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D4.5 Report on simulation at building skin level

T4.5 Simulation at building skin level

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BIPVBOOST

"Bringing down costs of BIPV multifunctional solutions and processes along the value chain, enabling widespread nZEBs implementation"

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Summary

This report describes the results of the task T4.5 of the project, where different simulation studies have been performed to support the design of the building skin systems developed under T4.1, T4.2 and T4.3. Two types of simulations have been carried out in parallel. On one hand, thermal and mechanical simulations using finite element method (FEM) software applied at product level. On the other hand, a simulation process has been followed in order to evaluate the products performance at building level by means of building energy analysis tool, BIPV electricity production tool and internal tools to optimize the PV distribution on the façades.

For a quick review of the work, results and conclusions, it is suggested to read the Sections 2, 4.1, 5.1, 5.2.

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Disclaimer

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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This report describes the results of the task T4.5 of the project, where different simulation studies have been performed to support the design of the building skin systems developed under T4.1, T4.2 and T4.3. Two types of simulations have been carried out in parallel. On one hand, thermal and mechanical simulations using finite element method (FEM) software applied at product level. On the other hand, a simulation process has been followed in order to evaluate the products performance at building level by means of building energy analysis tool, BIPV electricity production tool and internal tools to optimize the PV distribution on the façades.

With FEM software it has been studied the thermal behaviour of the multifunctional BIPV façade cladding system developed in T4.1 and the mechanical properties of the BIPV glass façade system developed under T4.3. No simulation was required for T4.2 product, and the efforts were focused on T4.3 product. These simulations have been done following the requirements of the product developers, so that they have been focused on their needs. Special efforts have been focused on T4.3 mechanical simulations as it required the analysis of several configurations, and the redesign process included several iterations. The results are described in detail in sections 3.1 and 3.3, and they are summarized in 5.1.

In another set of simulations, the products have been analysed from energy building performance simulations approach. The building energy demand was analysed with TRNSYS, then it was obtained the optimal distribution of the PV among the façades using EURACs internal developed simulation tool, the PV production was obtained with BIMSolar and, finally, in most of the cases the building energy demand was analysed again but including the BIPV solutions. Even though it was not planned in the T4.5 description, the economic payback time has been also calculated and analysed as it was enough information to do it. The methodology is introduced in 4.1 while is described in detail in sections 4.2, 0, 4.4 and 4.5. The results are described in detail in 4.6, and they are summarized in 5.2.

For a quick review of the work, results and conclusions, it is suggested to read the sections 2, 4.1, 5.1, 5.2.

1.2 Relation with other activities in the project

The relation with other activities in the project is shown as followed.
Table 1.1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within PVSITES project.

Table 1.1 Relation between current deliverable and other activities in the project

Project activity	Relation with current deliverable
T4.1 / D4.1	Some simulations described in this report are based on the multifunctional BIPV façade cladding system, developed in T4.1.
T4.2 / D4.2	Some simulations described in this report are based on CIGS on metal roof and façade systems, developed in T4.2.
T4.3 / D4.3	Some simulations described in this report are based BIPV glass façade systems, developed under the T4.3.
WP6	BIMSolar software, used for simulation of PV production in this report, is being improved under the WP6.

1.3 Reference material

No reference material required

1.4 Abbreviation list

BAPV	Building applied Photo Voltaic
BIPV	Building Integrated Photo Voltaic
BRU	Brussels
CIGS	Copper indium gallium selenide cells
COM	Commercial building
c-Si	Crystalline silicon
ETICS	External Thermal Insulation Composite Systems
FEM	Finite Element Method
IND	Industrial building
MAD	Madrid
MFH	Multifamily house
PBT	Payback time
PV	Photovoltaic
SC	Self-consumption
SFH	Single family house
SS	Self-sufficiency
STO	Stockholm
Tn	Task number
U	Thermal transmittance
WPn	Work package number

2 INTRODUCTION

This report describes the results of the simulation studies that have been performed within the T4.5 to support the design of the different building skin systems developed under T4.1, T4.2 and T4.3. **Two types of simulations** have been carried out in parallel. On one hand, **thermal and mechanical simulations using finite element method (FEM)** software applied at product level. On the other hand, a **simulation process has been followed to evaluate the products performance at building level by means of building energy analysis tool**, BIPV electricity production tool and internal tools to optimize the PV distribution on the façades.

The analyzed BIPV products are the ones developed within T4.1, T4.2 and T4.3 of the project, which are shown in Figure 2.1. Here below a little description of each of them:

- **T4.1 - BIPV façade cladding system** (ePIZ) consists of a composite element, obtained by integrating PIZ cladding product with different photovoltaic (PV) technologies. Thanks to this combination, the solution is a BIPV cladding system that can offer energy production, a high level of thermal insulation and a good level of acoustic insulation within one product along with an easy installation process. The PIZ cladding used is PIZ rock metabio H89, that has an 80mm thick layer of wool rock insulation coupled with a 9mm thick layer of mortar. This cladding product is then coupled with the PV modules by means of an adhesive. In this case, the product version analysed is the one coupled with c-Si glass glass PV modules as shown in Figure 2.1. It is capable of producing 80-90 W/m^2 and has a weight of 41.5 kg/m^2.
- **T4.2 - CIGS on metal BIPV roof system** is the combination of two technologies: the BIPV roof system Solrif® by Schweizer and the CIGS PV modules by Flisom. With this combination, the BIPV roof product aims to be lightweight, well-integrated, easily mounted, and cost-effective. On one side, the CIGS modules are laminated directly on a metal substrate instead of on polymer film, as done commonly. In this case the selected metal substrate is 3mm thick anodized Aluminium. On the other side, the Solrif system is framed around the module to create a roof module that can be easily mounted both in complete and partial roof installation. Although it was not the main target of this development, this technology could be also applied to the façade, and therefore this integration has been also analysed.
- **T4.3 - BIPV glass façade system** is based on an upgrade of the existing COSMOS mounting system by Tulipps with the aim of achieving a lightweight mounting system for PV modules as part of an aesthetic ventilated façade cladding system. This mounting system is the construction interface between the PV modules and the construction wall, which consists of two parts: the rear frame, which is made of aluminium profiles glued to the rear side of the PV module, including the click&go connectors. And the mounting rail system, which are the rails fixed to the construction wall, in which the click&go connectors are hooked.

Figure 2.1 Analyzed BIPV products: (from left to right) BIPV facade cladding system, CIGS on metal BIPV roof system, BIPV glass façade system

3 THERMAL AND MECHANICAL FEM SIMULATIONS OF PRODUCTS

The following section describes the set of mechanical and thermal simulations carried out to support the development of the three WP4 products. The mechanical simulations have been focused on analyzing the mechanical limitations of specific parts determined by the partners developing the products. The thermal simulations are focused on analyzing maximum temperatures that the products can reach under operation, determining the temperatures among the different components. The simulations have been done at TECNALIA using the **Siemens Simcenter 3D** software.

3.1 MULTIFUNCTIONAL BIPV FAÇADE CLADDING SYSTEM

This section describes the thermal simulations and the results obtained for the multifunctional BIPV façade cladding system.

3.1.1. Model

The complete model consists of a BIPV cladding system with PV modules resting on a mortar layer, a rockwool insulation floor and the building wall. The model geometry is displayed in Figure 3.1.

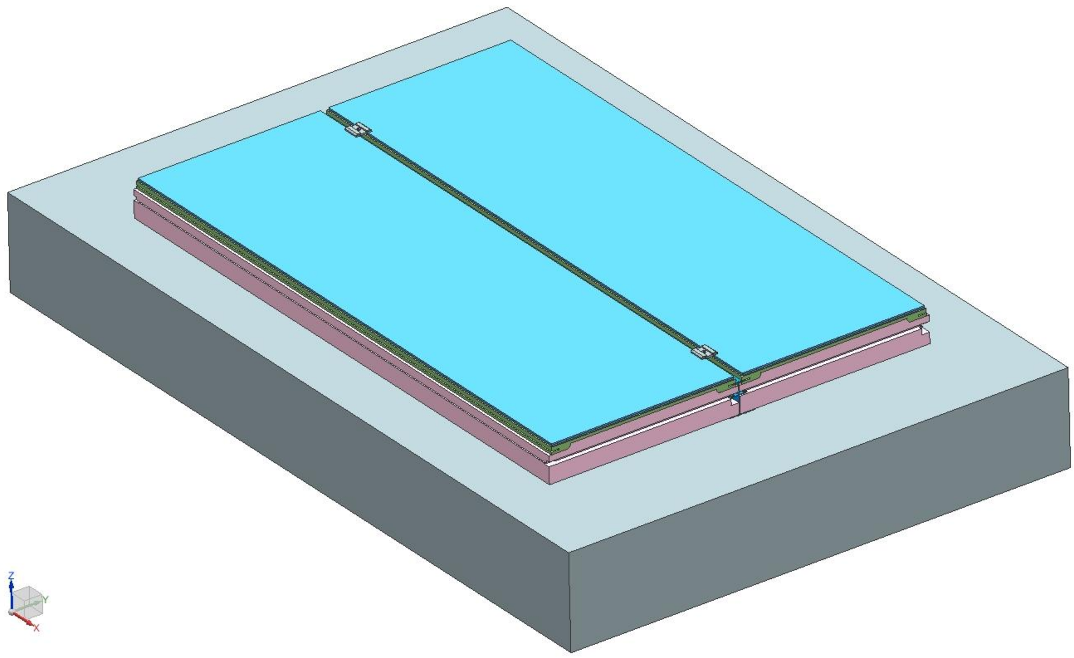


Figure 3.1 Multifunctional BIPV façade cladding system simulated

The existence of both geometric and boundary conditions symmetry planes makes it possible to substantially simplify the model. The Figure 3.2 shows the considered symmetry planes by which the model has been reduced.

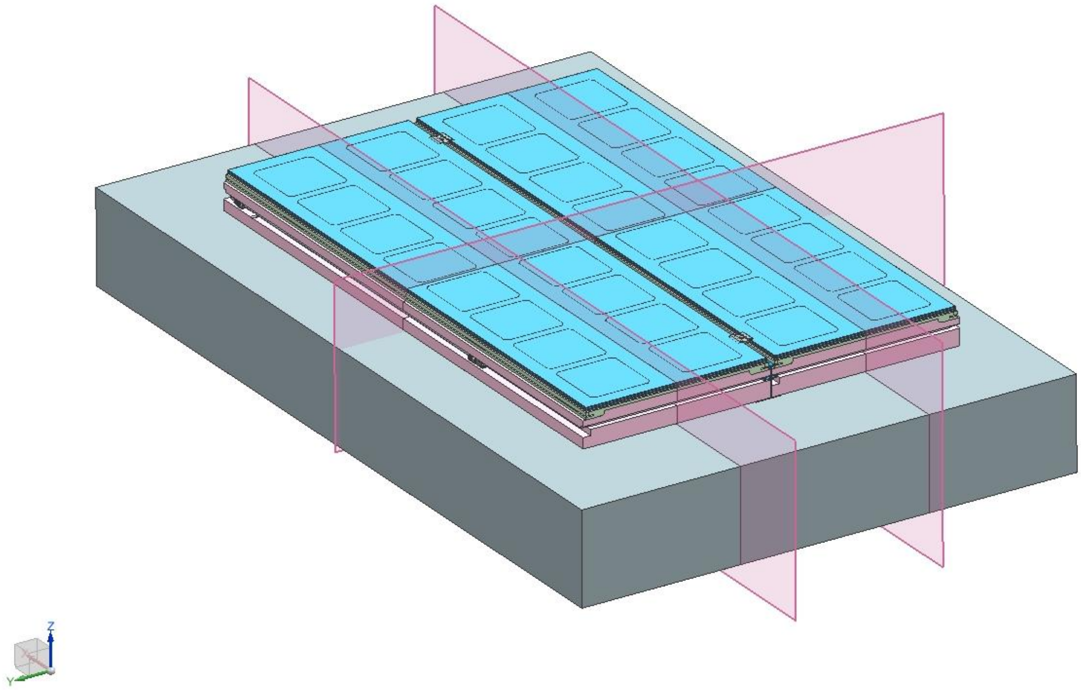


Figure 3.2 Symmetry planes considered for the reduction of the model

The resulting model that has eventually been analysed is, therefore, the one shown in the next figure. It consists of the central part of one half of the model.

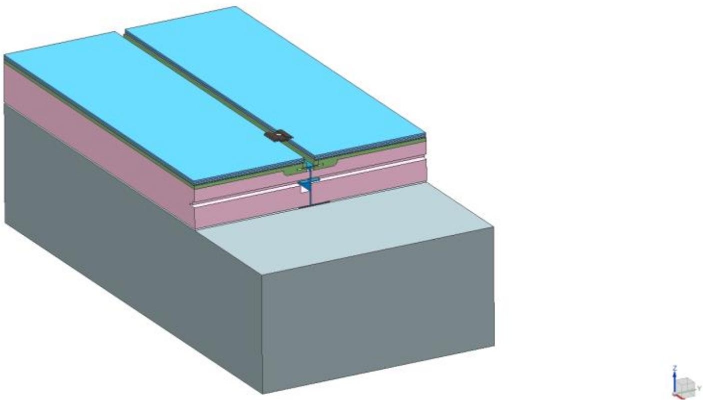


Figure 3.3 Resulting model after simplification by symmetry planes

The component breakdown of the model is explained in Figure 3.4, where the upper glass layer and EVA have been hidden to show the position of solar cells, and Figure 3.5, where the whole PV module has been hidden to show the mortar, silicone and junction box housing.

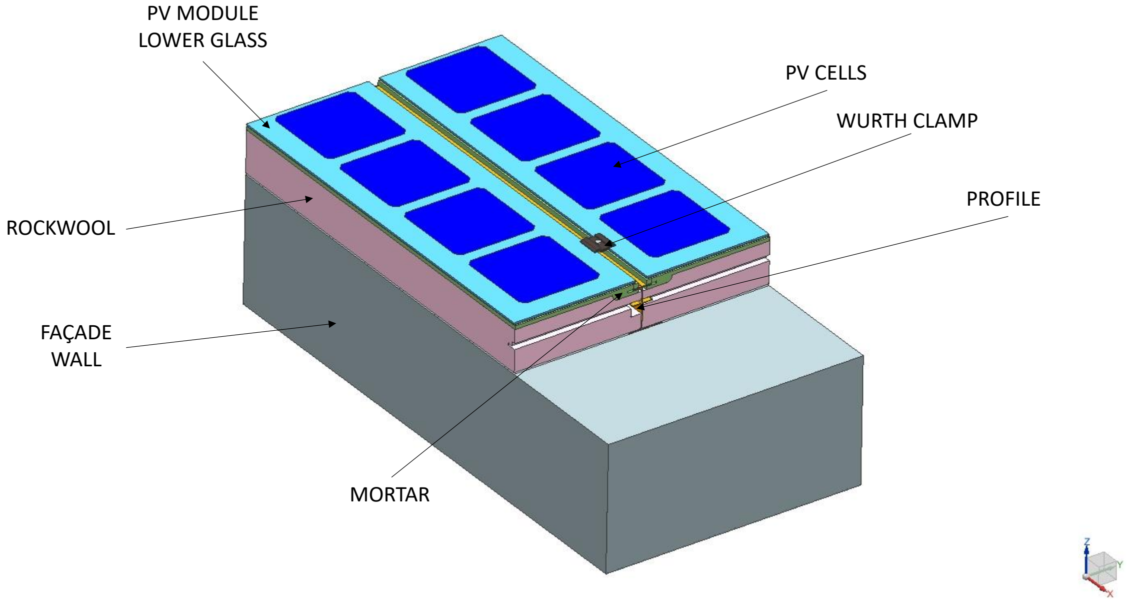


Figure 3.4 Components description (model with upper glasses and EVA encapsulants removed)

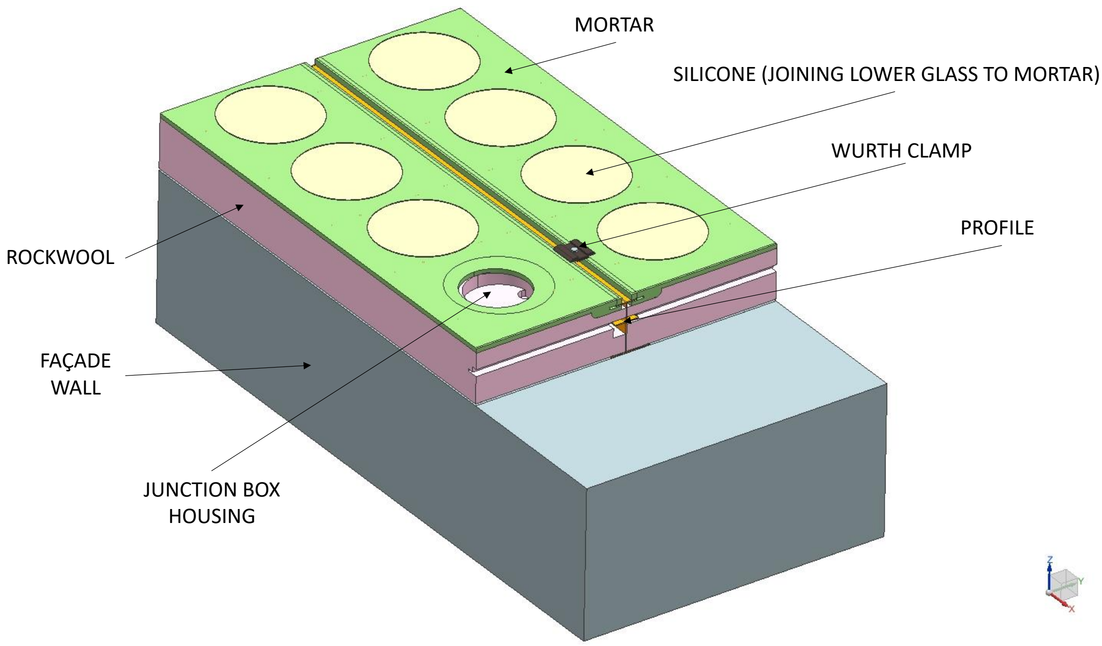


Figure 3.5 Components description (model with PV modules removed)

The components the model consists of and their thermal conductivity are listed in the Table 3.1:

Table 3.1 Thermal conductivity values for the involved components of the model

Part name	Thermal conductivity (W/m·K)
PV Module (glass)	1
PV Module (EVA)	0,24
Silicone	0,8
PV cells	148
Mortar	1,15
Rockwool	0,038
Façade wall	0,8
Profile	154,5
Clamp (Steel)	127
Clamp (rubber)	0,15

3.1.2. Thermal and boundary conditions

Ambient temperature

Regarding the external and boundary conditions, two cases for each month of the year have been considered, one corresponding to the maximum temperature registered for each month during the 2005-2016 years period, and the other for the minimum temperature registered in that same period.

Thermal loads: radiation

The maximum radiation value measured for each month has been used as the thermal load for each month's two cases of maximum and minimum temperatures. Both, the ambient temperature values (maximum and minimum) and the maximum radiation values for each month are shown in the Table 3.2.

Table 3.2 Maximum and minimum temperatures and maximum radiation values considered for the simulations

Monthly Max and Min Temperature and Radiation (South façade) at Morbegno for 2005-2016 period (based on PVGIS-SARAH data)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max} (°C)	15,4	19,6	22,8	27,3	31,1	33,0	33,4	34,6	31,8	25,8	19,5	12,3
T_{min} (°C)	-8,1	-11,8	-6,3	0,2	5,9	8,5	12,8	11,2	7,5	-0,7	-4,7	-7,6
R_{max} (W/m_2)	1054	1013	938	810	635	548	598	726	819	925	991	1041

Convection to environment

Free convection to environment is considered at the external side of the model, with a relatively low convection coefficient, corresponding to still air or a low wind speed:

h= 5 W/m²·K

Regarding the inner side, a constant temperature of 22°C has been applied.

