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Results of modelling at element and building level CIGS products

Project report

NOBATEK, TECNALIA

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www.pvsites.eu

Summary

This document describes the results obtained from the simulation activities conducted at element and building level for the CIGS thin film products developed in WP4 “BIPV modules based on CIGS thin film technology” of PVSITES project.

The first part of the document describes the objectives and the methodology used for the modelling at element and building level. It also exposes the links with other activities within the project.

The second part of the report provides the main results obtained in terms of individual modules performance in the configurations designed for the experimental buildings and demo sites and the performance of each BIPV product for specific building typologies and different locations.

The results presented herein will feed directly tasks 2.3 “BIPV products portfolio” and 9.8 “Implementation of the BIPV product portfolio”, dedicated to the definition and implementation of a BIPV products portfolio.

Acknowledgements

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The present report was mainly prepared by PVSITES project partner NOBATEK, with additional contributions from TECNALIA. The report was originally submitted to the European Commission as Project Deliverable D4.4 in March 2018.

Disclaimer

About the PVSITES project

PVSITES is an international collaboration co-funded by the European Union under the Horizon 2020 Research and Innovation program. It originated from the realisation that although building-integrated photovoltaics (BIPV) should have a major role to play in the ongoing transition towards nearly zero energy buildings (nZEBs) in Europe, the technology in new constructions has not yet happened. The cause of this limited deployment can be summarised as a mismatch between the BIPV products on offer and prevailing market demands and regulations.

The main objective of the PVSITES project is therefore to drive BIPV technology to a large market deployment by demonstrating an ambitious portfolio of building integrated solar technologies and systems, giving a forceful, reliable answer to the market requirements identified by the industrial members of the consortium in their day-to-day activity.

Coordinated by project partner Tecnalia, the PVSITES consortium started work in January 2016 and will be active for 3.5 years, until June 2019. This document is part of a series of public reports summarising the consortium's activities and findings, available for download on the project's website at www.pvsites.eu.

The PVSITES consortium:

Tecnalia Research & Innovation	CTCV	FormatD2
Onyx Solar	Flisom	Vilogia
BEAR-iD	Cricursa	R2M Solution Research to Market
Nobatek	CEA	CADCAMation
Film Optics	Acciona Infraestructuras	WIP - Renewable Energies

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1 EXECUTIVE SUMMARY

1.1 Description of the deliverable content and purpose

This document is associated with task 4.3 “Modelling at element and building level”. It provides the methodologies used for the simulation of the BIPV modules at element and building level and reports the corresponding results.

The aim of task 4.3 is to apply (and develop where needed) physical models for the BIPV products based on CIGS film technology, at element and building level, in order to characterize their main properties at different levels (optical, thermal, mechanical and electrical), make this information available for the manufacturer (FLISOM) and feed the BIPV products portfolio. In this sense, it complements the experimental work from task 4.4 (Performance validation testing).

The use cases associated with the demonstration sites have been simulated in the framework of task 8.1 “Design of demonstration installations.”. The main results in terms of impact of the BIPV products on the energy performance of the buildings and on the comfort (temperature and light level) are presented in deliverable D8.2 “Results of modelling and BIPV strategies for every demo site”, which also includes a set of conclusions about the BIPV impact according to the technology used. For this deliverable, a sensitivity analysis will be carried out to assess the impact of the chosen model assumption and of the BIPV modules on the building thermal behaviour.

1.2 Relation with other activities in the project

Table 1.1 depicts the main links of deliverable D4.4 to other activities (work packages, tasks, deliverables, etc.) within PVSITES project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1 Relation between D4.4 and other activities in the project

Project activity	Relation with current deliverable
WP2 – Task 2.3 and WP9 – Task 9.8	The results presented in D4.4 provide direct inputs to feed the BIPV product portfolio (tasks 2.3 and 9.8) and to generate useful information for dissemination materials.
WP3 – Task 3.6	Task 3.6 conducts a very similar approach as the one followed in task 4.3 but for the crystalline silicon technology provided by ONYX Solar.
WP4 – Task 4.4	The simulation work presented herein complements the laboratory testing in task 4.4 for the characterization of thin film CIGS products.
WP7	Some of the algorithms developed within this task have been or are being implemented in the software tool. The information generated will feed the database of products within the software tool.
WP8 – Task 8.1	D8.2 provides the simulation results obtained for the demonstration sites in terms of impact of the BIPV products on the energy performance of buildings as well as on the comfort (temperature and lighting).

