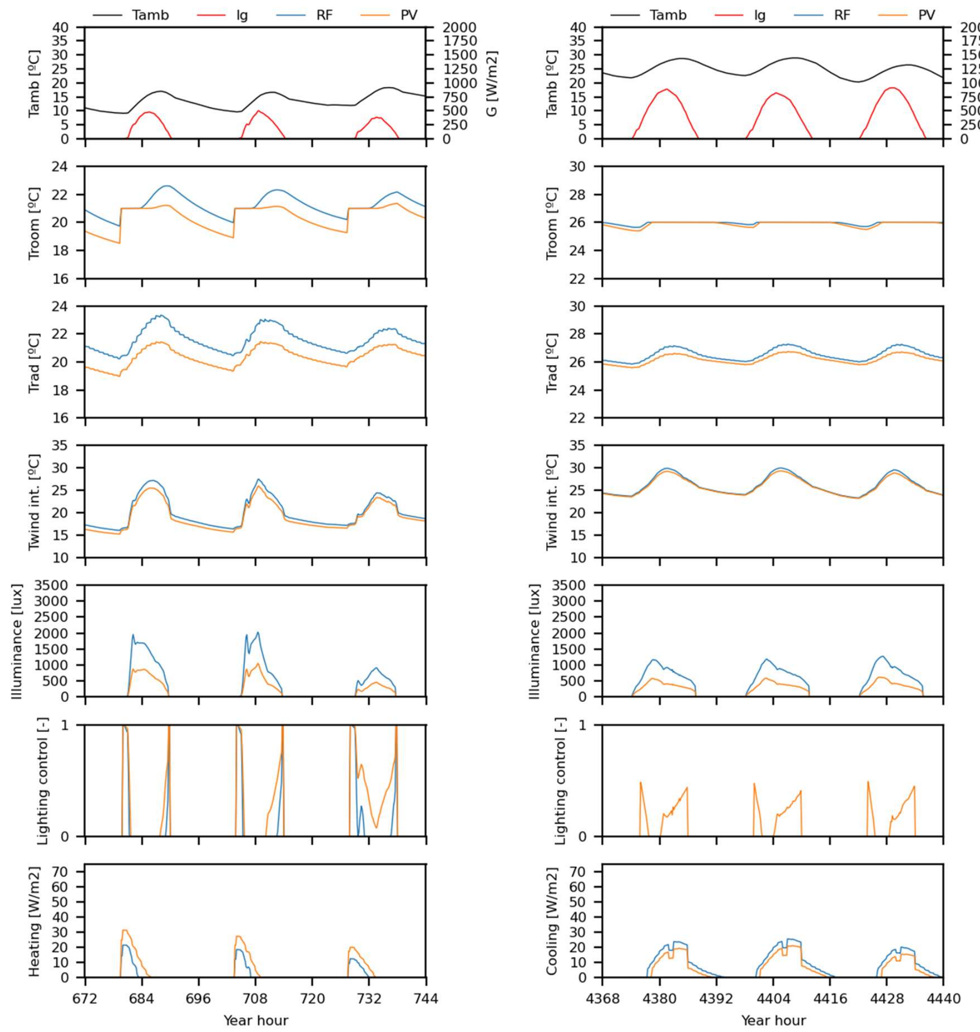


Fig. 5. Almería representative days for winter (left) and summer (right)

The different behaviour of the BIPV and conventional window results in the electricity consumption summarized in Tab. 9, Fig. 7 and Fig. 8. The change of electricity consumption for each end use ranges from 32% (heating in León) up to 155% (lighting in Almería). However, it is their relative weight in the total energy consumption that defines the impact on the energy balance. In the warm climate of Almería scenario, the reduction in cooling (4.79 kWh) compensates the increase of heating and lighting (4.1 kWh), with the total final energy decreasing -3.6%. In contrast, in the colder climate in León the reduction of cooling (-2.28 kWh) does not compensate the increase in heating and lighting (6.06 kWh), with the total final energy increasing 16.2%. Nevertheless, once the PV output is considered in the energy balance, the BIPV window improves the results of the conventional one in both scenarios.