Radiation to environment

For the radiative heat exchange to the external environment, the sky temperature for each of the external temperature conditions has been calculated.

For clear sky conditions the sky temperature can be calculated by Swinbank's formula:

$T_{sky} = 0{,}0553(T_a)^{1{,}5}$, where temperatures are given in Kelvin.

Values for each ambient temperature conditions considered are shown in the Table 3.3.

Table 3.3 Sky temperatures for each case, according to Swinbank's formula

Sky temperature considered for the radiative dissipation to environment (°C)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
T_{max}	15,4	19,6	22,8	27,3	31,1	33,0	33,4	34,6	31,8	25,8	19,5	12,3
Sky T	-2,1	3,8	8,4	14,8	20,3	23,1	23,7	25,4	21,3	12,7	3,7	-6,5
T_{min}	-8,1	-11,8	-6,3	0,2	5,9	8,5	12,8	11,2	7,5	-0,7	-4,7	-7,6
Sky T	-34,5	-39,5	-32,1	-23,2	-15,4	-11,8	-5,8	-8,0	-13,2	-24,5	-29,9	-33,8

3.1.3. Results and conclusions

Maximum temperature value at the PV module is given for each case in Table 3.4.

Table 3.4 Maximum T results in PV modules for each case

Maximum T in PV module (°C)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
R_{max} (W/m²)	1054	1013	938	810	635	548	598	726	819	925	991	1041
T amb $_{max}$	15,4	19,6	22,8	27,3	31,1	33,0	33,4	34,6	31,8	25,8	19,5	12,3
T_{max}	**91,8**	**92,3**	**89,8**	**84,5**	**76,3**	**71,9**	**75,8**	**85,7**	**89,4**	**91,4**	**90,8**	**88,8**
R_{max} (W/m²)	1054	1013	938	810	635	548	598	726	819	925	991	1041
T amb $_{min}$	-8,1	-11,8	-6,3	0,2	5,9	8,5	12,8	11,2	7,5	-0,7	-4,7	-7,6
T_{max}	**75,8**	**70,5**	**68,7**	**63,8**	**54,7**	**49,9**	**57,5**	**65,9**	**69,9**	**71,6**	**73,6**	**75,2**

An additional thermal study of interest could be the temperature at the junction box in operation. However, if a more detailed study of the junction box is needed, that region should be analyzed in detail, which would include the implementation in the model of a detailed box design. In addition, the operating conditions of the box should be determined and reproduced in the model, in terms of the generation of heat produced in it during its operation.

3.2 CIGS on metal roof and façade systems

Mechanical simulations on this system were initially planned once the final installation in demo site was defined. However, it was discarded afterwards because they were not required for the development of the solution and other products required more FEM simulation efforts.

3.3 BIPV GLASS FAÇADE SYSTEMS

This section describes the structural simulations and the results obtained for the BIPV glass façade cladding system with the “Lock&Go” frame system designed by TULIPPS.

3.3.1. Model

The simulation process of this product has gone through a long redesign process, in which some components of the assembly have been subjected to various variations in their geometry, thickness or position.

As an example of the different design evolutions, the back-structure profiles were updated, making the vertical profiles (50x15x2 mm) stronger than in previous versions (40x15x2 mm).

Other changes done on the model comprised re-dimensioning of the “Lockers”.

Moreover, different glass thickness values have been studied, namely 4+4 and 6+6 module configurations.

For reasons of confidentiality of the owner of the design of the structure and frame system of this product, only the final design and its corresponding results are described in this section.

The simulation of the complete system (module bonded on rear frame, connected on axle holders) takes a lot of calculation time. Furthermore, the implementation of the degrees of freedom and the correct behavior of the same in the model are difficult issues to define. To tackle this issue, it was decided to simulate the system and evaluate the results step by step. This helped to better understand the mechanical behavior and simplify the interpretation of the results.

The Figure 3.6 shows the definitive assembly that has been analyzed and subjected to structural simulation of a wind suction load. Size of each PV-module is 667 mm x 2000 mm.

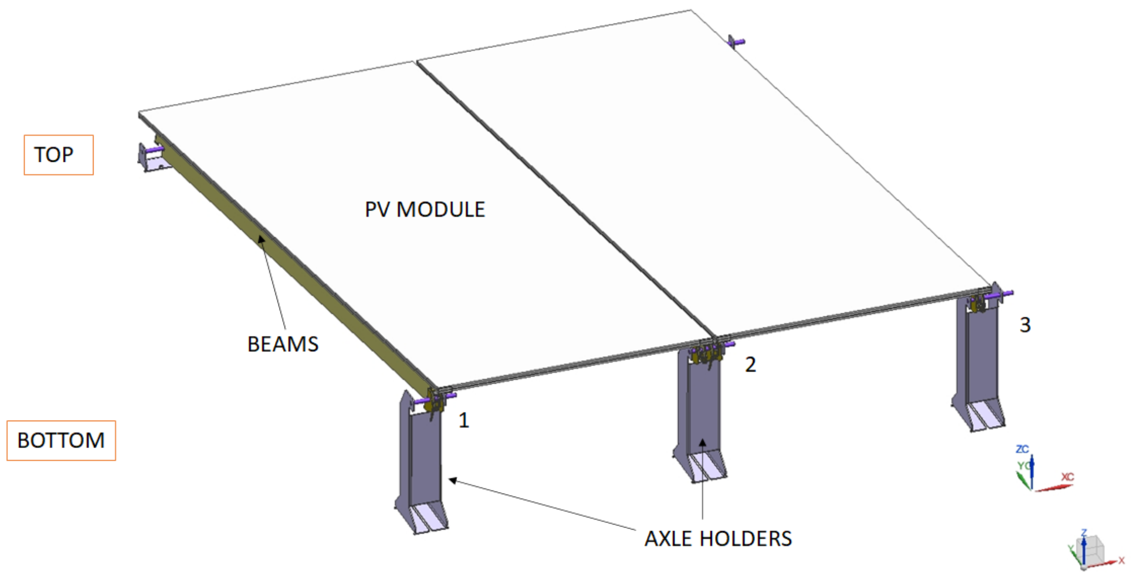


Figure 3.6 BIPV glass façade system simulated

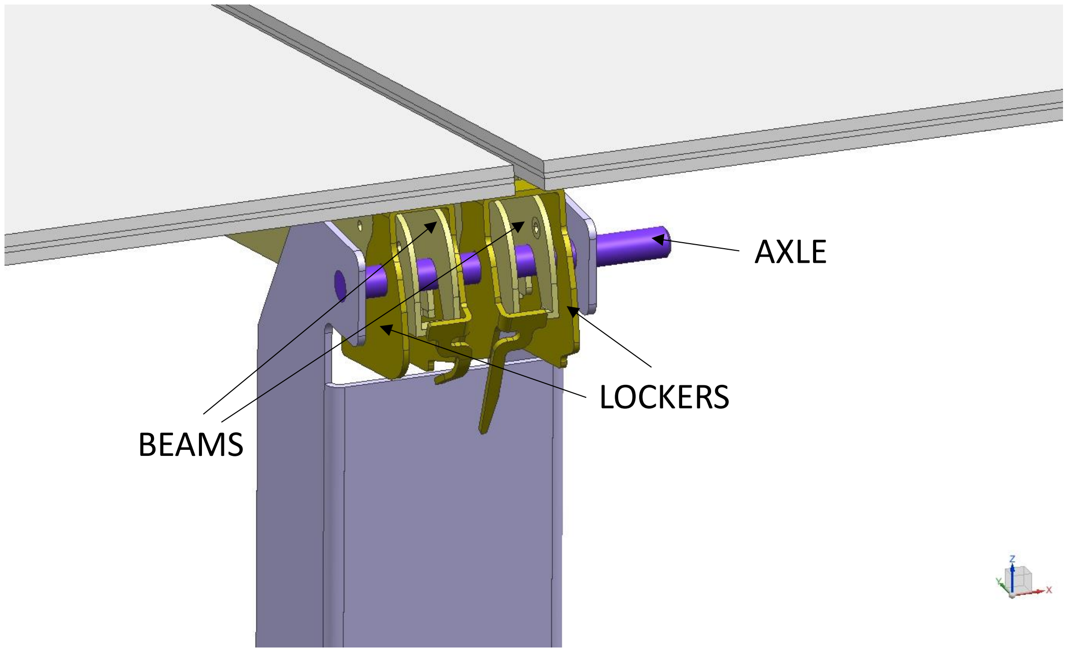


Figure 3.7 BIPV glass façade system. Connection points detail

The main components the assembly consists of are listed in Table 3.5:

Table 3.5 Main components and materials

Part name	Material
PV Module	Glass-EVA-Glass
Back structure beams	Aluminum
Axle Holders	Stainless steel
Axles	Stainless steel
Lockers	Stainless steel
Rollers at top end	POM (Polyoxymethylene)

The mechanical properties of each material taken into consideration for the simulations are shown in Table 3.6:

Table 3.6 Elastic properties of the materials involved

Material	Young modulus (MPa)	Poisson coefficient
Glass	70000	0,23
EVA	10,4	0,4
Stainless steel	200000	0,3
Aluminium	70000	0,33
POM	2000	0,44
Adhesive	3	0,45

3.3.2. Degrees of freedom

The four connection points at the corners of a module are designed in a way that internal forces, due to small movements, are kept low. So, no other than the external loads are transferred in the system. Figure 3.8 and Table 3.7 below show the design with respect to the degrees of freedom of the connection points.

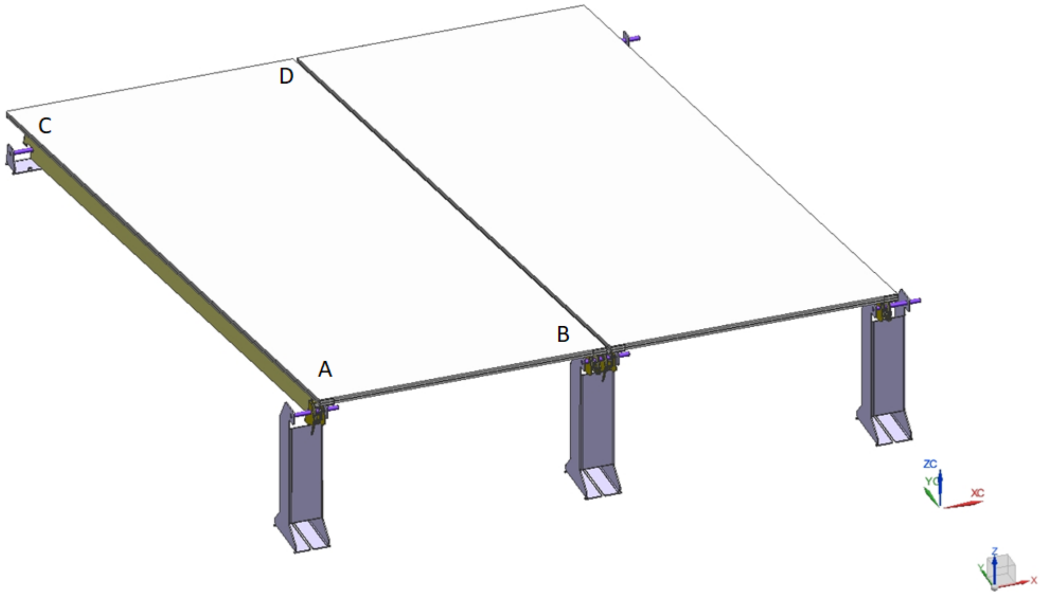


Figure 3.8 Figure general scheme to indicate the degrees of freedom per connector. A and B representing the bottom corners with locker. C and D are the top corners with shifting connectors

Table 3.7 Degrees of freedom for the four corners of every rear frame configuration

DOF	A	B	C	D
Displacement in X	√	x	√	√
Displacement in Y	x	x	√	√
Displacement in Z	x	x	x	x
Rotation in X	√	√	√	√
Rotation in Y	x	x	x	x
Rotation in Z	x	x	√	√
√: FREE / X: FIXED				

3.3.3. Load cases and limits

Two load cases were analyzed.

1.- Photovoltaic products must comply with IEC 61215 standard, which includes a static mechanical load test, with a minimum test load of 2400 Pa, uniformly distributed on the PV modules. For this load case 4+4 and 6+6 glass module configurations were simulated.

2.- Another load case was also considered, which consists of the wind load given by local basic building standards for the demo site, Mondragón in Spain, together with load factors and ultimate design strength values given by codes of practice for structural use of glass. According to these, a wind load of 1400 Pa has been considered. For this load case only the 4+4 glass module configuration was simulated.

On the other hand, the limits for the maximum allowable stress and deformation are based on state-of-art practices for structural use of glass (1). 50 MPa is considered as maximum allowable stress for glass, while maximum allowable deformation is 1/60 mm.

3.3.4. Results

Simulations were carried out for 4+4 and 6+6 glass-glass module configurations for the first load case, that of 2400 Pa distributed wind load. For the second load case, only the most restrictive case was analyzed, that is the 4+4 configuration.

a) 2400 Pa load case

The results given are maximum displacement for the whole assembly and maximum stress values in PV module's glass, the back-structure's profiles, the Lockers and the Axle Holders.

Maximum deformation

The maximum deformation of the whole system is shown in the figures Figure 3.9 and Figure 3.10:

- 4+4 module configuration:

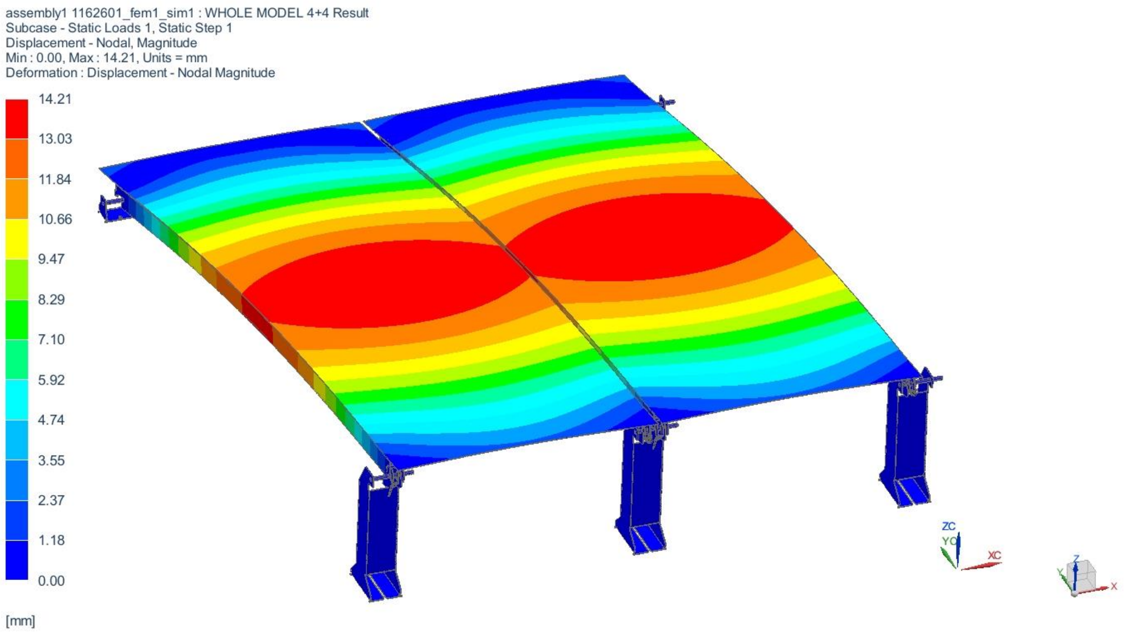


Figure 3.9 Maximum deformation for 2400 Pa wind load, 4+4 glass configuration

- 6+6 module configuration:

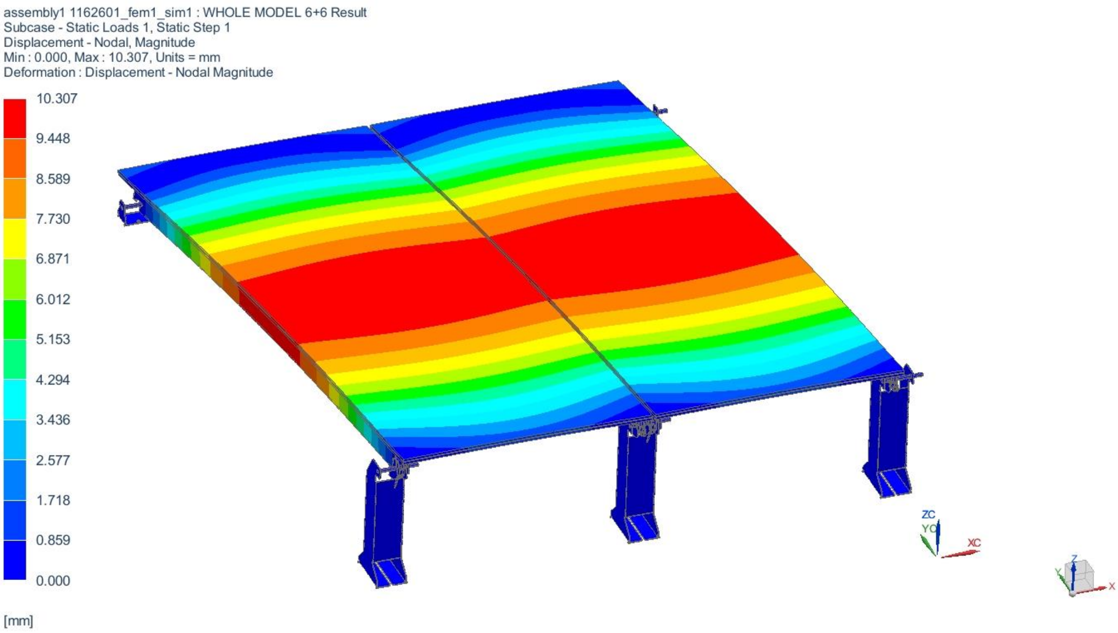


Figure 3.10 Maximum deformation for 2400 Pa wind load, 6+6 glass configuration

The maximum deformation criterion that we are considering is that given by some codes for structural use of glass, in which, for four side supported glass panes, the deflection limit is:

$$d_{lim} = \frac{1}{60} \text{ of the short spam } = \frac{1}{60}\ 667 = 11{,}1\ mm$$

According to this criterion, the 6+6 glass configuration would comply with the maximum deformation condition.

Maximum stress distribution

Table 3.8 Maximum stress values for the model's main components. 2400 Pa wind load

Component	Maximum stress (MPa)		Allowable stress (MPa)	Safety factor	
	4+4 module	6+6 module		4+4 module	6+6 module
Glass (PV module)	24	17,5	50	2,1	2,9
Profiles (back structure)	75,2	57	160	2,1	2,8
Lockers	203	194	230	1,1	1,2
Axle Holders	183,5	183,8	230	1,3	1,3

b) 1400 Pa load case.

The results given are maximum displacement for the whole assembly and maximum stress values in PV module's glass, the back structure's profiles, the Lockers and the Axle Holders.