1.3 Reference material

D8.1 “Energy audit of buildings and identification of BIPV possibilities in every demo site”, deliverable of the PVSITES project, delivered at M17.

D8.2 “Results of modelling and BIPV strategies for every demo site”, deliverable of the PVSITES project, in preparation, to be delivered in month 28.

D3.7 “Report on simulation work, c-silicon based BIPV elements”, deliverable of the PVSITES project, delivered in month 23.

1.4 Abbreviation list

ACH:	Air Change rate per Hour
BIPV:	Building-integrated photovoltaics
CPR:	Construction Products Regulation
EHG:	Ecole Hôtelière de Genève
EQE:	External Quantum Efficiency
FEM:	Finite Elements Method
GF:	Ground Floor
HVAC:	Heating Ventilation Air conditioning
IBC:	Interdigitated Back Contact
IR:	InfraRed
LVD:	Low Voltage Directive
MAE:	Mean Average Error
OT:	Operative Temperature
PV:	Photovoltaics
RMSE:	Root Mean Square Error
SA:	Sensitivity Analysis
SHGC:	Solar Heat Gain Coefficient
U:	U value, thermal transmittance coefficient
UA:	Uncertainty Analysis
WP:	Work Package

2 BIPV products

The aim of WP4 is to take lightweight flexible thin film CIGS solar modules to a pre-industrial stage by providing a multiple answer to the market needs identified and defined in task 1.1 “Market and stakeholder analysis and needs”. This section provides a short description of the technologies developed by FLISOM (sections 2.1 and 2.2) within WP4 of PVSITES project. The calculations have been focused on the technologies and configurations selected for the experimental buildings (CIGS roofing shingle on metal substrate to be tested in single-detached dwelling in Belgium and CIGS large area flexible roofing membrane and bendable elements to be tested on an industrial rooftop (Switzerland), on two carports located in Switzerland, on a façade of a building located in Switzerland and on the roof of an industrial building in Spain).

FLISOM products (X1 and X2/X4) are opaque black products. The fraction of solar radiation that is not converted into electricity is either reflected or absorbed and converted into thermal energy. Therefore, depending on the integration strategy (cladding, ventilated façade, roofing, etc.), it may affect the building thermal behaviour.

2.1 CIGS roofing shingle on metal substrate

FLISOM’s product is a photovoltaic module laminated onto a metalic roof tile. It is well adapted for residential roofs and is based on CIGS monolithically interconnected cell technology:

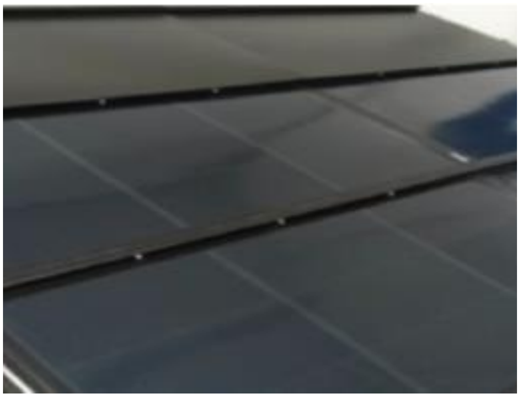

Figure 2.1: FLISOM CIGS roof tiles

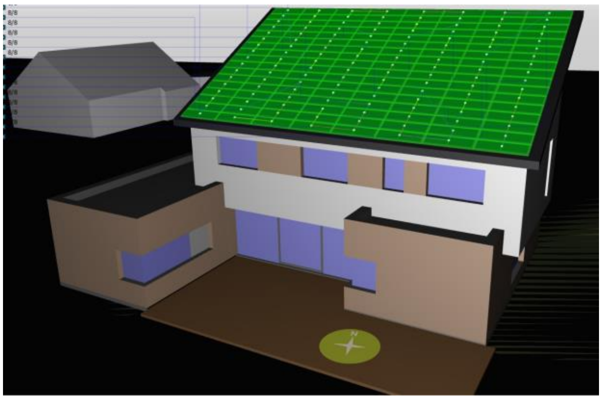

Figure 2.2: Application to a family house

The modules are ready for various types of integration, thus they may be used as ventilated façade, curtain wall, skylight, roofing shingle, shading system, etc.