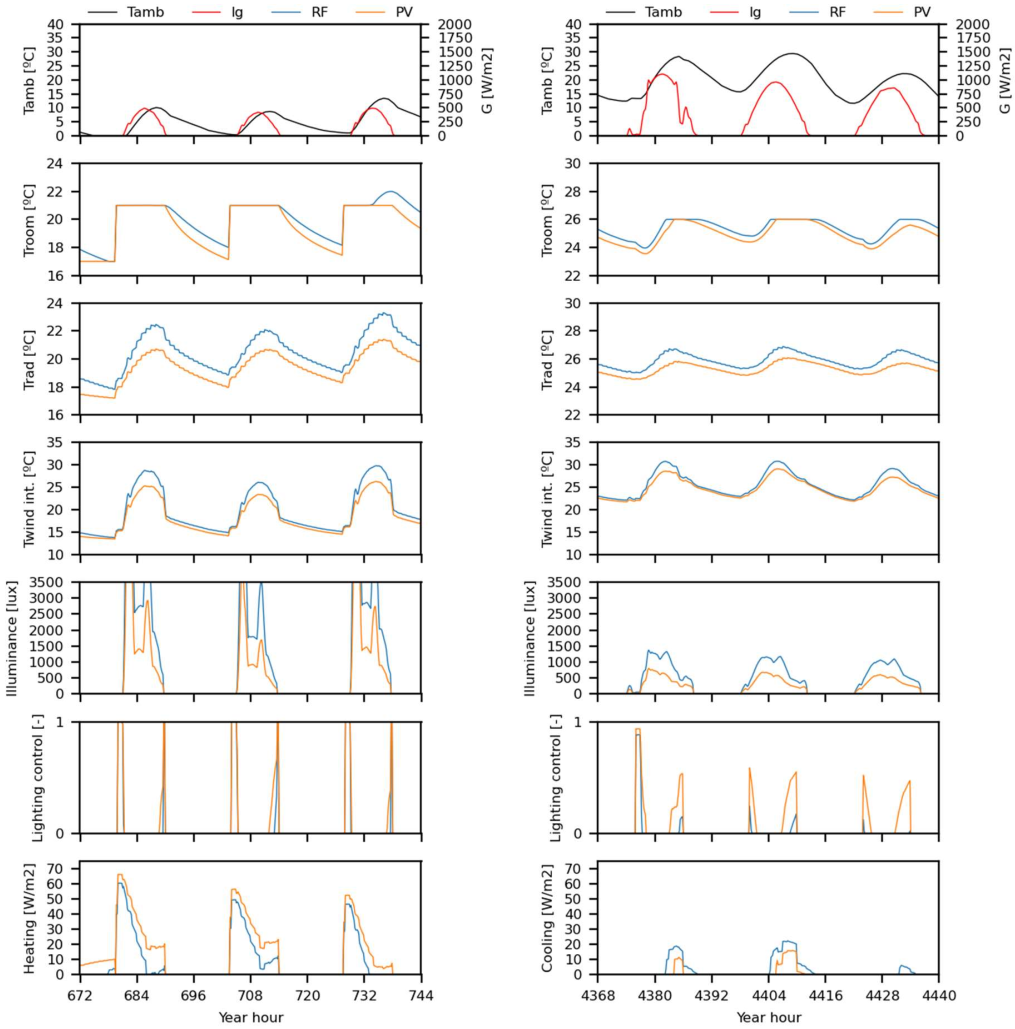


Fig. 6. León representative days for winter (left) and summer (right)

Tab. 9: Annual final energy results [kWh·m^{-2}]

Case		Ventilation	Lighting	Cooling	Heating	Total	PV	EBI
Almeria	REF	5.44	1.55	11.34	1.25	19.59	0.00	19.59
	BIPV	5.44 (0.0%)	3.97 (+155.2%)	6.55 (-42.3%)	2.93 (+133.3%)	18.88 (-3.6%)	8.54	10.34 (-47.2 %)
León	REF	5.44	2.91	4.22	10.80	23.36	0.00	23.36
	BIPV	5.44 (0.0%)	5.47 (+87.8%)	1.94 (-54.0%)	14.30 (+32.4%)	27.15 (+16.2%)	7.80	19.35 (-17.2%)

The monthly distribution, Fig. 7 and Fig. 8, shows that the highest difference in lighting consumption happens in summer, when the conventional window can best exploit the daylight during all occupancy hours. Regarding the PV output, the production in summer can be used for self-consumption easier than in summer, as the occupancy (equipment loads) and the cooling load match the PV output. In contrast, winter loads are concentrated in early morning and late afternoon, resulting in a higher fraction of exported electricity. Finally, the vertical position and South facing of the PV panels in the case studies result in higher electrical outputs in winter than in summer.