Maximum deformation

The maximum deformation of the whole system is shown in the Figure 3.11:

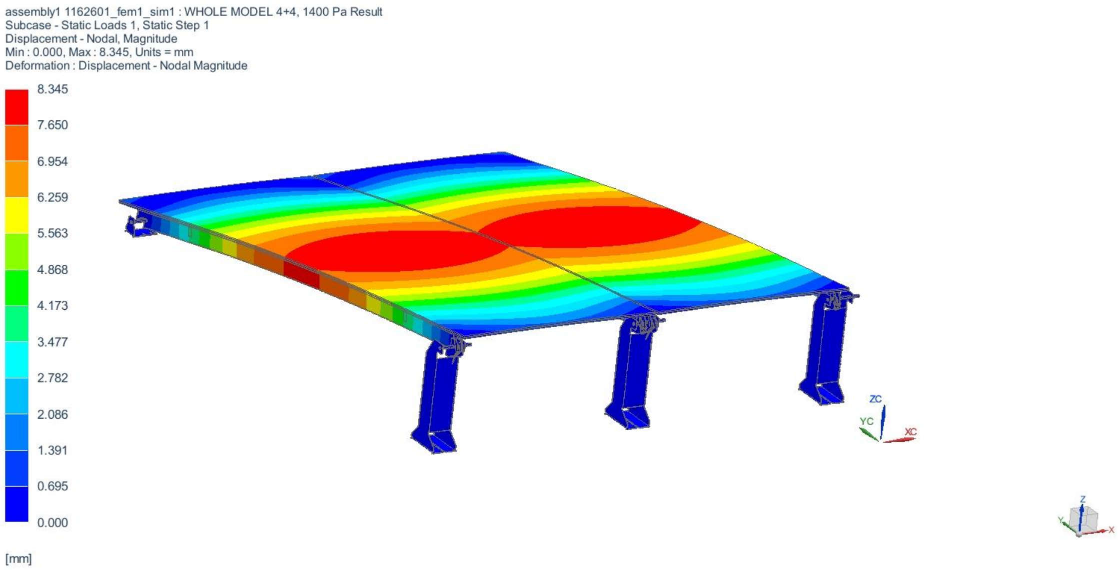


Figure 3.11 Maximum deformation for 1400 Pa wind load, 4+4 glass configuration

According to the maximum deformation criterion considered:

$d_{lim} = \frac{1}{60}$ of the short spam = $\frac{1}{60}\ 667 = 11{,}1\ mm$

According to this criterion, the 4+4 glass configuration would comply with the maximum deformation condition for this load case.

Maximum stress distribution

Table 3.9 Maximum stress values for the model's main components. 1400 Pa wind load

Component	Maximum stress (MPa)	Allowable stress (MPa)	Safety factor
Glass (PV module)	14	50	3,6
Profiles (back structure)	43,8	160	3,7
Lockers	98,9	230	2,3
Axle Holders	108,1	230	2,1

3.3.5. Conclusions

All the stress values for any component are below their respective allowable values for every PV module configuration and every load case considered.

Regarding the deformation values, according to the maximum deformation value criteria considered, corresponding to 1/60 of the module's shortest spam, for the 2400 Pa wind load case only the 6+6 glass module configuration would comply with such criteria. Regarding the 1400 Pa wind load case, both configurations, 4+4 and 6+6, would fulfill the maximum deformation limit. As a reminder, the Spanish building code requires 1400 Pa for the location and type of integration of this solution, while the 2400 Pa is a quite high value required by photovoltaic standards for products that can be located in non-urban areas with strong winds.

4 BUILDING ENERGY ANALYSIS OF BIPV PRODUCTS

4.1 INTRODUCTION

In this section, the energy performance of the developed BIPV solutions is analysed from a holistic building approach. The purpose is to assess the energy impact of the developed BIPV products in different building typologies, climates, and orientations. It has been intended to focus this analysis on general integrations of the products and not focused on the specific characteristics of project demonstrator.

Not every BIPV product is interesting for every type of building. Thus, Table 4.1 shows the selection of cases that have been analysed, and the type of integration of the product in the building (façade or roof). This selection has been done in collaboration with the technology providers based on the main applications of their BIPV products.

Table 4.1 Selection of building typologies and BIPV products integration

	BIPV façade cladding (T4.1)	CIGS on metal façade/roof (T4.2)	BIPV glass facade (T4.3)
Single Family House (SFH)	No	Yes (roof)	No
Multi Family House (MFH)	Yes (Façade)	No	Yes (Façade)
Commercial Building (COM)	Yes (Façade)	No	No
Industrial building (IND)	No	Yes (Façade)	Yes (Façade)

The buildings were selected with the aim of being representative of the European building stock. The building features such as wall and roof stratigraphy, windows etc. were selected based on standard features of that type of building in the different locations according to Tabula webtool (2). Considering that once these buildings are retrofitted, not only the BIPV solutions would be installed, but also their energy efficiency should be enhanced, **a standard energetic retrofit was considered for all the buildings**. The standard retrofitting considered is based on installation of ETICS on the façade. The thickness of the insulation was defined as the minimal to reach the thermal transmittance defined in the Italian minimum requirements, which are based on the EU directive 2010/31/UE (3) (4). These values are classified by climate zones, depending on the Heating Degree Days of each location. Hence, the HDD of the analysed cases were defined based on (5). The standard retrofitting does not consider the upgrade of the roof, since the existing roof compositions (2) were already compliant with the minimum roof thermal transmittance values (4). The 3D models of the buildings are shown in Figure 4.1, and their main characteristics are listed below:

- **Single family house (SFH):** It is a rectangular shaped (10 x 7.5 m) independent building with a total living area of 225 m^2. It consists on a ground floor, with the living area, a first floor and an attic, with the sleeping areas. The roof is pitched 25° in 2 inclinations. This model was adapted from the single family case studied in the H2020 4RinEU project (6) (7).
- **Multifamily house (MFH):** It is a rectangular shaped (33 x 16 m) building with a total of 3344 m^2 of living area divided in 46 apartments (32 units of 80 m^2 and 14 units of 50 m^2). It consists on a ground floor, with 4 apartments, a technical and a security room, and 7 floors with 6 apartments per floor. There is one staircase in the building and the roof is flat. This model was adapted from the English demo case studied in the H2020 BuildHeat project (8) (9).

- **Commercial building (COM):** It is a rectangular shaped (91 x 23 m) building with a total of 2090 m^2 of commercial area. It represents a shopping mall divided in 10 stores (8 small stores of 174 m^2 and 2 large stores of 348 m^2). They are all placed in the ground floor and the roof of the building is flat. The source of this model is the reference building data base created by the Office of Energy efficiency & renewable energy of USA, namely the strip mall building (10).
- **Industrial building (IND):** It is a rectangular shaped (100 x 46 m) building with a total of 4835 m^2 of net area. It is divided in three different zones: an office in the ground floor (237 m^2), a storage area next to the office and in a first floor above the office (1393 m^2), and an industrial production area (3205 m^2) in the ground floor. The roof is also flat. The source of this model is the reference building data base created by the Office of Energy efficiency & renewable energy of USA, namely the warehouse building (10).

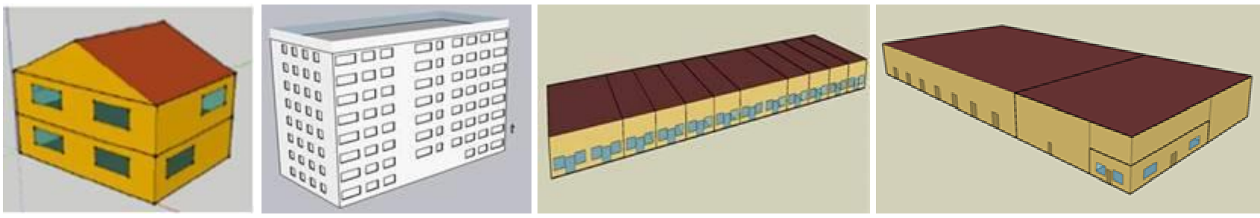


Figure 4.1 Building 3D models, from left to right: SFH, MFH, COM, IND

The procedure followed for the analysis of each combination pair of BIPV product and building typology is described in Figure 4.2. First, the heating, cooling, and electric demand of the standard retrofitted building (without PV) is analysed with TRNSYS simulation software. Second, the PV ratio distribution among the façades is optimized according to the energy demand based on a basic estimation of PV production i.e. it is analysed how the total PV capacity should be distributed among east-south-west façades so that the production profile better fits the demand profile. Third, the self-consumption and self-sufficiency of the building is analysed for several PV capacities (keeping the optimal PV ratio among the façades). Fourth, more accurate PV production estimations are made using BIMSolar software for the PV capacities where self-sufficiency = self-consumption (approximately), so that accurate PV production data is obtained for most interesting PV capacity. Fifth, final building energy performance simulations are made including the BIPV products integrated in the building, so not only the active properties (PV production) are considered, but also their passive (thermal energy impact) contribution to the building.

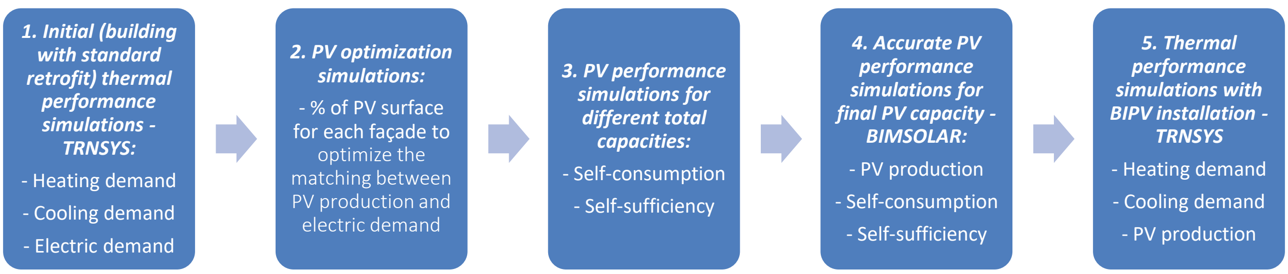


Figure 4.2 Simulation workflow: steps and main outputs achieved in each step

The locations selected for the study are Madrid, Brussels and Stockholm in order to represent Southern, Central and Northern European climates respectively. Moreover, the different cases were studied with the building facing the main four orientations. The different location and orientation combinations sum up a total of 12 different scenarios for each analysed case. In the cases in which the buildings are symmetric, the total number of different scenarios was reduced to 6 cases.

4.2 BUILDING ENERGY DEMAND

In this section the step 1 of Figure 4.2 is described. Once the different cases, the reference buildings and the boundary conditions were defined, the first step was to model the buildings. This first modelling aimed at identifying the energy demand of the buildings with the standard retrofit (only the minimum required insulation thickness) but without the integration of any PV solution. This initial energy demand of the building was useful for two reasons: set up the baseline case to which compare the different impacts of the PV integration and identify the building energy demand to estimate the optimal PV installation to be done in each case.

A TRNSYS model was used for each building. These models were taken from the abovementioned references respectively and adapted to be consistent with the analysed cases and scope. All of them calculate the yearly energy balance of the building, with a time step of 1h, and a month of simulation pre-conditioning that is not considered in the results. The models get as input the weather files, the different zones occupancy, internal gains (due to occupants, lighting, and appliances) schedules, temperature set points for ideal heating and cooling system, infiltration, and ventilation rates among others. Most of these inputs were adapted for each building typology and use of the different areas of the building, based on several sources (7), (9), (10), (11), (12), (13), (14), (15), (16), (17). Details of the used inputs for each building type can be seen in the Annex. Moreover, in order to avoid excessive cooling loads and discomfort, in the residential cases and in the office area of the industrial case, shading devices were applied to the windows and controlled based on solar irradiance, internal temperature and external temperature. The weather files used were created with Meteonorm v7, for the location of the airports next to the analysed cities (Madrid, Brussels, Stockholm).

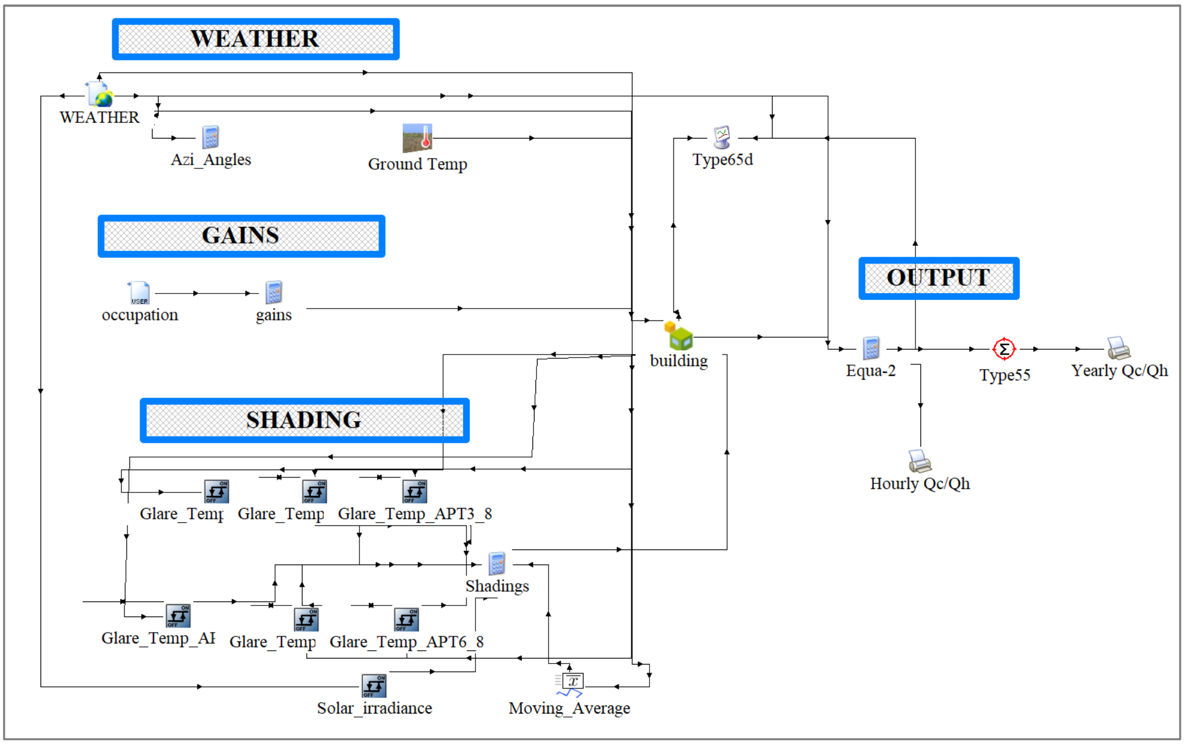


Figure 4.3 TRNSYS Simulation Studio model of the MFH

Based on all the mentioned inputs, the model calculates the energy balance of the different thermal zones of the building at each time step. Thanks to these calculations, hourly and yearly accumulated outputs were collected, in this case, for the whole building. It was assumed that both the heating and cooling demands of the building are covered with a heat pump. Thus, the hourly electric consumption profile was obtained dividing the hourly thermal demand of the building by a COP/EER of a commercial standard heat pump, dependent on the external air temperature and assuming a supply water temperature of 30°C for heating and 15°C for cooling. Hence, the model provides the hourly heating, cooling, and electrical demand, as well as the yearly accumulated demands in absolute values and in values per surface area. It should be mentioned that the electrical demand is the one related exclusively to the heat pump that supplies then the heating and cooling loads, but not all the other electrical consumptions due to lighting, appliances etc.

Figure 4.4 shows the hourly heating, cooling, and electric demand along the year in the commercial case for the three analysed climates. This was calculated for the different orientations of each building type. The electrical demand of each case was used then as input for the PV optimization, as explained in the next section.

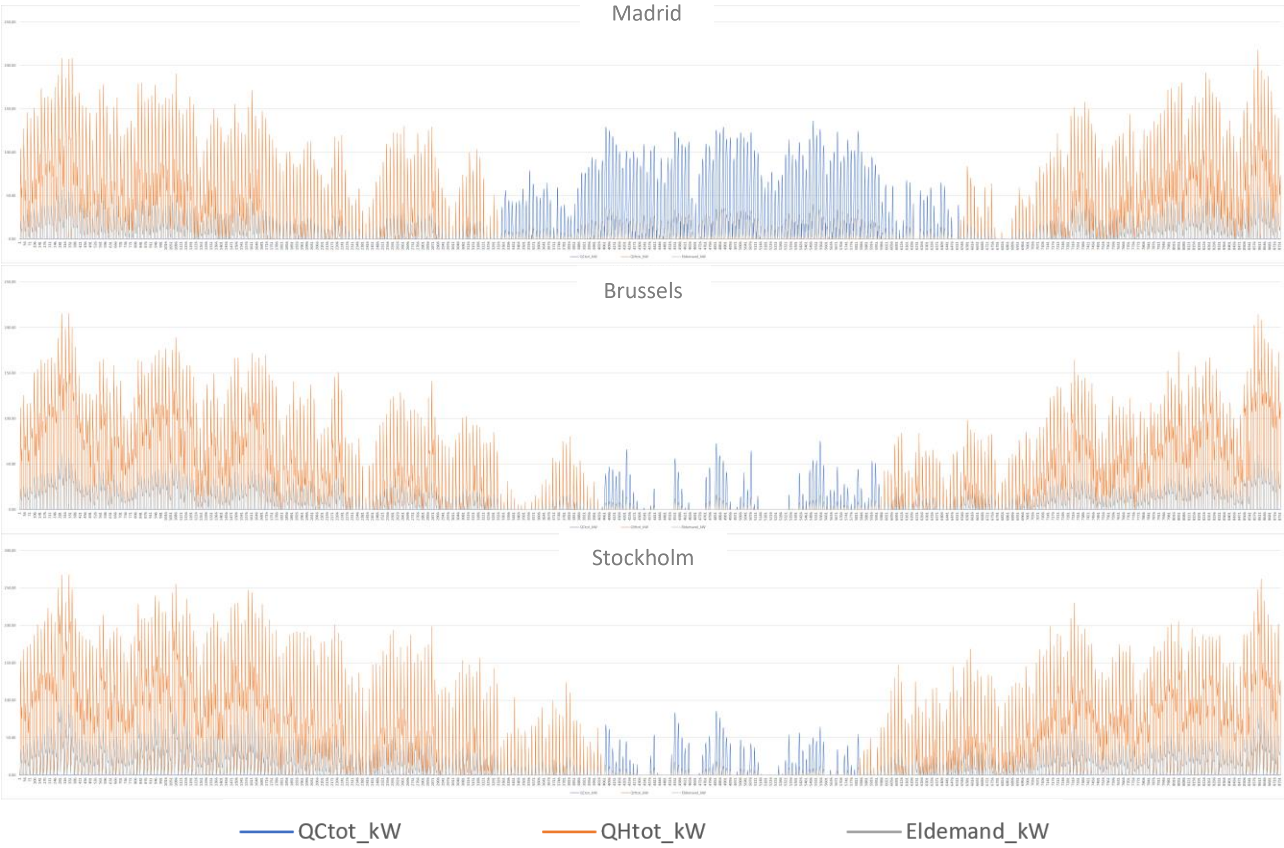


Figure 4.4 Hourly heating, cooling, and electric demand of COM building in Madrid, Brussels and Stockholm

4.3 DEFINITION OF PV INSTALLATION: PV OPTIMIZATION

In this section the steps 2 and 3 of Figure 4.2 are described.

The BIPV system for each building type and location selected has been designed starting from the results of an optimization process performed with the tool presented in (18). The tool takes as input the location of the building, the weather file, the surfaces available for the installation of BIPV modules, a set of techno-economic inputs such as modules efficiency, temperature coefficients, etc. and the hourly consumption profile of the building, supplied by the previously done TRNSYS simulations. The following table summarizes the inputs used in the optimization process.

Table 4.2 Inputs used in the PV optimization process

	BIPV façade cladding and BIPV glass facade	CIGS on metal façade/roof
Building location	Madrid, Brussels, Stockholm	
PV module dimensions [m]	1.6 x 1	
PV module efficiency [%]	20	9
Performance Ratio of the system at STC (19)	0.82	
Ross coefficient [m²K/W] (20)	0.034	0.054
Temperature Coefficient of Pmax [%/°C]	-0.451	-0.35

Given the inputs reported in Table 4.2, the electric consumption profile, the weather file and the geometry of the building, the optimization tool provides as output the optimal configuration of the system which maximizes (or minimizes) a target function. In this task it has been decided to **maximize the load matching between generation and the electric consumption profile excluding the possibility to install an electric storage**. Thus, only direct self-consumption has been considered in the optimization, while the energy sent to the grid, at this step, has been considered lost without any remuneration. However, final economic analysis in section 4.6 considers remuneration from grid injected energy.

Since the optimization tool used to configure the BIPV system is based on simplified models that could lead to different results compared with detailed simulations, only the façade distribution of modules has been considered as output. Moreover, this assumption decreases the number of optimizations to be performed (optimization is typically a time-consuming phase). This means that the number of modules installed by the optimization tool on the surfaces of façades (West, South, East) and roofs has been divided by the total number of modules to obtain the optimal distribution that maximizes the matching between generation and consumption. In Table 4.3, the results in terms of modules distribution percentage among the different facades/roof sides for each case have been reported.

Table 4.3: % of PV modules distribution on façades

	MFH					
Case	**Madrid**		**Brussels**		**Stockholm**	
	G1	**G2**	**G3**	**G4**	**G5**	**G6**
West [%]	50	44	2	0	0	0
South [%]	38	52	98	100	100	100
East [%]	12	4	0	0	0	0

Case	COM											
	Madrid				Brussels				Stockholm			
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
West [%]	26	43	8	40	0	6	0	7	17	27	2	15
South [%]	66	37	92	37	69	41	100	41	51	28	71	23
East [%]	9	20	0	23	31	53	0	52	32	45	27	62

Case	IND c-Si											
	Madrid				Brussels				Stockholm			
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
West [%]	37	29	35	28	0	0	0	0	0	0	0	0
South [%]	63	71	65	72	100	100	100	100	100	100	100	100
East [%]	0	0	0	0	0	0	0	0	0	0	0	0

Case	IND CIGS											
	Madrid				Brussels				Stockholm			
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
West [%]	46	30	39	29	0	0	0	0	0	0	0	0
South [%]	54	70	61	71	100	100	100	100	100	100	100	100
East [%]	0	0	0	0	0	0	0	0	0	0	0	0

Case	SFH											
	Madrid				Brussels				Stockholm			
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
West [%]	14	0	13	0	25	0	31	0	37	0	37	0
South [%]	0	100	0	100	0	100	0	100	0	100	0	100
East [%]	86	0	88	0	75	0	69	0	63	0	63	0

Assuming the modules distribution presented in the previous table and using the pvlib-python module (21), a parametric analysis of the impact of the nominal power of the system on the self-consumption and self-sufficiency indexes has been done. In other words, the nominal power of the system has been varied in a range with a fixed step (for example 1-75 kWp in steps of 5 kWp for the MFH with BIPV façade cladding) while keeping fixed the PV modules distribution. The self-consumption (SC) and self-sufficiency (SS) Key Performance Indicators have been calculated according to the following formula:

$$SC = \frac{Self - consumed\ energy}{Energy\ generated} \qquad SS = \frac{Self - consumed\ energy}{Energy\ consumption}$$

where the self-consumed energy has been calculated on an hourly basis from the PV generation and the electric consumption.

The systems obtained have been simulated with the pvlib-python package. As an example, the results of the parametric analysis performed for the multifamily house (MFH) with BIPV façade cladding are reported in terms of self-consumption and self-sufficiency indexes in Table 4.4. For each scenario (G1, G2, etc.), the solutions that do not respect the limits on surface availability have been excluded. These cases have been highlighted in red in Table 4.4.

Table 4.4 Results of parametric analysis of MFH case (BIPV façade cladding) in terms of self-consumption (SC) and self-sufficiency (SS) indexes

	System capacity [kWp]														
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
G1															
SS [%]	15	25	32	36	40	42	44	46	47	48	49	50	50	51	51
SC [%]	55	46	39	33	29	26	23	21	19	18	16	15	14	13	13
G2															
SS [%]	17	27	33	37	40	42	44	45	46	47	48	49	49	50	50
SC [%]	50	39	32	27	23	21	18	17	15	14	13	12	11	11	10
G3															
SS [%]	10	16	20	23	25	27	28	29	30	30	31	32	32	33	33
SC [%]	48	38	32	27	24	21	19	17	15	14	13	12	12	11	10
G4															
SS [%]	11	17	20	23	25	26	27	28	29	29	30	31	31	32	32
SC [%]	44	34	28	23	20	18	16	14	13	12	11	10	10	9	9
G5															
SS [%]	7	11	13	15	16	17	18	19	20	20	21	21	21	22	22
SC [%]	52	40	33	28	24	22	20	18	16	15	14	13	12	12	11
G6															
SS [%]	7	10	13	14	15	16	17	18	18	19	19	20	20	21	21
SC [%]	47	36	29	25	22	19	17	16	14	13	12	12	11	10	10

Among the remaining solutions, it has been decided to select the configuration corresponding to the most balanced solution in terms of self-consumption and self-sufficiency. It corresponds to the intersection point (or the closest configuration available) between the self-consumption and self-sufficiency curves. As an example, Figure 4.5 reports these curves for the G3 scenario, i.e. a multifamily house located in Brussels. The intersection point corresponds to the PV capacity (25 kWp) considered for the detailed simulations done in BIMSolar for that specific case.

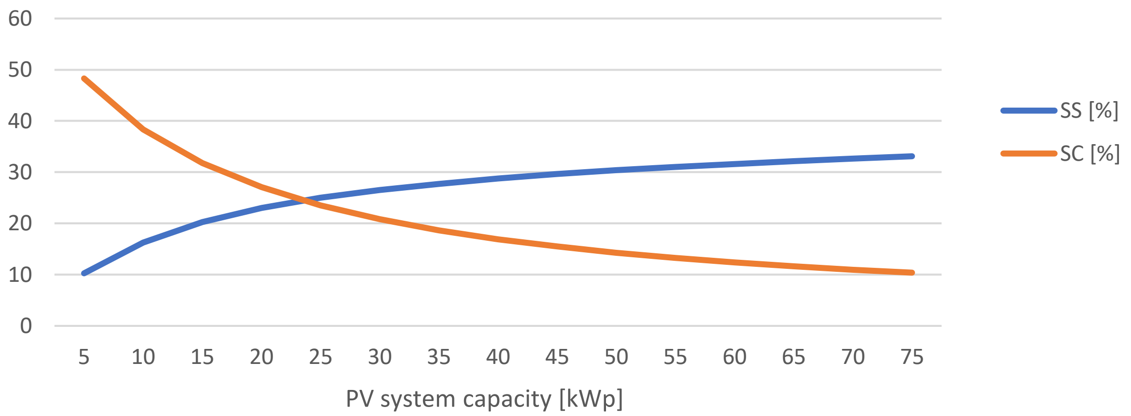


Figure 4.5 Self-consumption (SC) and self-sufficiency (SS) curves from the parametric of MFH – G3 scenario

The process has been repeated for all the locations and buildings type to obtain the final configuration of all the systems under analysis. The final nominal power to be installed on each façade are described in results section 4.6, within tables showing results for the different cases (i.e.Table 4.6, Table 4.8, Table 4.10…).

Finally, the detailed simulations of the optimal PV systems have been performed with BIMSolar and the results discussed in the following sections.

4.4 PV PRODUCTION ESTIMATION

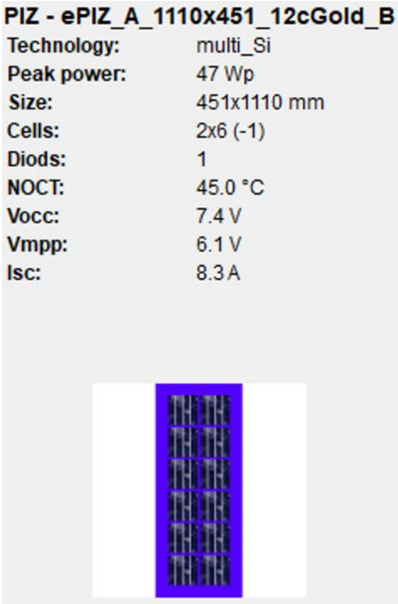
In this section the step 4 of Figure 4.2 is described.

After the first analysis with TRNSYS and the use of BIPV optimization tool developed by EURAC and described in section 0, it was obtained optimal distribution of PV among the envelope to match the energy demand, and the approximate self-sufficiency and the self-consumption for different PV capacities for every building and every orientation.

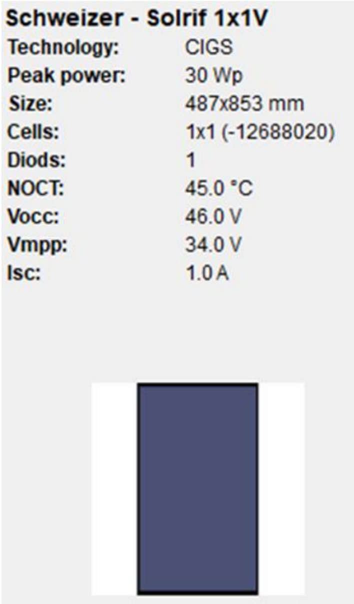
At this point, the option to be further studied was the one that, in theory, has a similar self-sufficiency and self-consumption, i.e. it was selected for deeper study the PV capacity that approximately satisfies self-sufficiency = self-consumption. However, there are some cases where this condition cannot be achieved because the required PV capacity exceeds the available surface to install PV panels. In this case, the maximum capacity that can be installed according to available surface, and keeping the distribution rates among the façades, was selected for deeper study.

The PV production estimation was carried out by means of BIMSolar software. This tool has been specifically developed to analyse the production of BIPV products and is being further developed within WP6 of this project. The analysed cases respond to the cases described in Table 4.1. The weather files used in BIMSolar are the same than in simulations with TRNSYS in order to avoid result discrepancies due to this model input.

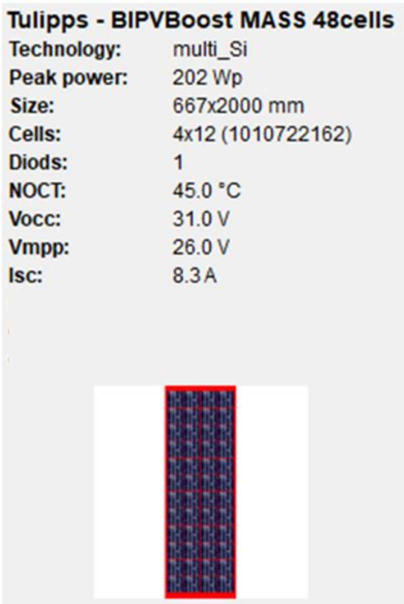
Thus, the different products were described in BIMSolar using the BIPV or BAPV module editor tool, according to most recent module characteristics described by the manufacturers. Some products have been developed in different dimensions or peak power versions, so for this study the considered most representative module version has been chosen. The main characteristics are depicted in Figure 4.6.



BIPV façade cladding system with integrated insulation (T4.1)



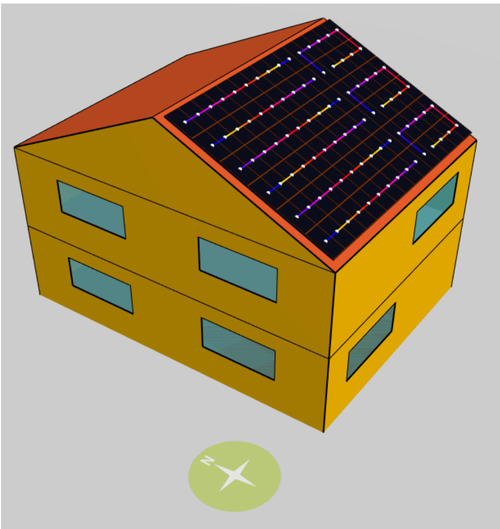
CIGS on metal roof and façade systems (T4.2)



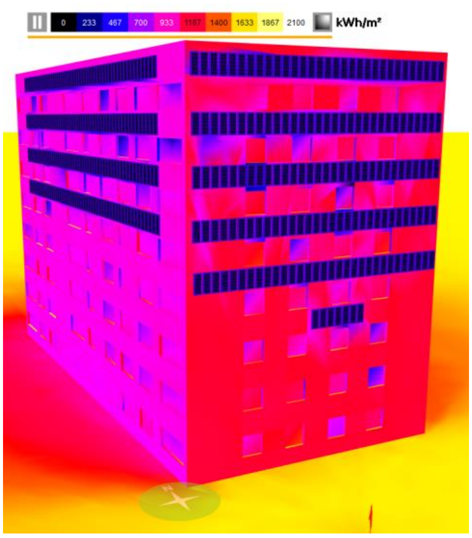
BIPV glass façade systems (T4.3)

Figure 4.6 Description of BIPV product modules in BIMSolar

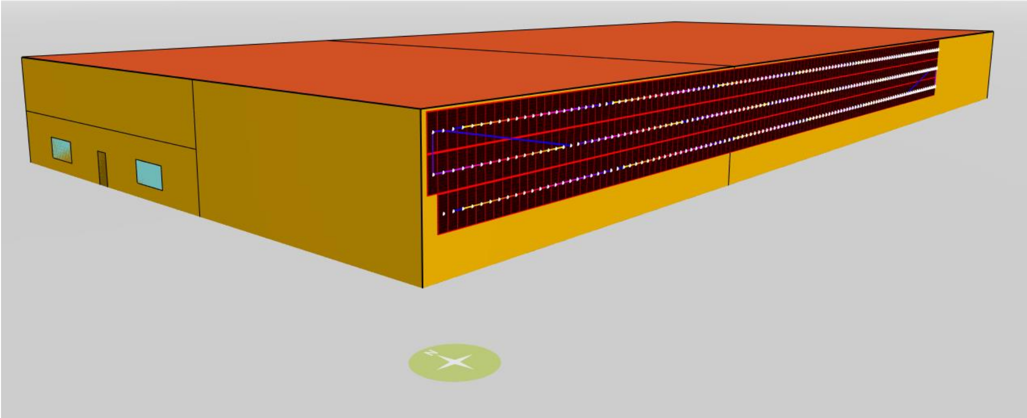
Then, the products are described in the 3D building model. The Figure 4.7 shows examples of product description integrated on different buildings.



T4.2 product integrated in Single Family House



T4.1 product integrated in MultiFamily House among façades. Irradiation map.



T4.3 product integrated in Industrial building

Figure 4.7 Example of integration modelling of products and buildings with BIMSolar

As the purpose is to get PV production data that can be generally used, the PV production should not be limited by the electrical installation, in other words, the electrical installation should impact as less as possible the final PV production except for a general decrease according to general inverter and cabling losses. Thus, the inverters and other electrical elements were selected with high enough peak power to avoid significant clipping losses and connections were made according to MPPT voltage operating ranges. In case of PV modules on several façades or orientations, normally an individual MPPT (or individual inverter) was selected (Figure 4.8).

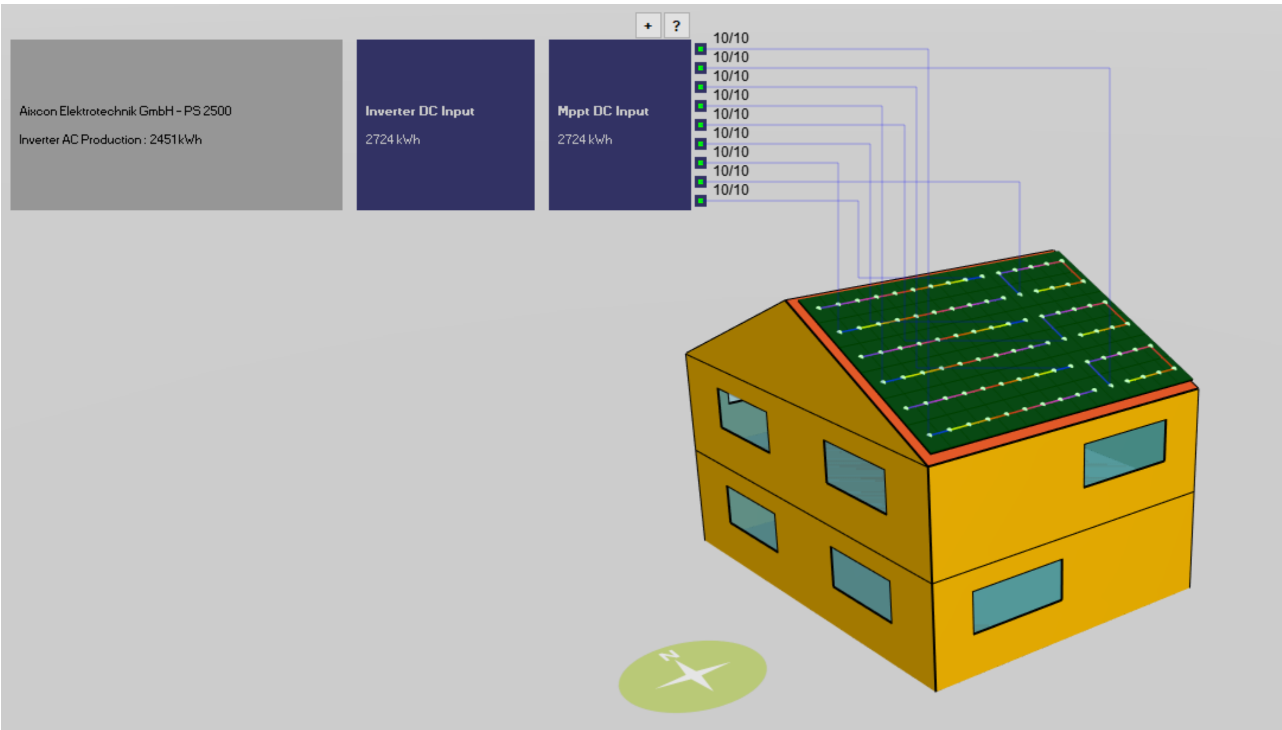


Figure 4.8 Example of electrical system description for SFH with T4.2 product

Finally, the hourly AC PV production was obtained for the different façades involved in the installation (Figure 4.9).

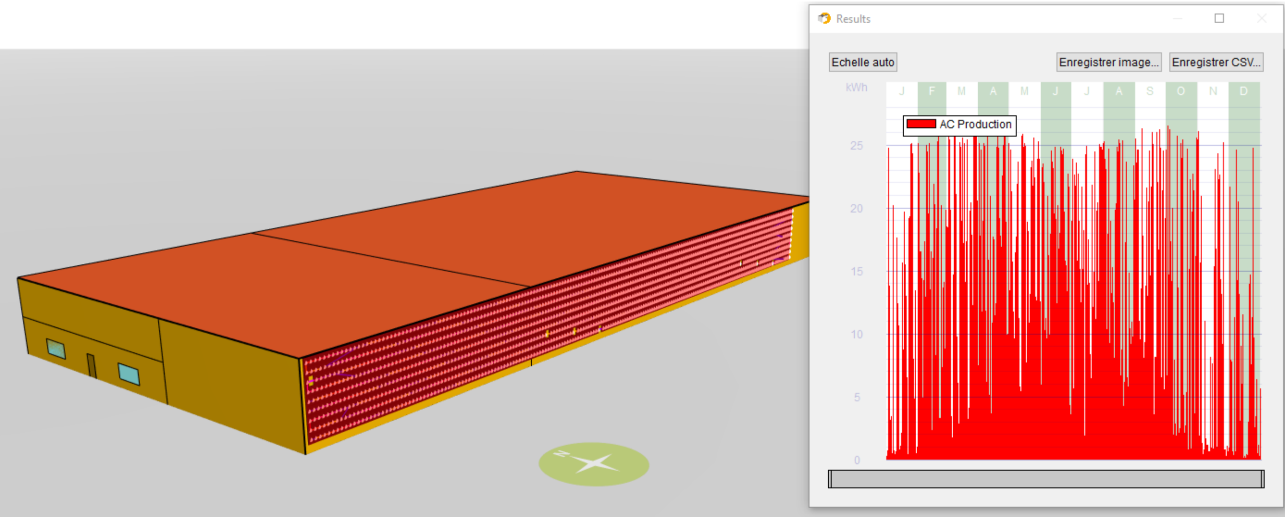


Figure 4.9 Example of hourly AC PV production data for industrial building with T4.2 product on South façade only, as determined for Stockholm

The final obtained PV productions are described in results section 4.6, within tables showing results for the different cases (i.e.Table 4.6, Table 4.8, Table 4.10…).