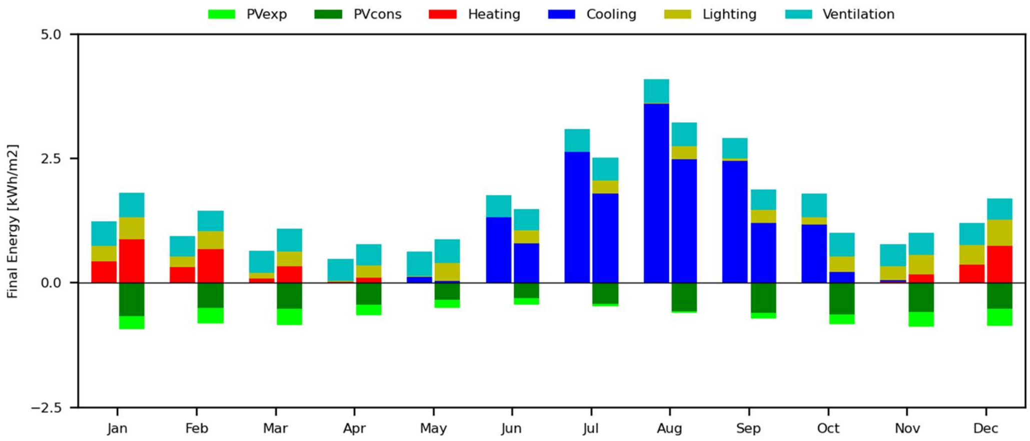


Fig. 7: Almeria monthly final energy (left column for RF and right for PV).

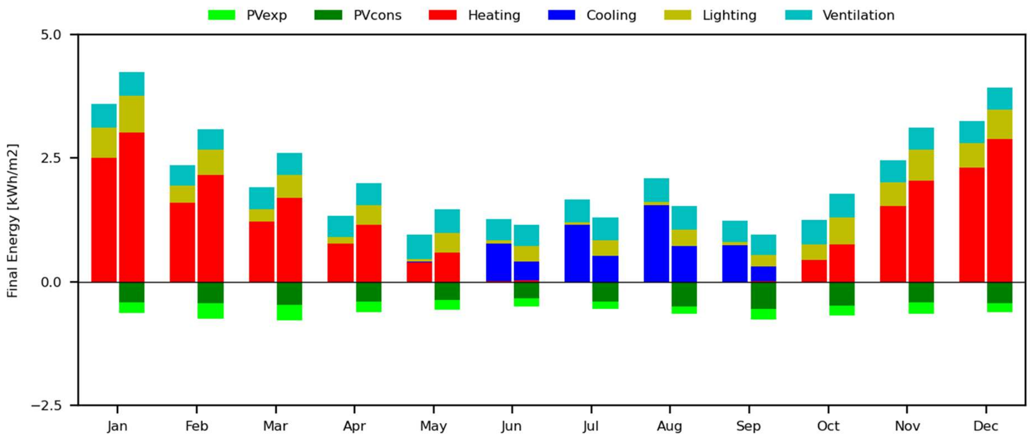


Fig. 8: Leon monthly final energy (left column for RF and right for PV).

As seen in the lighting consumption, the PV window has a negative impact in the daylighting of the building due to its lower τ_{vis}. This results in a significant decrease of the daylighting autonomy and continuous daylighting autonomy, as summarized in Tab. 10. However, the PV window significantly reduces the time with excessive illuminance, by 100% and 67.4% for Almería and León, respectively.

5. Discussion

The results highlight the complex assessment of implementing transparent BIPV as replacement for conventional fenestration systems. Its impacts on the heating, cooling, and lighting consumption need to be evaluated, as well as the design to maximise the PV production. The optical properties of the BIPV glazing may have favourable impact on the building performance in hot sunny climates, with a low SHGC and τ_{vis} to regulate the cooling loads. However, it can have a negative impact on the heating loads, as it reduces the solar heat gains, and lighting, due to a usually lower τ_{vis}. This analysis becomes more complex once the building envelope design is considered. In the current study a single façade solution is used for both the conventional and BIPV glazing system, in both cases disregarding any shading system and/or double skin configuration. As an example, an external shading system could reduce the cooling load and excessive illuminance hours with a conventional glazing, but it cannot be used with transparent BIPV if PV generation is to be maximized. Moreover, the BIPV window impacts on the radiant temperature of the room, hence to the thermal comfort of occupants. Consequently, the results showcase the need to implement an integrated simulation. The methodology presented allows to model the BIPV performance together with the building heating, cooling, lighting, and ventilation loads using a modified version of TRNSYS Type56 Complex Fenestration System (CFS) add-on.

Tab. 10. Daylighting results.