4.5 BUILDING ENERGY DEMAND WITH BIPV PRODUCTS

In this section the step 5 of Figure 4.2 is described. Once the building energy consumption baselines were calculated, the optimal PV installation defined for each case together with its estimated PV performance, the next step was to evaluate the building energy demand once the BIPV solutions are installed in the building. These simulations aim at estimating the impact that the BIPV products installation could have in the thermal energy demand of the buildings.

These simulations were performed in TRNSYS, adding the BIPV solutions to the initial baseline models explained in section 4.2. The BIPV solutions were modelled with the Type 567 of TRNSYS that represents a glazed BIPV and calculates its main outputs, such as the PV production and the temperatures in the different layers including the building wall behind the PV module. These BIPV models can be coupled with the building Type 56 in order to consider the thermal impact of one into the other. Hence, the temperature behind the PV was applied as boundary condition to the part of the building wall or roof that integrates the BIPV solution. In these simulations the amount and positioning of PV modules used for each case was the same as the one used in the PV performance simulations in BIMsolar.

The BIPV models were adapted to the different features of each of the three analysed products, such as the efficiency (as shown in Figure 4.6), temperature coefficient and different layers properties, as listed in Table 4.5.

Table 4.5 Main parameters of the BIPV technologies considered in the TRNSYS model

Parameter	Unit	BIPV façade cladding (T4.1)	CIGS on metal roof (T4.2)	BIPV glass facade (T4.3)
Cover Emissivity	-	0.9	0.9	0.9
Cover Conductivity	kJ/hmK	3.3732	0.9	3.3732
Cover Thickness	m	0.003	0.0005	0.004
Substrate Resistance	hm^2K/kJ	0.00201	0.0000046	0.00119
Channel Emissivity - Top	-	0	0.9	0.9
Channel Emissivity - Bottom	-	0	0.9	0.9
Channel Height	m	0 (no airgap)	0.05	0.05
Absorptance	-	0.9	0.9	0.9
Reference PV Efficiency	-	0.094	0.072	0.151
Reference Temperature	°C	25	25	25
Reference Radiation	kJ/hm^2	3600	3600	3600
Efficiency Modifier - Temperature	1/°C	-0.000423	-0.0002528	-0.0006829
Efficiency Modifier - Radiation	hm^2/kJ	0.000025	0.000025	0.000025

Moreover, for simplicity reasons, only one BIPV model (Type 567) was implemented for each façade/roof orientation, as shown in Figure 4.10. However, each of them considers the equivalent inputs to model the total BIPV surface applied to that specific orientation. Another important concept regarding the BIPV modelling, was the ventilation air gap behind the BIPV module. As shown in Table 4.5, the BIPV cladding has no rear ventilation (airgap = 0), while the other two products have a rear ventilation gap of 5cm. Different airgap dimensions were tested and the impact was considered negligible for the scope of this analysis. In the rear-ventilated cases, the air is naturally driven by the stack effect, therefore the air inlet velocity and mass flow rate were calculated applying the equations of the ISO 15099 (Ventilation – thermally driven) (22). This was calculated separately for each façade/roof orientation, as can be seen in Figure 4.10.

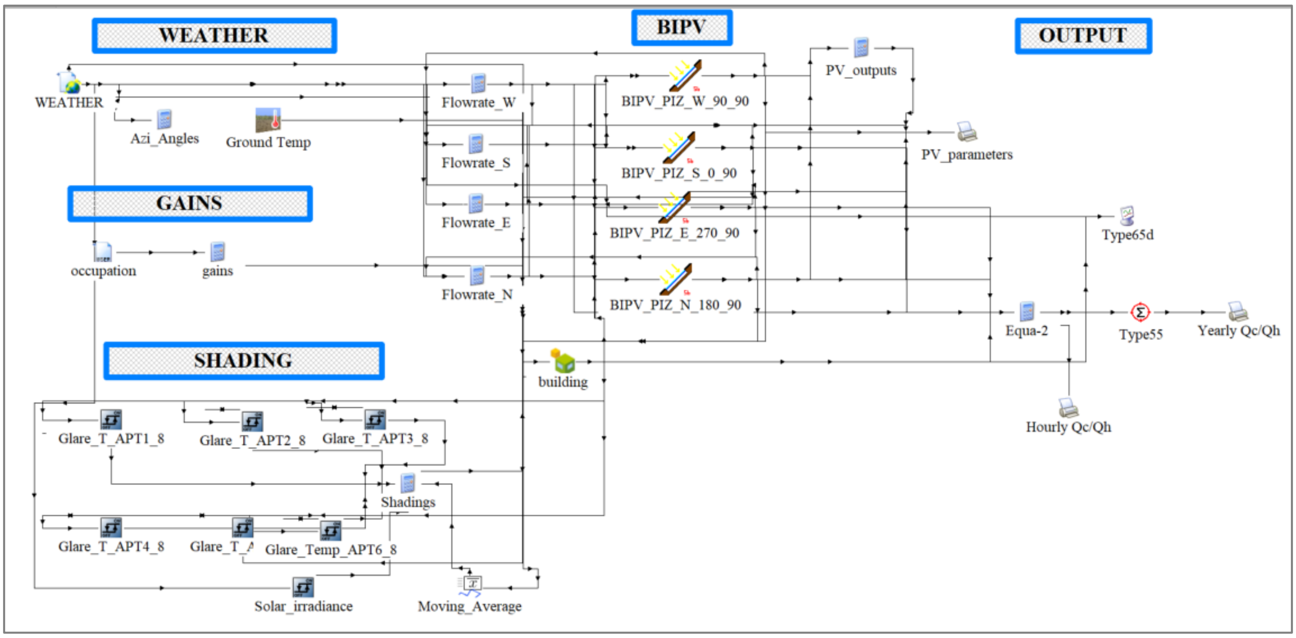


Figure 4.10 TRNSYS Simulation Studio model of the MFH with BIPV façade ventilated

Except for the addition of the PV solutions with their corresponding impacts in the building boundary conditions, the other parts of the simulation models remained the same as explained in section 4.2. So, thanks to these calculations, the hourly and yearly accumulated building heating, cooling, electric demand, and PV production are estimated. In addition, some PV specific outputs such as mass flow rate, different layers temperatures, PV production per façade, etc. were added to the models. These PV outputs were mainly used to check the correct functioning of the models and to identify the temperature trends along the year, so that the thermal impact of these BIPV solutions could be better understood.

4.6 RESULTS

In this section the results from the whole simulation process described in sections 4.2, 0, 4.4 and 4.5 are shown. The subsections correspond to each product and includes energy analysis and simplified economic results.

The energy requirements of the buildings are presented together with the PV production, the self-sufficiency (SS) and the self-consumption (SC). The analysis includes the heating and cooling loads of the building, the optimal distribution of the PV among the façades, the optimal PV peak power to approximately get SS=SC, the PV production and PV yield and, finally, the building heating and cooling consumptions with the BIPV product.

In addition to PV production and building energy requirements, the estimated economic payback time has been calculated. It is considered 14 c€/kWh as average EU-27 electricity price with VAT and without levies (23) and 6 c€/kWh as remuneration from the energy supplied to the grid. However, two different remuneration schemes have been analysed for the electricity not directly consumed:

1) The producer gets 6 c€/kWh because sells the electricity to the grid at market price
2) The producer gets 14 c€/kWh because the surplus is discounted from future consumption

According to these assumptions, a simple calculation of economic payback time is presented for every case under the assumptions of 14-6 c€/kWh (not consumed electricity sell to the grid at market price) and 14-14 c€/kWh (not consumed electricity discounted from future consumption), in order to roughly asses the economic potential of the products. This is based on a simple calculation dividing the BIPV extra cost by yearly remuneration where inflation rates or other yearly variation quantities has not been considered. The BIPV extra cost is calculated with the cost of BIPV product minus the cost of equivalent no-PV product of the whole installation.

4.6.1. Multifunctional BIPV façade cladding system

This section focuses on the main results achieved for the BIPV façade cladding system through the simulations at building level. As shown in Table 4.1, the main applications selected for this product were the multifamily house and the commercial building.

- **Multifamily house**

Initially, all the energy results are explained, covering the different simulations performed in the steps shown in Figure 4.2. Secondly, the cost estimation results are presented, which were calculated based on the PV performance simulations.

Table 4.6 gathers the results of the different energy simulations performed to the various scenarios of the multifamily house with the BIPV cladding solution. In this case, there are 6 different scenarios, based on the 3 climates and the different building orientations, as shown in Figure 4.11. Besides the location and orientation, the insulation thickness added as retrofit for each case is also mentioned. It is worthy to highlight that the original walls of the buildings in Spain and Brussels had no insulation, while the ones in Sweden had already 5 cm of insulation. Consequently, the required insulation addition in the retrofit of the Swedish case is lower, as the original wall was already better insulated.

Table 4.6 Summary of energy results of the MFH case with the BIPV cladding system

CASE			THERMAL NO PV (Sec 4.2)			PV optimization (Sec 0)	PV performance (Sec 4.4)			THERMAL with PV (Sec 4.5)		
Ref	Location (ins. cm)	Or	Qc - NoPV [kWh/m2]	Qh - NoPV [kWh/m2]	Annual building consum. [kWh]	PV capacity (façade distribution) [kW] - [%]	Annual PV prod. [kWh]	SS [%]	SC [%]	Qc - PV [kWh/m2]	Qh - PV [kWh/m2]	Annual PV prod. [kWh]
G_1	MAD - ins **11 cm**	0	18.01	9.25	19425	20 [W50,S38,E12]	16137.92	35	42	17.980	9.235	16516.50
G_2	MAD - ins **11 cm**	90	14.38	7.88	16029	15 [W44,S52,E4]	12463.43	31	40	14.354	7.861	12588.27
G_3	BRU - ins **12 cm**	0	7.48	15.90	16595	25 [W2,S98]	13137.18	22	28	7.472	15.878	15589.21
G_4	BRU - ins **12 cm**	90	5.51	14.54	14481	20 [S100]	11437.8	21	26	5.506	14.516	12532.25
G_5	STO - ins 5 **+ 8 cm**	0	6.27	29.91	29260	21.7* [S100]	12634.79	15	35	6.265	29.885	14339.57
G_6	STO - ins 5 **+ 8 cm**	90	4.27	28.61	27119	34.9* [S100]	22847.22	16	19	4.269	28.586	23061.47

*Cases in which the PV capacity was adapted due to limited surface available

- Ref: Reference number - Or: Orientation of building - ins: insulation thickness - Qc/Qh: Annual cooling demand/heating demand	- consum: consumption - prod: production - SS: Self-sufficiency - SC: Self-consumption

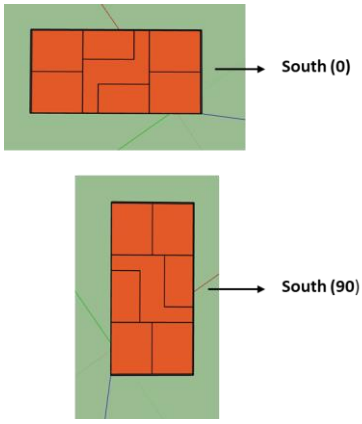


Figure 4.11 MFH building orientations

The first batch of results (thermal – No PV) show the annual cooling and heating load of the building by surface area and the estimated required annual building electric consumption of the heat pump to provide those thermal loads. Due to the higher heating demand in the Nordic climate, the building consumption is considerably higher in this scenario.

Based on that hourly electrical consumption, the PV optimization results show the optimal PV distribution along the different facades in order to best fit that load profile. As explained in section 0, the total PV capacity installed was selected aiming at having a compromise between the self-sufficiency and self-consumption. However, in all cases the available surfaces did not allow to reach such capacities, and therefore, the final PV installed capacity was determined by the maximum available wall opaque surface. This is the case of scenarios G_5 and G_6, in which the objective PV capacity was 35 kW installed in South façade. However, this value was reduced to the maximum available south facing façade in each case. It is also interesting to highlight the different façade distribution between the various scenarios. In Madrid, where the irradiation is higher and the load is more cooling predominant, the tool leads to exploit mainly West and South façade and little East façade. In Stockholm, however, with a lower irradiation availability and heating predominant load, the tool leads to exploit only and as much as possible the south façade of the building.

The third batch of results (PV performance) show the more accurate PV performance outputs with the selected PV capacity installation. The annual PV production, as well as the self-sufficiency and self-consumption (calculated as explained in section 0) are presented. The higher PV production in G_6 should be looked together with the higher PV capacity installed in that case. That is why the PV yield could be more useful to compare the results of the different scenarios. This PV yield is around 800 kWh/kWp for Spain, around 550 kWh/kWp for Belgium and around 600 kWh/kWp for Sweden. Concerning the self-sufficiency, for a stand-alone configuration, the PV installation would be able to cover the demand at a maximum percentage of 35% for Madrid (G_1), 22% for Brussels (G_3) and 16% for Stockholm (G_6). Concerning the self-consumption, it gives an impression of which percentage of the PV production is directly self-consumed onsite in a stand-alone configuration. The values do not go above the 42% in the best case (G_1), showing how much PV produced energy would be “wasted” in a stand-alone configuration or supplied to the grid for a grid-connected scheme. However, if we would check the balance with the annual accumulated PV production and consumption instead of hourly, the balance between PV production and building consumption would raise up to 83% (G_1), 79% (G_3) and 84% (G_6).

Finally, the building thermal simulations with the BIPV installation are shown. As for the baseline thermal simulations, the annual cooling and heating demand is presented per surface area. The comparison of these values before and after the BIPV installation shows the low impact that the installation of BIPV solutions have in the thermal demand of the building. When comparing the thermal behaviour of a standard façade and a

BIPV cladded façade the main differences are: the higher absorptance of the BIPV façade combined with the fact that part of this absorbed energy is transformed in electricity instead of heat, and the additional layers applied to the wall stratigraphy (in this case the 9mm mortar and 3+3mm glass, since the insulation was already considered in the baseline). The detailed analysis of the different layers temperatures leads to the following conclusions:

- During winter, with low temperatures and high irradiance in the vertical façade, the BIPV cladded façade reaches higher temperatures during the day than the bare façade. However, due to the presence of insulation, this effect has very little impact on the internal temperatures. At night, instead, the internal temperature is higher when the PV is present, which could be due to the thermal insulation of the additional layers of the BIPV cladding. As a consequence, the heating demand is slightly lower when the BIPV cladding is present.
- During summer, with high temperatures and low irradiance in the vertical façade, the bare façade reaches higher temperatures during the day than the BIPV cladded wall. This, together with the high external temperatures and the lack of additional layers, lead to higher internal temperatures in the bare case than the BIPV cladded one. As a consequence, the cooling demand is slightly lower when the BIPV cladding is present.

At quantitative level, these impacts on the thermal demand are very low, as can be seen in Table 4.6. On the one hand, the reduction of cooling demand thanks to the BIPV cladding installation varies from 0.05% (G_3) to 0.17% (G_2), mainly due to the extra layers of the BIPV wall. On the other hand, the reduction of the heating demand varies from 0.08% (G_5) to 0.23% (G_2), mainly due to the extra layers of the BIPV wall and a little part due to the higher absorptance of the BIPV cladding and consequent higher wall temperatures during winter. However, it can be concluded that the thermal impact of the installation of such BIPV solution is negligible.

Finally, the TRNSYS simulation also estimated the annual PV production, which is in all the cases higher than the one calculated through BIMSOLAR. As they are different software that model the PV systems in a different way, it was expected to get slightly different values. In the TRNSYS model only the PV product is modelled, without considering any performance ratio of the rest of the losses of the system, such as wiring, MPPT, inverters and so on, while the BIMsolar model does, being therefore its PV performance results more accurate.

According to the previous PV production data, self-consumption, BIPV extra cost and the two economic schemes based on different remuneration of the electricity injected to the grid (6 c€/kWh or 14 c€/kWh) described at the beginning of this section (4.6), the payback time is calculated. Results are shown in Table 4.7.

Table 4.7 Summary of economic payback time results of the MFH case with the BIPV cladding system

Ref	Self-consumed [kWh/y]	Supplied to grid [kWh/y]	BIPV extra cost [€]	Payback time 14-6 c€ [years]	Payback time 14-14 c€ [years]
G_1	6771	9367	36640	23,7	16,0
G_2	4995	7468	27480	23,5	15,5
G_3	3712	9425	45800	41,5	24,7
G_4	3021	8417	36681	38,9	22,7
G_5	4480	8155	39780	34,9	22,2
G_6	4393	18454	63976	36,7	19,9

The economic payback time under the 14-6 scheme goes from 23 year for Madrid up to 41 year in one Brussels case. The differences are mainly due to much higher yields in Madrid case due to higher irradiation, but also due to higher self-consumption rates that reaches 40-42% for Madrid compared to 28% for G_3 case. The worst payback time cases are strongly improved under the 14-14 scheme, as the self-consumption rate does not affect the results. In this case, the values are reduced below the threshold of 25 years that is the standard PV lifespan.

- **Commercial building**

As presented for the previous case, initially, all the energy results are explained, followed by the cost estimation results.

Table 4.8 gathers the results of the different energy simulations performed to the various scenarios of the commercial building with the BIPV cladding solution. In this case, as the building is not symmetric, there are 12 different scenarios, based on the 3 climates and the four different building orientations, as shown in Figure 4.12. The building stratigraphy used for this case are the same as for the single-family house. The original walls of the buildings in Spain and Brussels had no insulation, while the ones in Sweden had already 10 cm of insulation. Consequently, the required insulation addition in the retrofit of the Swedish case is lower, as the original wall was already better insulated. Moreover, another difference of the commercial case is that the thermal simulations with the PV installation have not been performed since its impact in the thermal demand of the building was evidenced as negligible in the multifamily house, as aforementioned.

Table 4.8 Summary of energy results of the COM case with the BIPV cladding system

CASE			THERMAL NO PV (Sec 4.2)			PV optimization (Sec 0)	PV performance (Sec 4.4)		
Ref	Location (ins. cm)	Or	Qc - NoPV [kWh/m2]	Qh - NoPV [kWh/m2]	Annual building consum. [kWh]	PV capacity (façade distribution) [kW] - [%]	Annual PV prod. [kWh]	SS [%]	SC [%]
G_1	MAD - ins **11 cm**	0	37.80	81.40	54732	30.3* [W26,S66,E9]	24579	27	61
G_2	MAD - ins **11 cm**	90	39.58	85.69	57355	29.24* [W43,S37,E20]	22553	25	65
G_3	MAD - ins **11 cm**	180	35.79	88.58	56904	20 [W8,S92]	16965	20	68
G_4	MAD - ins **11 cm**	270	40.33	85.24	57312	25 [W40,S37,E23]	19459	23	67
G_5	BRU - ins **12 cm**	0	5.39	110.07	53041	30 [S69,E31]	16239	15	48
G_6	BRU - ins **12 cm**	90	5.45	112.84	54266	20 [W6,S41 E53]	10461	10	52
G_7	BRU - ins **12 cm**	180	4.66	114.86	54804	20 [S100]	11155	11	54
G_8	BRU - ins **12 cm**	270	5.68	112.74	54298	25 [W7,S41 E52]	13061	12	50
G_9	STO - ins 10 + **4 cm**	0	5.69	165.06	86947	30 [W17,S51 E32]	17451	11	53

G_10	STO - ins 10 + **4 cm**	90	5.88	167.28	88074	30 [W27,S28 E45]	16403	10	53
G_11	STO - ins 10 + **4 cm**	180	5.01	169.24	88589	30 [W2,S71 E27]	18540	11	54
G_12	STO - ins 10 + **4 cm**	270	5.67	166.93	87825	30 [W15,S23,E62]	16441	10	53

*Cases in which the PV capacity was adapted due to limited surface available

- Ref: Reference number - Or: Orientation of building - ins: insulation thickness - Qc/Qh: Annual cooling demand/heating demand	- consum: consumption - prod: production - SS: Self-sufficiency - SC: Self-consumption

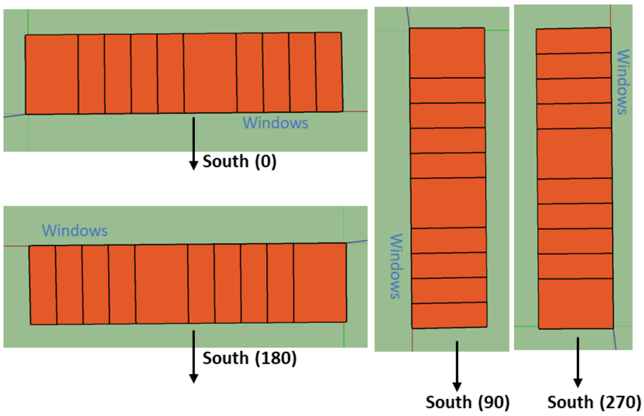


Figure 4.12 COM building orientations

The baseline thermal simulations show the high thermal demand of this building, compared to the residential cases. This is especially remarkable in the case of the heating demand for all locations, and the cooling demand for Madrid cases. This high thermal demand could be caused by different reasons, such as the large surface exposed to the external conditions, such as the ground floor and the roof, the lower internal gains due to lower use hours, occupancy density, appliance density and the lower transparent facade area to allow solar gains. This results in building annual electricity needs of the heat pump in the range of 53 (G_5) to 88 (G_11) MWh.

Based on that thermal loads, the PV optimization results in PV installation distributed along the three facades (west, south, and east) in most of the scenarios. Moreover, the PV installed capacity selected in most of the scenarios is higher than in the MFH case, aiming at covering as much as possible the thermal load. However, the opaque façade surface available is limited and so is the PV modules that can be installed. Given the large roof surface available, the installation of a BIPV roof technology for this type of building could have led to better results. However, this remains out of the scope of this work.

The combination of these two issues (high building demand and low PV installation capacity) results in quite low self-sufficiency (10-27%), i.e. low coverage of the demand by the PV production in a stand-alone configuration. However, if we would check this indicator with the annual accumulated PV production and consumption instead of hourly, the energy balance between production and consumption would raise up to (19-45%). Concerning self-consumption, the values reach 68% in the best case (G_3), showing that in this case, more produced energy would be self-used directly on site, and less wasted in a stand-alone system or supplied to the grid in a grid-connected scheme. Concerning the PV production yield, i.e. the ratio between the actual PV production and the nominal installed PV power, is similar as the one calculated for the MFH: around 800 kWh/kWp for Spain, around 550 kWh/kWp for Belgium and around 600 kWh/kWp for Sweden.

According to the previous PV production data, self-consumption, BIPV extra cost and the two economic schemes based on different remuneration of the electricity injected to the grid (6 c€/kWh or 14 c€/kWh) described at the beginning of this section (4.6), the payback time is calculated. Results are shown in Table 4.9.

Table 4.9 Summary of economic payback time results of the COM case with the BIPV cladding system

Ref	Self-consumed [kWh/y]	Supplied to grid [kWh/y]	BIPV extra cost [€]	Payback time 14-6 c€ [years]	Payback time 14-14 c€ [years]
G_1	14924	9655	55510	20,2	15,8
G_2	14593	7961	53568	20,7	16,6
G_3	11531	5433	36640	18,4	15,1
G_4	13064	6395	45800	20,1	16,4
G_5	7826	8413	54961	33,5	23,8
G_6	5463	4998	36640	33,6	24,6
G_7	6008	5147	36640	31,1	23,0
G_8	6568	6493	45800	34,1	24,6
G_9	9297	8154	54961	29,9	22,1
G_10	8678	7725	54961	31,9	23,5
G_11	10103	8436	54961	27,9	20,8
G_12	8656	7785	54961	31,9	23,4

The economic payback time under the 14-6 scheme goes from 18 years for Madrid up to 34 years in one Brussels case. Similar than MFH building, the differences are mainly due to much higher yields in Madrid case due to higher irradiation, but also due to higher self-consumption rates that reaches 61-68% for Madrid compared to 48-55% for Brussels and Stockholm cases. The 14-6 payback time results are strongly improved under the 14-14 scheme. In this case, all the values are reduced below the standard PV lifespan threshold of 25 years.

4.6.2 CIGS on metal roof and façade systems

This section focuses on the main results achieved for the CIGS on metal roof and facade system through the simulations at building level. As shown in Table 4.1, the main applications selected for this product were the single family house for the roof integration and the industrial building for the façade integration.

- **Single family house – CIGS on metal BIPV roof**

As explained for the previous cases, initially all the energy results are explained, covering the different simulations performed in the steps shown in Figure 4.2, and secondly, the cost estimation results are presented, which were calculated based on the PV performance simulations. In this case, the BIPV solution is applied to the roof and corresponds to the CIGS on metal roof system developed within T4.2.

Table 4.10 gathers the results of the different energy simulations performed to the various scenarios of the single-family house with the CIGS on metal BIPV roof solution. In this case, there are 12 different scenarios, based on the 3 climates and the 4 different building orientations, as shown in Figure 4.13Figure 4.. As explained before, the standard retrofitting did not consider the installation of insulation on the roof since the already existing roof compositions presented acceptable thermal transmittance values (Uroof = 0.235 W/m^{2}K (MAD), 0.196 W/m^{2}K (BRU), and 0.173 W/m^{2}K (STO)).

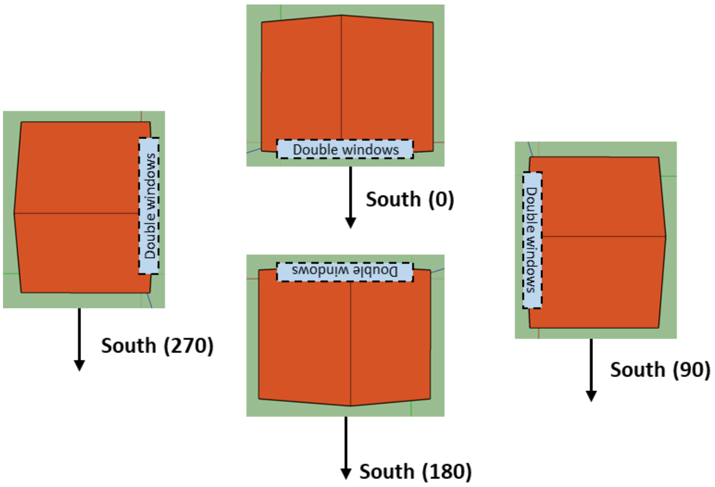


Figure 4.13 SFH building orientations

Table 4.10 Summary of energy results of the SFH case with the CIGS on metal BIPV roof system

CASE			THERMAL NO PV (Sec 4.2)			PV optimization (Sec 0)	PV performance (Sec 4.4)			THERMAL with PV (Sec 4.5)		
Ref	Location	Or	Qc - NoPV [kWh/m2]	Qh - NoPV [kWh/m2]	Annual building consum. [kWh]	PV capacity (façade distribution) [kW] - [%]	Annual PV prod. [kWh]	SS [%]	SC [%]	Qc - PV [kWh/m2]	Qh - PV [kWh/m2]	Annual PV prod. [kWh]
G_1	MAD	0	3.368	31.83	1735	31.5* [W14,E86]	3750	47	22	3.287	31.914	3961.85
G_2	MAD	90	3.578	34.01	1849	27* [S100]	3783	47	23	3.492	34.196	4061.58
G_3	MAD	180	3.430	35.11	1893	30.9* [W12,E88]	3684	46	24	3.375	35.158	3886.59
G_4	MAD	270	3.524	33.97	1844	27* [S100]	3783	46	23	3.469	34.091	4059.65
G_5	BRU	0	0	44.49	2216	36* [W25,E75]	2841	28	22	0	44.522	2702.44
G_6	BRU	90	0	45.89	2283	27* [S100]	2424	27	25	0	45.977	2431.70
G_7	BRU	180	0	46.71	2321	39* [W31,E69]	3078	29	22	0	46.732	2924.24
G_8	BRU	270	0	45.97	2286	27* [S100]	2424	27	25	0	46.020	2431.05

G_9	STO	0	0.0050	68.53	3794	42.9* [W37,E63]	3177	20	24	0.0045	68.543	3049.50
G_10	STO	90	0.0066	69.73	3857	27* [S100]	2452	19	30	0.0061	69.801	2365.27
G_11	STO	180	0.0046	70.76	3905	42.9* [W37,E63]	3177	20	25	0.0042	70.768	3049.31
G_12	STO	270	0.0061	69.82	3860	27* [S100]	2452	19	29	0.0058	69.862	2364.41

*Cases in which the PV capacity was adapted due to limited surface available

- Ref: Reference number
- Or: Orientation of building
- ins: insulation thickness
- Qc/Qh: Annual cooling demand/heating demand
- consum: consumption
- prod: production
- SS: Self-sufficiency
- SC: Self-consumption

The baseline thermal simulations show a very low cooling demand, indeed null for Brussels and almost null for Stockholm, together with a considerably high heating demand when comparing with the other residential case, i.e. the multifamily house. This is consistent with the much lower occupancy density in the SFH and therefore lower internal heat gains. Moreover, the lower window to wall ratio of the modelled SFH results in lower solar heat gains entering, which limits the cooling demand in summer but results in higher heating demand in winter. As a consequence, the building heat pump annual consumption is considerably lower than in previous cases (1-4 MWh). These results were compared and validated with the similar cases presented in (24).

The PV optimization results show how the tool suggests to use the maximum possible South facing roof surface when the building is oriented North-South, and to split the installation between the two roof faces, maximizing the East one, when the building is oriented West-East. It is important to mention that the PV final capacity installed had to be adapted to the maximum available roof surface in all the scenarios, forcing thus to install a lower PV capacity than the one aiming at Self-sufficiency equal Self-consumption.

Based on the selected PV installation, simulations performed in BIMsolar show the more accurate PV performance outputs. Concerning the PV production, it is noteworthy the high impact of the orientation in the achieved output, in some cases even more than the PV installed capacity. When comparing the PV output of G_1 and G_2 for example, the annual energy produced by the second case is higher, even if it has almost 4 kW less of PV capacity installed. However, in G_2 all the PV is installed facing South. This impact was not seen in the previous cases in which the PV was applied vertically on the façade. However, in this case the installation on a 25° inclined roof results in this different PV production behaviour. This impact can be also seen when analysing the PV yield in the different cases:

- *Madrid:* PV yield varies from 1200 kWh/kWp when installed in West-East, to 1400 kWh/kWp when PV installed only in South
- *Brussels:* PV yield varies from 800 kWh/kWp when installed in West-East, to 900 kWh/kWp when PV installed only in South
- *Stockholm:* PV yield varies from 740 kWh/kWp when installed in West-East, to 900 kWh/kWp when PV installed only in South

Concerning the self-sufficiency, for a stand-alone configuration, the PV installation would be able to cover the demand at a maximum percentage of 47% for Madrid (G_1, G_2), 29% for Brussels (G_7) and 20% for Stockholm (G_9, G_12). Concerning the self-consumption the values reach 30% in the best case (G_10), showing the large percentage of energy produced (min 70%) that is not possible to self-used directly onsite and therefore should be supplied to the grid or stored when batteries present. However, if we would check the annual balance between the onsite PV production and building consumption instead of hourly, the energy balance would increase to (81-216%). This means that in the scenarios in Spain and Brussels the annual PV production is higher than the annual building consumption, and could be exploited with a different connection scheme, such as including storage onsite or connected to the grid not to lose the produced energy that cannot be self-used at the production moment.

The last batch of results presented in Table 4.10 corresponds to the building thermal simulations with the BIPV roof installation. The comparison of the heating and cooling demand before and after the BIPV installation shows the low impact that the installation of these BIPV solutions have in the thermal demand of the building, still the impact is slightly higher than the one found for the BIPV cladding system. When comparing the thermal behaviour of a standard non-ventilated roof and a BIPV ventilated roof, the main differences are: the higher absorptance of the BIPV roof combined with the fact that part of this absorbed energy is transformed in electricity instead of heat, the addition of the ventilation airgap of 5 cm, and the additional layers applied to the roof (in this case mainly the 3mm Aluminium sheet).

These roof differences result in a reduction of cooling demand and a little increase of the heating demand when the PV roof is present. The cooling demand decreases up to 2.4% for Madrid and 9.6% in Stockholm. The cooling load in Stockholm is almost 0 (around 0.005 kWh/m2), so the reduction of that parameter can be considered irrelevant. However, for the Spanish scenario the reduction of Qcool between 1.5 to 2.4% is more relevant. This cooling reduction is mainly due to the presence of the air ventilation gap, that helps to cool down slightly the roof temperature and therefore the cooling needs. Moreover, this cooling reduction is not affected by the PV installation orientation (East-West or South inclination). On the other hand, the heating demand in presence of the BIPV roof is increased in all the cases, varying from 0.006% (G_11) to 0.54% (G_2). This heating demand increase is higher when the PV is installed facing South than East-West, independently of the lower covered surface area. This heating increase could be also explained thanks to the air ventilation gap that cools down slightly the roof temperature and therefore increases the heating needs.

Finally, the TRNSYS simulation also estimated the annual PV production, which in the Spanish scenarios is higher than the one calculated through BIMSOLAR, and lower in the rest. As explained for the MFH case, the software used are different and model differently the PV systems, so these different results were expected and considered acceptable, always considering the ones from BIMSolar more accurate in terms of PV production.

According to the previous PV production data, self-consumption, BIPV extra cost and the two economic schemes based on different remuneration of the electricity injected to the grid (6 c€/kWh or 14 c€/kWh) described at the beginning of this section (4.6), the payback time is calculated. Results are shown in Table 4.11.

Table 4.11 Summary of economic payback time of the SFH case with the CIGS on metal BIPV roof system

Ref	Self-consumed [kWh/y]	Supplied to grid [kWh/y]	BIPV extra cost [€]	Payback time 14-6 c€ [years]	Payback time 14-14 c€ [years]
G_1	820	2930	3097	10,5	5,9
G_2	864	2919	2654	8,8	5,0
G_3	878	2806	3038	10,3	5,8
G_4	851	2931	2654	8,9	5,0
G_5	623	2218	3539	15,9	8,8
G_6	612	1812	2654	13,4	7,8
G_7	679	2399	3834	15,8	8,8
G_8	610	1814	2654	13,5	7,8
G_9	761	2416	4218	16,5	9,4
G_10	727	1725	2654	12,7	7,7
G_11	795	2382	4218	16,3	9,4
G_12	723	1729	2654	12,7	7,7

The economic payback time under the 14-6 scheme goes from 8 years for Madrid up to 17 years in one Brussels case. Contrary to other combination of BIPV products with building typology, the self-consumption rate is similar for all the cases, between 23-30%, so the main difference is due to much higher yields in Madrid case compared to Brussels and Stockholm, due to higher irradiation. The payback time cases are reduced about 4-7 years under the 14-14 scheme. Both under the 14-6 and 14-14 remuneration schemes, the payback times are below the threshold of 25 years that is the standard PV lifespan.

- **Industrial building – CIGS on metal BIPV facade**

As presented for the previous cases, initially, all the energy results are explained, followed by the cost estimation results. In this case, the BIPV solution is applied to the facade and corresponds to the eFlex CIGS modules glued to a metal facade system.

Table 4.12 gathers the results of the different energy simulations performed to the various scenarios of the industrial building with the CIGS on metal BIPV façade solution. In this case, as the building is not symmetric, there are 12 different scenarios, based on the 3 climates and the four different building orientations, as shown in Figure 4.14. The building stratigraphy used for this case are the same as for the single-family house and commercial building. The original walls of the buildings in Spain and Brussels had no insulation, while the ones in Sweden had already 10 cm of insulation. Consequently, the required insulation addition in the retrofit of the Swedish case is lower, as the original wall was already better insulated. Same as for the commercial case, also for this case the thermal simulations with the PV installation have not been performed since its impact in the thermal demand of the building was evidenced as negligible in the multifamily house, as explained before.

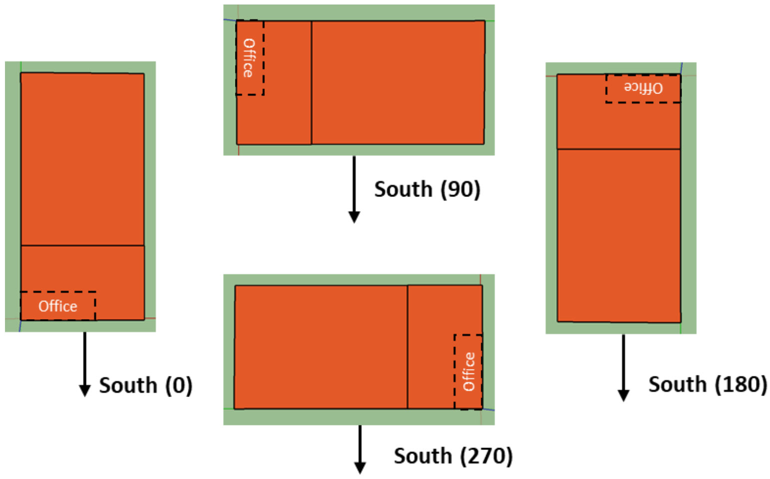


Figure 4.14 IND building orientations

Table 4.12 Summary of energy results of the IND case with the CIGS on metal BIPV façade system

CASE			THERMAL NO PV (Sec 4.2)			PV optimization (Sec 0)	PV performance (Sec 4.4)		
Ref	Location (ins. cm)	Or	Qc - NoPV [kWh/m2]	Qh - NoPV [kWh/m2]	Annual building consum. [kWh]	PV capacity (façade distribution) [kW] - [%]	Annual PV prod. [kWh]	SS [%]	SC [%]
G_1	MAD - ins **11 cm**	0	14.58	6.01	22191	20 [W46,S54]	16396	26	35
G_2	MAD - ins **11 cm**	90	14.49	6.12	22208	20 [W30,S70]	17222	26	33
G_3	MAD - ins **11 cm**	180	14.61	6.17	22392	20 [W39,S61]	16798	26	34
G_4	MAD - ins **11 cm**	270	14.50	6.05	22151	20 [W29,S71]	17276	26	33
G_5	BRU - ins **12 cm**	0	0.55	9.28	10973	20 [S100]	12039	21	19
G_6	BRU - ins **12 cm**	90	0.54	9.35	11036	20 [S100]	11314	20	20
G_7	BRU - ins **12 cm**	180	0.55	9.38	11083	20 [S100]	12039	21	19
G_8	BRU - ins **12 cm**	270	0.55	9.30	10998	20 [S100]	11314	20	20
G_9	STO - ins 10 + **4 cm**	0	2.08	38.69	52231	23.58* [S100]	15791	8	26
G_10	STO - ins 10 + **4 cm**	90	2.08	38.73	52268	65 [S100]	40925	12	16
G_11	STO - ins 10 + **4 cm**	180	2.09	38.78	52337	25.11* [S100]	16816	8	26

G_12	STO - ins 10 + **4 cm**	270	2.07	38.69	52229	65 [S100]	40925	12	16

*Cases in which the PV capacity was adapted due to limited surface available

- Ref: Reference number - Or: Orientation of building - ins: insulation thickness - Qc/Qh: Annual cooling demand/heating demand	- consum: consumption - prod: production - SS: Self-sufficiency - SC: Self-consumption

The baseline thermal simulations of the industrial case show a moderate thermal demand of this building. This is due to the peculiarities of this building, such as the very low transparent façade area (only windows in the office zone), the high internal gains in the production area due to the industrial activity (45 W/m^2) (16) (25), and the relaxed temperature set-points in the production and storage area (Set point heating: 7°C, set point cooling 30°C). The demand in Spain is very cooling dominant, as shown in Figure 4.15Figure 4., while in the other locations the heating is predominant.