Case		Almeria		León	
		REF	BIPV	REF	BIPV
CDA	Jan	80%	72%	62%	52%
	Feb	85%	74%	75%	62%
	Mar	93%	79%	84%	69%
	Apr	99%	83%	91%	72%
	May	99%	77%	96%	75%
	Jun	100%	82%	95%	78%
	Jul	100%	81%	97%	80%
	Aug	99%	83%	96%	78%
	Sep	96%	81%	95%	83%
	Oct	91%	81%	80%	66%
	Nov	82%	74%	69%	58%
	Dec	72%	64%	66%	58%
Annual CDA		91%	78%	84%	69%
Annual DA		85%	46%	71%	40%
Annual Ill > 2000 lux [h]		300.7	0.0	292.2	95.0

The results of the currently in development Tech4win BIPV glass have promising results for reducing the energy consumption of office buildings in Spain, according to the considered case studies. In the warm and sunny case of Almería, the final energy use decreases by 3.6% with the overall energy balance decreasing by 47.2% due to the PV energy production. In the colder León case, the final energy use increases by 16.2% mainly due to worst heating and lighting performance, although the PV generation offsets this increase leading to a reduction of the overall energy balance by 17.2%. Nevertheless, the current study does not consider the optimization of the conventional windows for each case study, only looking to comply with Spanish building code. However, using a solar control window in the Almería scenario will improve the reference case performance, reducing the savings related to the BIPV window. Therefore, the optimal building envelope design will change depending on the glazing solution, affecting the overall energy balance which will also affect the economic feasibility.

Finally, the current study is based on data of a BIPV glass still in development. The PV efficiency considered is taken from measurements on laboratory scale devices, as data from up scaled large size modules is not yet available. As reference, CIGS technology consistently achieves cell efficiencies around 20%, but development of modules showed efficiencies stagnating at 14-15% (losses above 25%) (Bermúdez and Pérez-Rodríguez, 2018). However, the losses of the new tandem technology are unknown, their assessment still on-going. Fig. 9 shows an estimation of the impact on the energy balance of the reduced PV efficiencies from the cell levels values. In the Almería case, even minimal efficiencies will lead to an improvement in the energy balance. On the contrary, in León case the solar control properties of the BIPV window are not desirable, meaning a minimum level of efficiency, around 3%, needs to be guaranteed in order to improve the energy balance. Nevertheless, it is reasonable to assume higher investment cost of BIPV windows, hence, the reduction in operation cost within the lifetime needs to offset the increase in capital costs.

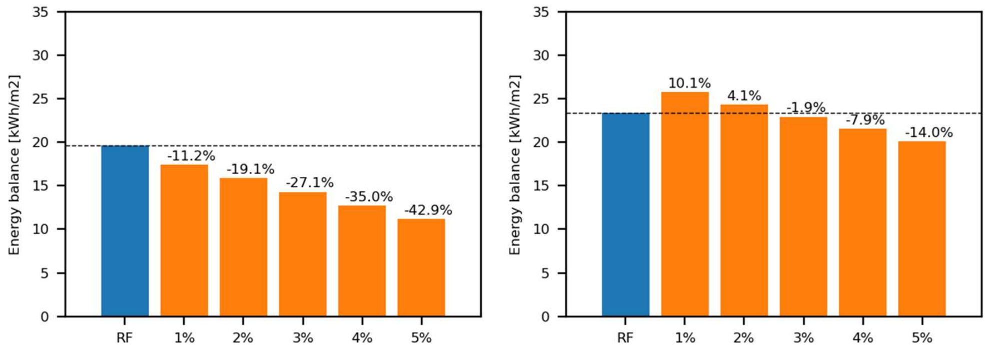


Fig. 9. BIPV window energy balance comparison at different PV efficiencies in Almería (left) and Leon (right) cases.

6. Conclusions

An evaluation of the implementation of the transparent PV glazing developed in Tech4win project in Spanish office building is presented. The research is based in the latest experimental optical and electrical performance data on laboratory devices. The simulation is carried out with a modified version of TRNSYS Type 56 Complex Fenestration System, allowing and integrated evaluation of the impact on the heating, cooling, lighting, and PV generation loads.

The results showed that the transparent BIPV glazing can reduce the overall energy balance of office buildings in Spain. The optical characteristics gives the BIPV glazing solar control properties, which improves the performance of building in sunny warm climates by reducing cooling demand, although these characteristics increase the heating demand in cold climates. Additionally, the BIPV window increases the lighting demand due to lower visible transparency, although it also reduces the visual discomfort risk. Nevertheless, the currently available efficiency data leads to overall energy savings in the two cases considered. However, the envelope design needs to be optimized for both the conventional and BIPV glazing including the shading system management in order to have a comprehensive evaluation of the best solution in every specific case.

Further work will include economic evaluation with estimation of the BIPV window cost and the impact of variable electricity prices, as well as extension to other climatic regions. Moreover, the impacts on visual and thermal comfort, with improvement of the daylighting calculations will be assessed.

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