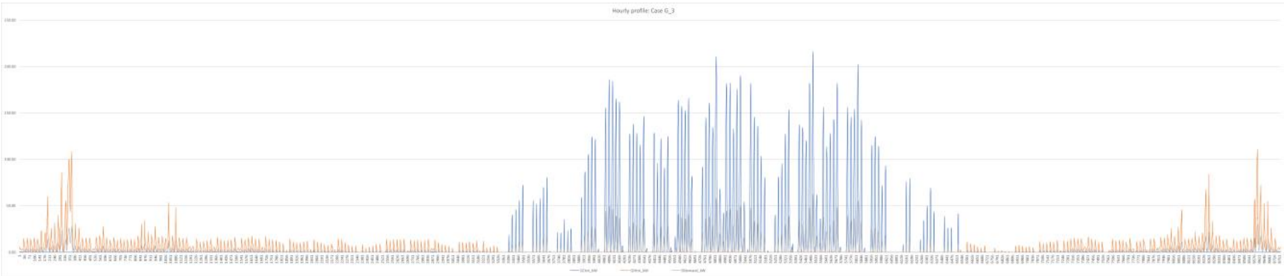


Figure 4.15 Hourly heating, cooling and electric demand of IND case in Madrid (G_3)

Based on those thermal load profiles, the PV optimization tool suggests installing the PV along the West and South façades for the Spanish climate to better fit the demand profile. For the Belgian and Swedish climates, instead, it suggests installing the PV only on the South façade. When the building is oriented with the smaller façade facing South (orientation 0 and 180) the installed PV capacity is limited to the maximum façade surface available, resulting thus in lower PV power installed in those scenarios.

Due to the different integration (roof/façade) and orientations, the PV yield of this case is very different to the one calculated for the SFH, even if the installed PV products are similar. In this case, with the vertical façade integration, the PV yield is around 840 kWh/kWp for Spain, around 580 kWh/kWp for Belgium and around 650 kWh/kWp for Sweden. The impact of the orientation in this case is very little compared to the one found for the roof installation.

Concerning self-sufficiency, it is very different depending on the location, as it ranges from 8% (G_9, G_11) to 26% (G_1, G_2, G_3, G_4). Concerning the self-consumption, the values reach 33-35% in the Spanish cases (G_1, G_2, G_3, G_4), showing the little energy that is direct self-used in a stand-alone configuration for this case. However, if we do not consider the hourly production-consumption matching, but the annual accumulated onsite production-consumption balance, this parameter raises up to 74-78% for Madrid, 103-110% for Brussels and 30-78% for Stockholm. The high difference for Stockholm is due to difference on peak power PV installation based on limited available surface when small façade is the one facing South. In the Belgian cases , more energy is produced onsite thanks to the PV installation than consumed by the building at an annual basis, i.e. resulting in a positive annual net energy balance building.

According to the previous PV production data, self-consumption, BIPV extra cost and the two economic schemes based on different remuneration of the electricity injected to the grid (6 c€/kWh or 14 c€/kWh) described at the beginning of this section (4.6), the payback time is calculated. Results are shown in Table 4.13.

Table 4.13 Summary of economic payback time of the IND case with the CIGS on metal BIPV roof system

Ref	Self-consumed [kWh/y]	Supplied to grid [kWh/y]	BIPV extra cost [€]	Payback time 14-6 c€ [years]	Payback time 14-14 c€ [years]
G_1	5678	10718	19663	13,4	8,5
G_2	5694	11529	19663	13,0	8,1
G_3	5735	11063	19663	13,2	8,3
G_4	5653	11624	19663	13,0	8,0
G_5	2263	9776	19663	21,5	11,6
G_6	2235	9079	19663	22,6	12,3
G_7	2291	9748	19663	21,4	11,6
G_8	2216	9098	19663	22,7	12,3
G_9	4170	11621	23182	17,8	10,4
G_10	6414	34512	63904	21,3	11,1
G_11	4335	12481	24687	17,9	10,4
G_12	6367	34559	63904	21,3	11,1

The economic payback time under the 14-6 scheme goes from 13 years for Madrid up to 23 years in one Brussels case. This is due to different self-consumption rates, that in Madrid are about 33-35% while for Brussels and Stockholm are about 16-26%, and also due to much higher yields in Madrid case compared to Brussels and Stockholm, due to higher irradiation. The payback time cases are reduced between 5-10 years under the 14-14 scheme.

Both under the 14-6 and 14-14 remuneration schemes and both types of buildings, the payback times of CIGS on metal product are below the threshold of 25 years that is the standard PV lifespan. These good results are due to the low BIPV cost increase (about 1€/Wp) compared to no-PV product.

4.6.3 BIPV glass façade systems

This section focuses on the main results achieved for the BIPV glass facade system through the simulations at building level. As shown in Table 4.1, the main applications selected for this product were the multifamily house and the industrial building. In both cases the system is integrated vertically in the opaque façade with a rear ventilation gap.

- **Multifamily house**

In this section, all the energy results are explained covering the different simulations performed in the steps shown in Figure 4.2. Secondly, the cost estimation results are presented, which were calculated based on the PV performance simulations.

Table 4.14 gathers the results of the different energy simulations performed to the various scenarios of the multifamily house with the BIPV glass facade solution. This case differs with the one presented in section 4.6.1 only in the applied BIPV solution. This means that the analysed 6 scenarios of boundary conditions are the same, based on the 3 climates and the different orientations shown in Figure 4.11. Moreover, the building thermal baseline results, i.e. without the PV solution, are also the same as the ones shown in Table 4.6. However, the rest of the outputs are different in this case due to the diverse PV solution applied, which has different features than the BIPV cladding solution.

Table 4.14 Summary of energy results of the MFH case with the BIPV glass facade system

CASE			THERMAL NO PV (Sec 4.2)			PV optimization (Sec 0)	PV performance (Sec 4.4)			THERMAL with PV (Sec 4.5)		
Ref	Location (ins. cm)	Or	Qc - NoPV [kWh/m2]	Qh - NoPV [kWh/m2]	Annual building consum. [kWh]	PV capacity (façade distribution) [kW] - [%]	Annual PV prod. [kWh]	SS [%]	SC [%]	Qc - PV [kWh/m2]	Qh - PV [kWh/m2]	Annual PV prod. [kWh]
G_1	MAD - ins **11 cm**	0	18.01	9.25	19425	20 [W50,S38,E12]	16905.89	36	41	17.95	9.25	16715.86
G_2	MAD - ins **11 cm**	90	14.38	7.88	16029	15 [W44,S52,E4]	13881.54	34	39	14.33	7.87	12767.13
G_3	BRU - ins **12 cm**	0	7.48	15.90	16595	25 [W2,S98]	13855.99	23	27	7.44	15.90	15559.18
G_4	BRU - ins **12 cm**	90	5.51	14.54	14481	20 [S100]	11951.97	21	26	5.47	14.54	12562.89
G_5	STO - ins 5 **+ 8 cm**	0	6.27	29.91	29260	35 [S100]	23332.84	17	22	6.20	29.95	23182.10
G_6	STO - ins 5 **+ 8 cm**	90	4.27	28.61	27119	35 [S100]	23436.72	16	19	4.22	28.64	23182.10

*Cases in which the PV capacity was adapted due to limited surface available

- Ref: Reference number - Or: Orientation of building - ins: insulation thickness - Qc/Qh: Annual cooling demand/heating demand	- consum: consumption - prod: production - SS: Self-sufficiency - SC: Self-consumption

As shown in Table 4.2, for the PV optimization process, the same inputs were used for the BIPV glass façade system and the BIPV cladding system, as both integrate the same PV technology (c-Si cells). This leads to same PV distribution among the façade and same PV capacity proposal in both cases, exploiting the three orientations for the Spanish climate, and only the South facing façade for the Nordic climate. However, when checking the final PV capacity to be simulated in BIMSolar, the final PV solution features were used, as shown in Figure 4.6. The higher PV efficiency of the BIPV glass façade system (15%) compared to the one of the BIPV cladding (9%), results in lower façade area required to reach the total PV capacity. Consequently, in all the scenarios with the BIPV glass façade system the installed PV capacity was the one suggested to reach similar SS and SC, with no scenario in which it had to be adapted due to lower available facade surface.

The PV performance results calculated with BIMSolar show the more accurate outputs that could be achieved with such façade BIPV installations. The annual PV production is obviously mainly dependent on the installed capacity and the location. That is why the higher annual PV production in Stockholm should be looked together with the higher installed PV power in those scenarios. Therefore, when checking the PV yield for the different scenarios, it is around 880 kWh/kWp for Spain, around 570 kWh/kWp for Belgium and around

670 kWh/kWp for Sweden. Regarding the capacity of the PV installation to cover the building demand in a stand-alone configuration, the self-sufficiency would be in the best cases 36% for Madrid (G_1), 23% for Brussels (G_3) and 17% for Stockholm (G_5). On the other hand, regarding the capacity of direct self-used the PV production, the self-consumption indicator would be in the best cases 41% for Madrid (G_1), 27% for Brussels (G_3) and 22% for Stockholm (G_5). This latter parameter gives an impression of how much PV produced would be directly self-used onsite, and the opposite, i.e. 100% - SC, how much PV produced would be “wasted” in a stand-alone configuration without batteries, that could be otherwise stored if batteries present or supplied to the grid for a grid-connected scheme. However, if we check the annual balance between onsite production and consumption, instead the hourly matching, the demand coverage percentage would go up to 87% (G_1), 83% (G_4) and 80% (G_6).

Finally, the thermal simulations of the building with the BIPV installation show the new building heating and cooling demands. When comparing the thermal behaviour of a standard façade (the one used in the initial thermal simulations) and a BIPV ventilated façade the main differences are: the higher absorptance of the BIPV façade combined with the fact that part of this absorbed energy is transformed in electricity instead of heat, the addition of the ventilation airgap of 5 cm, and the additional layers applied to the facade (in this case mainly the 4+4mm glass). These features are applied only to the part of the façade that is covered with the BIPV facade system, remaining the rest of the façade as it was in the baseline case.

These façade behaviour differences have a low impact in the thermal demand of the building, causing a slight decrease of the cooling demand and different impact in the heating demand depending on the scenario. Thanks to the presence of the ventilation airgap, that helps to cool down slightly the wall temperature, the building cooling demand with the BIPV façade decreases up to 0.3% for Madrid, 0.7% for Brussels and 1.3% for Stockholm. The impact on the heating demand, instead, is much lower and different for the several scenarios. The presence of the BIPV ventilated façade reduces the heating demand in a 0.01-0.1% for Spain and almost zero (0.002%) for Brussels. This reduction could be due to the higher temperatures reached by the PV surface in winter (vertical positioning, consequently higher direct irradiation in winter) compared to the bare wall, although the impact of this internally is very low when the insulation is present. Moreover, another effect that could contribute to this heating demand reduction is the presence of these additional wall layers (airgap and 4+4mm glass) that could protect slightly more the façade during the night, when there is no irradiation and therefore low stack effect and air flow in the ventilation gap. On the contrary, in Stockholm, the presence of the BIPV ventilated façade increases the heating needs in a 0.09-0.12%. This increase could be due to the presence of the ventilation airgap that cools down slightly the wall and therefore increases the heating demand, being more effective for this climate this effect than the others before mentioned.

Finally, the TRNSYS simulation also estimated the annual PV production, which is in most of the cases a good estimation if compared with the BIMSolar outputs. However, the results achieved by BIMSolar are considered more accurate for this scope.

According to the previous PV production data, self-consumption, BIPV extra cost and the two economic schemes based on different remuneration of the electricity injected to the grid (6 c€/kWh or 14 c€/kWh) described at the beginning of this section (4.6), the payback time is calculated. Results are shown in Table 4.15.

Table 4.15 Summary of economic payback time results of the MFH case with the BIPV glass facade system

Ref	Self-consumed [kWh/y]	Supplied to grid [kWh/y]	BIPV extra cost [€]	Payback time 14-6 c€ [years]	Payback time 14-14 c€ [years]
G_1	6937	9968	27208	17,0	11,3
G_2	5382	8500	20406	15,8	10,4
G_3	3785	10071	34010	29,5	17,4
G_4	3075	8877	27208	27,8	16,1
G_5	5063	18270	47615	26,0	14,5
G_6	4471	18965	47615	26,7	14,4

The economic payback time under the 14-6 scheme goes from 15 years for Madrid up to 30 years in one Brussels case. This is due to different self-consumption rates, that in Madrid are about 40% while for Brussels and Stockholm are about 19-27%, and due to much higher yields in Madrid case compared to Brussels and Stockholm, due to higher irradiation. The payback time cases are reduced between 5-6 years for Madrid while for others the decrease is 12 years because of low self-consumption. The payback time is under the threshold of 25 years in Madrid for 14-6 scheme, and for all cases under 14-14 scheme, with a minimum of about 10 years.

- **Industrial building**

As presented for the previous case, initially, all the energy results are explained, followed by the cost estimation result of the industrial building with the implementation of the BIPV glass façade.

Table 4.16 gathers the results of the different energy simulations performed to the various scenarios of the industrial building with the BIPV glass facade solution. This case differs with the one presented in section 4.6.2 only in the applied BIPV solution. This means that the analysed 12 scenarios of boundary conditions are the same, based on the 3 climates and the different orientations shown in Figure 4.14. Moreover, the building thermal baseline results, i.e. without the PV solution, are also the same as the ones shown in

Table 4.12. However, the rest of the outputs are different in this case due to the diverse PV solution applied, which has different features than the CIGS on metal facade solution.

Table 4.16 Summary of energy results of the IND case with the BIPV glass facade system

CASE			THERMAL NO PV (Sec 4.2)			PV optimization (Sec 0)	PV performance (Sec 4.4)		
Ref	Location (ins. cm)	Or	Qc - NoPV [kWh/m2]	Qh - NoPV [kWh/m2]	Annual building consum. [kWh]	PV capacity (façade distribution) [kW] - [%]	Annual PV prod. [kWh]	SS [%]	SC [%]
G_1	MAD - ins **11 cm**	0	14.58	6.01	22191	20 [W37,S63]	17150	26	33
G_2	MAD - ins **11 cm**	90	14.49	6.12	22208	20 [W29,S71]	17737	26	32

G_3	MAD - ins **11 cm**	180	14.61	6.17	22392	20 [W35,S65]	17211	26	34
G_4	MAD - ins **11 cm**	270	14.50	6.05	22151	20 [W28,S72]	17779	26	32
G_5	BRU - ins **12 cm**	0	0.55	9.28	10973	20 [S100]	11956	21	19
G_6	BRU - ins **12 cm**	90	0.54	9.35	11036	20 [S100]	11973	21	19
G_7	BRU - ins **12 cm**	180	0.55	9.38	11083	20 [S100]	11956	21	19
G_8	BRU - ins **12 cm**	270	0.55	9.30	10998	20 [S100]	11973	21	19
G_9	STO - ins 10 + **4 cm**	0	2.08	38.69	52231	48.88* [S100]	30314	11	19
G_10	STO - ins 10 + **4 cm**	90	2.08	38.73	52268	70 [S100]	47050	13	15
G_11	STO - ins 10 + **4 cm**	180	2.09	38.78	52337	54.94* [S100]	34072	12	18
G_12	STO - ins 10 + **4 cm**	270	2.07	38.69	52229	70 [S100]	47050	13	14

*Cases in which the PV capacity was adapted due to limited surface available

- Ref: Reference number
- Or: Orientation of building
- ins: insulation thickness
- Qc/Qh: Annual cooling demand/heating demand
- consum: consumption
- prod: production
- SS: Self-sufficiency
- SC: Self-consumption

Same as for the CIGS BIPV façade product, also for the BIPV glass façade product the PV optimization tool suggests installing PV along the West and South façades for the Spanish climate to better fit the demand profile of the IND building. For the Belgian and Swedish climates, instead, it suggests installing the PV only on the South façade. The PV capacity suggested to reach similar SS and SC is almost the same as the proposed for CIGS product, and the final values are very similar in both cases. The capacity proposed is limited by the available façade area in Stockholm G_9 and G_11 cases because the small façade of the building is the one facing South for these cases.

Concerning the PV production, the PV yield of these cases is around 880 kWh/kWp for Spain, around 570 kWh/kWp for Belgium and around 650 kWh/kWp for Sweden. These results are very similar to the ones achieved for the integration of this product in the MFH, as it was expected. Regarding the self-sufficiency of the building i.e. its capacity to fulfil the consumption with PV production, the best values are for Madrid with 26% while for Brussels is 21% and for Stockholm about 12%. On the other hand, regarding the capacity of direct self-used the PV production, the highest values are for Madrid that are between 32-34%, while for Brussels and Stockholm are 19% and between 14-19% respectively. Checking the annual balance between onsite production and consumption (independently on grid connections schemes and hourly matching), the demand coverage would be about 80% for Madrid, 108% for Brussels and between 58-90% for Stockholm. The high difference for Stockholm is due to difference on peak power PV installation based on limited available surface when small façade is the one facing South. The Belgian case shows that more energy is produced onsite thanks to the PV installation than consumed by the building at an annual basis, i.e. resulting in a positive annual net energy balance building.

According to the previous PV production data, self-consumption, BIPV extra cost and the two economic schemes based on different remuneration of the electricity injected to the grid (6 c€/kWh or 14 c€/kWh) described at the beginning of this section (4.6), the payback time is calculated. Results are shown in Table 4.17.

Table 4.17 Summary of economic payback time results of the IND case with the BIPV cladding system

Ref	Self-consumed [kWh/y]	Supplied to grid [kWh/y]	BIPV extra cost [€]	Payback time 14-6 c€ [years]	Payback time 14-14 c€ [years]
G_1	5731	11419	27208	18,0	11,2
G_2	5758	11979	27208	17,5	10,8
G_3	5773	11439	27208	17,9	11,2
G_4	5713	12066	27208	17,5	10,8
G_5	2284	9672	27208	29,9	16,1
G_6	2308	9664	27208	29,8	16,1
G_7	2313	9644	27208	29,8	16,1
G_8	2288	9684	27208	29,8	16,1
G_9	5700	24614	66503	28,9	15,6
G_10	6860	40190	95229	28,0	14,4
G_11	6028	28044	74747	29,2	15,6
G_12	6812	40237	95229	28,0	14,4

The economic payback time under the 14-6 scheme goes from 17 years for Madrid up to 30 years in one Brussels case. This is due to different self-consumption rates, that in Madrid are about 32-34% while for Brussels and Stockholm are about 14-19%, and due to much higher yields in Madrid case compared to Brussels and Stockholm, due to higher irradiation. The payback time cases are reduced between 7 years for Madrid while for others the decrease is 13-14 years because the low self-consumption effect is eliminated in this scheme. The payback time is under the threshold of 25 years in Madrid for 14-6 scheme, and for all cases under 14-14 scheme, with a minimum of about 11 years.

5 SUMMARY AND CONCLUSIONS

Within this task (T4.5) of the project, different simulation studies have been performed to support the design of the different building skin systems developed under T4.1, T4.2 and T4.3.

5.1 FEM SIMULATIONS

First, a **thermal simulation** of the **multifunctional BIPV façade cladding** system developed under T4.1 was done **with FEM** (finite element method) software tool, where maximum temperatures up to nearly 92,3 ºC were found for a façade facing South located at Morbegno (Italy). The model included the hourly temperature, incident radiation and conservative convection coefficient.

Regarding the **BIPV glass façade system**, several **mechanical FEM simulations** were done through a long redesign process changing components geometries, thicknesses and positions in combination with two glazing systems of 4+4 mm and 6+6 mm. However, only the results of final system are shown in this report. These results show that the stresses achieved in the glazing and other structural parts are within the allowable range, both for 1400 Pa and 2400 Pa wind pressure scenarios and 4+4 and 6+6 glazing configurations. The maximum deformation is within the allowable range for all cases except for the combination of 4+4 mm glazing under 2400 Pa. This should be considered for applications where required wind pressure is 2400 Pa, but for project demonstrator purposes, the required wind pressure is 1400 Pa. Moreover, it should be considered that there is not a clear criteria regarding maximum deformation values for glass, as they are not normally linked to structural purposes but to avoid causing alarm on building users (26).

5.2 BUILDING SIMULATIONS

In another set of simulations, the products have been analysed from **energy building simulations approach**. The building energy demand has been analysed with TRNSYS, then it was obtained the optimal distribution of the PV among the façades using EURACs internal developed simulation tool, the PV production was obtained with BIMSolar and, finally, in most of the cases the building energy demand was analysed again but including the BIPV solutions.

5.2.1. Self-Sufficiency (SS) and Self-Consumption (SC)

In general, it is difficult to match the production with the demand, so to get high **ratios of self-consumption (SC) and self-sufficiency (SS).** The self-sufficiency values are between 8-47% with an average of 22%, while the self-consumption is between 14-68% with an average of 32%. This is the reason why self-consumption without surpluses should include a battery system, or the importance of self-consumption with surpluses and net balance (also called net metering). Results are shown in Table 5.1. As a reminder, the formula of SS and SC are shown below.

$$SC = \frac{Self - consumed\ energy}{Energy\ generated} \qquad SS = \frac{Self - consumed\ energy}{Energy\ consumption}$$

Regarding **locations**, Madrid has the highest values of SS and SC with averages of 31% and 39% respectively, Brussels has intermediate values of SS and SC with averages of 21% and 28% respectively and Stockholm has the lowest average value of SS with 14% and 28% of SC. The reason why Madrid has better SS and SC values is because the energy demand is more distributed along the year, with lower heating demand in the winter than other locations and significant cooling demand during the summer.

Regarding **building types**, there are some differences in the SS and SC rates that can be explained due to different energy demand profiles. In the case of single-family house (SFH), only simulated with CIGS on metal integrated in the roof, the average SS and SC are 31% and 25% respectively, which are relatively good values. For the multifamily house (MFH) the average SS and SC are 24% and 30% respectively. For the commercial building (COM), only simulated with BIPV façade cladding product, the average SS and SC are 15% and 57% respectively, this big difference is because in most cases the available surface in the building limited the PV power, so that the required PV power to get SS=SC criteria was not achievable. In other words, the energy demand of the considered commercial building is quite high compared to its available facade surface. Finally, for the industrial building (IND) the average SS and SC are 19% and 24% respectively. As a reminder, the PV peak power was selected in order to get approximately SS=SC (see Figure 4.2, step 3), but the latter PV simulation with BIMSolar yielded lower PV production than expected, so the SC is in general slightly higher than the SS. In addition, the PV installed capacity is limited due to façades available surface in some cases (specially in COM), which causes also higher SC than SS.

Regarding the **products**, the results of SS and SC are not affected significantly, as the main differences come from the building types where they have been analysed. The only parameter that can affect the results is the different power density as it impacts on the maximum PV power that can be installed when façade surface is limited.

Table 5.1 Summary of average SS and SC by location, building type and BIPV product

		SS	SC
General data of complete analysis	MAX	47	68
	MIN	8	14
	AV	22	32
By location (averages)	Madrid	31	39
	Brussels	21	28
	Stockholm	14	28
By building type (averages)	SFH	31	25
	MFH	24	30
	COM	15	57
	IND	19	24
By BIPV product (averages)	BIPV facade cladding (T4.1)	18	48
	CIGS on metal BIPV roof (T4.2)	25	25
	BIPV glass façade system (T4.3)	21	25

5.2.2. Power distribution and final energy impacts due to BIPV

The energy demand profile also determined the **location of the PV**. In **central and northern European locations**, it is mostly required energy during the winter, so the **optimal position for the PV was the South façade**. This fact is also linked with the lower Sun elevation in higher latitudes. On the other hand, **in southern regions** cooling is required during the summer, and thus the PV **can be installed also in west façade** to produce electricity in the afternoon and evening to feed the cooling system. It should be considered that, except in single family house (SFH), the roof has not been included as an option because façades are the interesting application for most of the products developed within WP4 and analysed in this study.

It was expected from the BIPV products to get **active and passive energy impacts**. On the active side, the **PV production is according with the installed peak power of each case**, linked with technology efficiency and the area occupied with the product.

On the passive side, the **installation of the BIPV products has a minimal impact in the building thermal demand**, being in most of the cases negligible. Considering that the **baseline cases already included insulation**, the different thermal behaviour of the BIPV envelope (darker appearance and consequent higher solar absorptance, additional layers to the wall/roof stratigraphy, air ventilation gap in some cases…) resulted in very limited impact inside the building and therefore in its thermal needs. The implementation of the **multifunctional BIPV façade cladding system** in the MFH results in a **heating and cooling demand reduction** of 0.2% each in Madrid, while in the other climates the impact is lower. The installation of the **CIGS roof system** (retro-ventilated) in the SFH results in a **cooling demand reduction** of 1.5-2.4% and a **heating demand increase** of 0.54% in Spain. The implementation of the **BIPV glass façade system** (retro-ventilated) results in a **negligible impact in the heating demand**, and **cooling demand reduction** of 0,3%, 0,7% and 1,3% for Madrid, Brussels, and Stockholm respectively.

5.2.3. Economic payback-time

As an additional study (it was not planned in the T4.5 of the project) a simplified **economic payback time (PBT)** has been calculated i.e. the number of years required to recover the extra money spent in BIPV solutions from savings. It has been analysed using simplified assumptions and calculations, not including inflation rates, interest rates or another time-dependent economic variables. At the time of this report, the product costs are still highly dependent on production volumes, so **the purpose is to provide a rough idea of the product competitiveness at this intermediate state**. A detailed study of the payback time of standard BIPV solutions under different remuneration schemes, buildings and climates is described in D1.1, available in the BIPVBOOST public deliverables repository (https://bipvboost.eu/public-reports/).

The price of electricity is assumed to be the average of EU with taxes and without levies, this is 14 c€/kWh. Two remuneration approaches have been used for grid injected energy: could be sell at 6 c€/kWh, or could be discounted in future bills, so the user recovers 14 c€/kWh. The lifespan of BIPV products is normally about 25 years so, in general, PBT < 10 can be considered a very successful result, 10 < PBT < 20 intermediate result and PBT > 20 is a non-successful result. The equation used for the calculation of the payback time (PBT) is:

$$PBT = \frac{BIPV\ over\ cost}{Yearly\ savings}$$

Where the BIPV over cost is calculated considering the difference between the cost of BIPV solution and an equivalent non-PV, including all the elements needed for the BIPV (f.i. additional structure). The yearly savings are calculated from the SS and SC yearly energy and the remuneration schemes 14-14 or 14-6. Results are shown in Table 5.2.

For the 14-6, the PBTs are between 8,8-41,5 years with an average value of 23 years. For the 14-14, the PBTs are between 5-24,7 years, with an average of 14 years. Obviously the PBT is lower for the 14-14 scheme, as it gets more money for the electricity injected to the grid, which means that the net metering scheme decreases significantly the PBT. This difference between both schemes is especially high in cases with low self-consumption.

Regarding **locations**, the lowest PBT are in Madrid with averages of 16 and 11 years for 14-6 and 14-14 schemes respectively, while the highest are for Brussels with averages of 27 and 16 years. Stockholm have slightly better PBT than Brussels with averages of 25 and 15 years for 14-6 and 14-14 schemes respectively.

Obviously, the highest irradiation in Madrid is an important reason for the better PBTs, but also the highest SC rates due to yearly distributed energy demand impacts on the better results under the 14-6 scheme. To get better PBTs under 14-6 in Brussels and Stockholm, could be reasonable to reduce the PV power, so the SC would increase but the SS would decrease.

About the different **buildings**, its demand profile and installed PV power determine the SC rate, that impacts on PBT under 14-6 scheme. The best PBTs are for SFH case with 13 and 7 years, for the MFH are 29 and 17 years, for the COM are 28 and 21 years and for IND are 22 and 12 years, all of them under 14-6 and 14-14 schemes respectively.

It should be noted that the integration in the SFH building has been made on the roof instead of façades, so the yearly irradiation is significantly higher.

By type of **product**, the PBT is obviously strongly affected by the different products cost, but also by the cost of their equivalent no-PV production product as the BIPV extra cost is considered. The average PBTs of T4.1 product are 30 and 21 years under 14-6 and 14-14 schemes respectively.

These are quite high PBTs partially caused by the increase introduced by the extra PV laminated glass, as it does not replace any pre-existing material of the no-PV product version. The average PBTs of T4.2 product are 16 and 9 years under 14-6 and 14-14 schemes respectively. The PBTs are quite good for T4.2 as it has the lowest €/Wp cost or, in other words, the additional PV CIGS PV layer (not glass encapsulated) adds PV power at a reasonable cost. The results of T4.2 product are also affected by the good results in SFH where the product has been installed in the roof, with more irradiation, instead of façades. The average PBTs of T4.3 product are 25 and 14 years under 14-6 and 14-14 schemes respectively. The T4.3 product shows an intermediate case because is based on PV glass, but it replaces conventional no-PV material, so the extra BIPV cost is not so high as for T4.1 product.

Table 5.2 Summary of average PBTs by location, building type and BIPV product

PBT [years]		14-6 c€/kWh	14-14 c€/kWh
General data of complete analysis	MAX	41,5	24,7
	MIN	8,8	5
	AV	23	14
By location (averages)	Madrid	16	11
	Brussels	27	16
	Stockholm	25	15
By building type (averages)	SFH	13	7
	MFH	29	17
	COM	28	21
	IND	22	12
By BIPV product (averages)	BIPV facade cladding (T4.1)	30	21
	CIGS on metal BIPV roof (T4.2)	16	9

	BIPV glass façade system (T4.3)	25	14

The price increase is 1,83 €/Wp, 0,98 €/Wp and 1,51 €/Wp for T4.1, T4.2 and T4.3 respectively, including in this cost not only the PV module but also additional structural elements that could be required. For T4.1 product, the extra cost comes from the PV panel and joining procedure, thus the no-PV is an equivalent insulating façade panel without the PV. For T4.2 product, the extra cost comes mainly from additional CIGS layer, while the no-PV product would include the coated metal surface with corresponding structure. For T4.3 product, the extra cost is due to customized PV glass-glass and a boded frame required for PV, so the no-PV would not include this extra bonded frame, but it requires an aluminium sandwich panel instead of PV panel.

The cost of PV module is the main driver for the BIPV extra cost, and it strongly depends on the manufacturing quantity. **The T4.1 and T4.3 products are based on the use of customized PV double laminated glass whose price per unit can be significantly reduced if a high number of units is ordered, thus their high PBT could be reduced**. The use of standard double-glazing PV modules could significantly reduce the extra cost but, in this case, the dimensions, thicknesses, PV occupancy ratios and the type and position of junction box are already determined, so their integration on the construction product would require additional studies and its final customization could be very limited. As a reference, the price increase using standard PV modules could be about 0,4 €/Wp, significantly lower than previously mentioned price increases. Finally, it should be reminded that the façade, where most cases have been analysed (except T4.2-SFH) normally receives significantly less yearly irradiation that reasonably well-oriented roofs, thus **the PBTs could be significantly reduced for roof integration**.

A study of the economic payback time from a general viewpoint (generic building types and remuneration schemes) has been done to get an indicator of the expected competitiveness of the BIPV products at this intermediate state of the development and market deployment. However, the results depend significantly on several variables. For instance, under a net metering scheme, the SC indicator could be ignored and install PV power according to our expected yearly consumption. Contrary, if we sell the injected electricity at pull market price, we should consider the buy-sell price gap and match the production and demand as much as possible. Thus, **the PBTs results should be interpreted with caution, as they can be highly variable depending on the case analysed**.

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7 Annex

Table 7.1 Main building parameters used in the TRNSYS model of the Single family house building

SINGLE FAMILY HOUSE (SFH)							
Parameters		**MADRID**		**BRUSSELS**		**STOCKHOLM**	
External wall	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Brick inner	11.3	Plasterboard	1.4	Woodsiding	1
		Cavity	0.4	Brick inner	7.5	Mineral wool	10
		Brick outer	6.5	Cavity	0.3	Woodsiding	1
		-	-	Concrete	15	-	-
		*Mineral wool	11	*Mineral wool	12	*Mineral wool	4
	U wall [W/m²K]	0.274		0.246		0.239	
	External solar absorptance [-]	0.6		0.6		0.6	
External roof	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Aerated concrete	30	Concrete	30	Woodsiding	1
		Mineral wool	8	Mineral wool	16	Mineral wool	20
		Stone chipping	0.3	-	-	-	-
	U roof [W/m²K]	0.235		0.196		0.173	
	External solar absorptance [-]	0.6		0.6		0.6	
Window	U glazing [W/m²K]	1.69		1.09		0.8	
	g value [-]	0.66		0.66		0.52	
	U frame [W/m²K]	1.8		1.8		1.3	
	U window** [W/m²K]	1.72		1.3		0.95	
Shading	Presence	Yes - External		Yes - External		Yes - External	
	Shading factor [%]	90		72		72	
Infiltration rate [ACH]		0.15		0.15		0.15	
Ventilation rate [ACH]		0.72 (12)		0.72 (12)		0.72 (12)	
Heating set point [°C]		20		20		20	
Cooling set point [°C]		26		26		26	
Internal gains (references)		(7) (11) (12) (17)					
* Insulation added to the existing wall as part of the retrofit							
**U window calculate for a window of 1 m²							

Table 7.2 Main building parameters used in the TRNSYS model of the multifamily house building

MULTIFAMILY HOUSE (MFH)							
Parameters		MADRID		BRUSSELS		STOCKHOLM	
External wall	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Brick inner	11.3	Plasterboard	1.4	Plasterboard	1.4
		Cavity	0.4	Concrete	7.5	Concrete	7.5
		Brick outer	6.5	Cavity	0.3	Mineral wool	5
		-	-	Concrete	15	Concrete	15
		*Mineral wool	11	*Mineral wool	12	*Mineral wool	8
	U wall [W/m^2K]	0.274		0.246		0.237	
	External solar absorptance [-]	0.6		0.6		0.6	
External roof	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Aerated concrete	30	Concrete	30	Concrete	30
		Mineral wool	8	Mineral wool	16	Mineral wool	16
		Stone chipping	0.3	-	-	-	-
	U roof [W/m^2K]	0.235		0.196		0.196	
	External solar absorptance [-]	0.6		0.6		0.6	
Window	U glazing [W/m^2K]	1.69		1.09		0.8	
	g value [-]	0.66		0.66		0.52	
	U frame [W/m^2K]	1.8		1.8		1.3	
	U window** [W/m^2K]	1.72		1.3		0.95	
Shading	Presence	Yes - External		Yes - External		Yes - External	
	Shading factor [%]	90		72		72	
Infiltration rate [ACH]		0.15		0.15		0.15	
Ventilation rate [ACH]		0.3		0.3		0.3	
Heating set point [°C]		20		20		20	
Cooling set point [°C]		26		26		26	
Internal gains (references)		(9) (11)					
* Insulation added to the existing wall as part of the retrofit							
**U window calculate for a window of 1 m^2							

Table 7.3 Main building parameters used in the TRNSYS model of the Commercial building

COMMERCIAL BUILDING (COM)							
Parameters		MADRID		BRUSSELS		STOCKHOLM	
External wall	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Brick inner	11.3	Plasterboard	1.4	Woodsiding	1
		Cavity	0.4	Brick inner	7.5	Mineral wool	10
		Brick outer	6.5	Cavity	0.3	Woodsiding	1
		-	-	Concrete	15	-	-
		*Mineral wool	11	*Mineral wool	12	*Mineral wool	4
	U wall [W/m²K]	0.274		0.246		0.239	
	External solar absorptance [-]	0.6		0.6		0.6	
External roof	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Aerated concrete	30	Concrete	30	Woodsiding	1
		Mineral wool	8	Mineral wool	16	Mineral wool	20
		Stone chipping	0.3	-	-	-	-
	U roof [W/m²K]	0.235		0.196		0.173	
	External solar absorptance [-]	0.6		0.6		0.6	
Window	U glazing [W/m²K]	1.69		1.09		0.8	
	g value [-]	0.66		0.66		0.52	
	U frame [W/m²K]	1.8		1.8		1.3	
	U window** [W/m²K]	1.72		1.3		0.95	
Shading	Presence	No		No		No	
Infiltration rate [ACH]		0.5		0.5		0.5	
Ventilation rate [ACH]		1.04 (14)		1.04 (14)		1.04 (14)	
Heating set point [°C]		21		21		21	
Cooling set point [°C]		24		24		24	
Internal gains (references)		(13) (15)					
* Insulation added to the existing wall as part of the retrofit							
**U window calculate for a window of 1 m²							

Table 7.4 Main building parameters used in the TRNSYS model of the Industrial building

INDUSTRIAL BUILDING (IND)							
Parameters		**MADRID**		**BRUSSELS**		**STOCKHOLM**	
External wall	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Brick inner	11.3	Plasterboard	1.4	Woodsiding	1
		Cavity	0.4	Brick inner	7.5	Mineral wool	10
		Brick outer	6.5	Cavity	0.3	Woodsiding	1
		-	-	Concrete	15	-	-
		*Mineral wool	11	*Mineral wool	12	*Mineral wool	4
	U wall [W/m^{2}K]	0.274		0.246		0.239	
	External solar absorptance [-]	0.6		0.6		0.6	
External roof	Stratigraphy (inside - outside)	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*	*Material*	*Thickness [cm]*
		Aerated concrete	30	Concrete	30	Woodsiding	1
		Mineral wool	8	Mineral wool	16	Mineral wool	20
		Stone chipping	0.3	-	-	-	-
	U roof [W/m^{2}K]	0.235		0.196		0.173	
	External solar absorptance [-]	0.6		0.6		0.6	
Window	U glazing [W/m^{2}K]	1.69		1.09		0.8	
	g value [-]	0.66		0.66		0.52	
	U frame [W/m^{2}K]	1.8		1.8		1.3	
	U window** [W/m^{2}K]	1.72		1.3		0.95	
Shading	Presence	Yes – External (office)		Yes – External (office)		Yes – External (office)	
	Shading factor [%]	70		70		70	
Infiltration rate [ACH]		0.5		0.5		0.5	
Ventilation rate [ACH]		0.67 (Office) (12) / 0.25 (Storage and Production zones) (16)					
Heating set point [°C]		21 (Office) / 7.2 (Storage and Production zones)					
Cooling set point [°C]		24 (Office) / 30 (Storage and Production zones)					
Internal gains (references)		(15), (16), (25)					
* Insulation added to the existing wall as part of the retrofit							
**U window calculate for a window of 1 m^2							