2.2 CIGS large area flexible roofing membrane and bendable elements

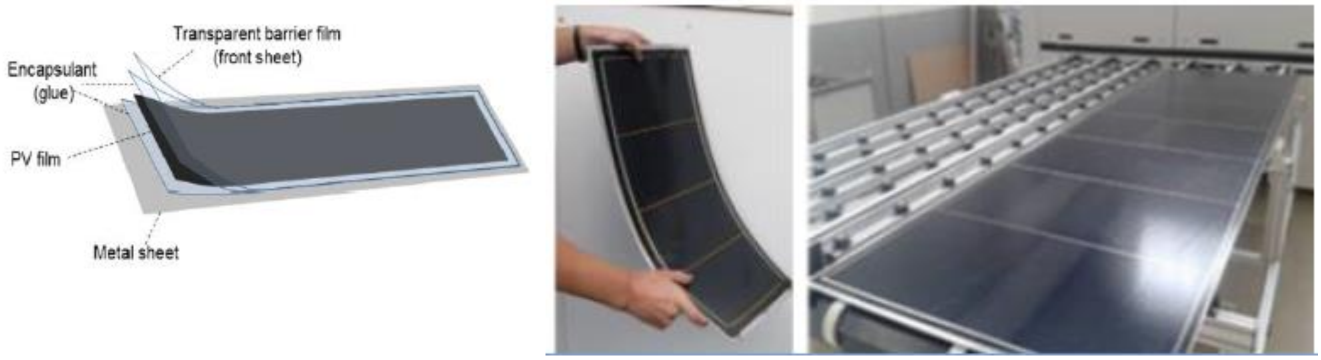

Figure 2.3: FLISOM CIGS large area flexible roofing membrane and bendable elements

This product is a lightweight photovoltaic module laminated onto a metallic back sheet (steel). The PV plate is designed for integration on façades roofs or other building elements. The modules can be integrated in several ways:

- Adhesive bonding,
- Velcro tape,
- Mechanical fixation,
- Back rails,
- Usage of larger overlapping metal back sheet and bending the same into structural system.

A full description of this technology can be found in D4.1-D4.2 “Roofing tiles and façade elements prototypes with 10% - 14% efficiency ".

3 Modelling objectives

According to EN 50583 standard for BIPV modules and systems, photovoltaic modules are considered to be building-integrated if they constitute a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. In this context, the term “function” refers to one or more of the following:

- Mechanical rigidity or structural integrity
- Primary weather impact protection: rain, snow, wind, hail
- Energy economy, such as shading, daylighting, thermal insulation
- Fire protection
- Noise protection
- Separation between indoor and outdoor environments
- Security, shelter or safety

As electrical systems, BIPV modules are subject to the applicable electro-technical requirements as stated in the Low Voltage Directive (LVD) 2006/95/EC and the corresponding CENELEC standards.

Any BIPV product entering the market needs, therefore, to demonstrate the fulfillment with these EU regulations, and both manufacturers and project designers need tools for a full characterization of BIPV products in this sense. The approach to show compliance with CPR and LVD is the testing according to the corresponding standards, as described in Tasks 1.3 “Standardization needs” and 4.4 “Performance validation testing” of PVSITES project. Additionally, some of these standards (e.g. for the optical and thermal properties) require a standardized calculation.

The general objective of the modeling activities proposed herein is to complement the experimental laboratory testing from Task 4.4 in order to provide a complete characterization of the BIPV products that can be used by the manufacturer for market activities and the architects and project designers in order to evaluate the potential performance of a building with integrated photovoltaic products. In addition to this, the newly developed calculation models will form part of the software tool developed in WP7 to support the design stages of BIPV products.

The simulation activities will be considered both at element and building levels in order to generate a complete set of information on the products performance and their influence on specific building and climate conditions.

4 Simulation at element level

4.1 Optical characterization at element level

The picture below shows the spectral reflectance (no units, values from 0 to 1) of CIGS based modules as measured with a JASCO V-670 UV-Vis-NIR spectrophotometer equipped with a 150 mm integrating sphere. In this case, there is no need for additional calculations for every configuration, as the modules are opaque and only the backsheet changes for each product. This characterization is used as an input for the thermal calculations described in section 4.2.

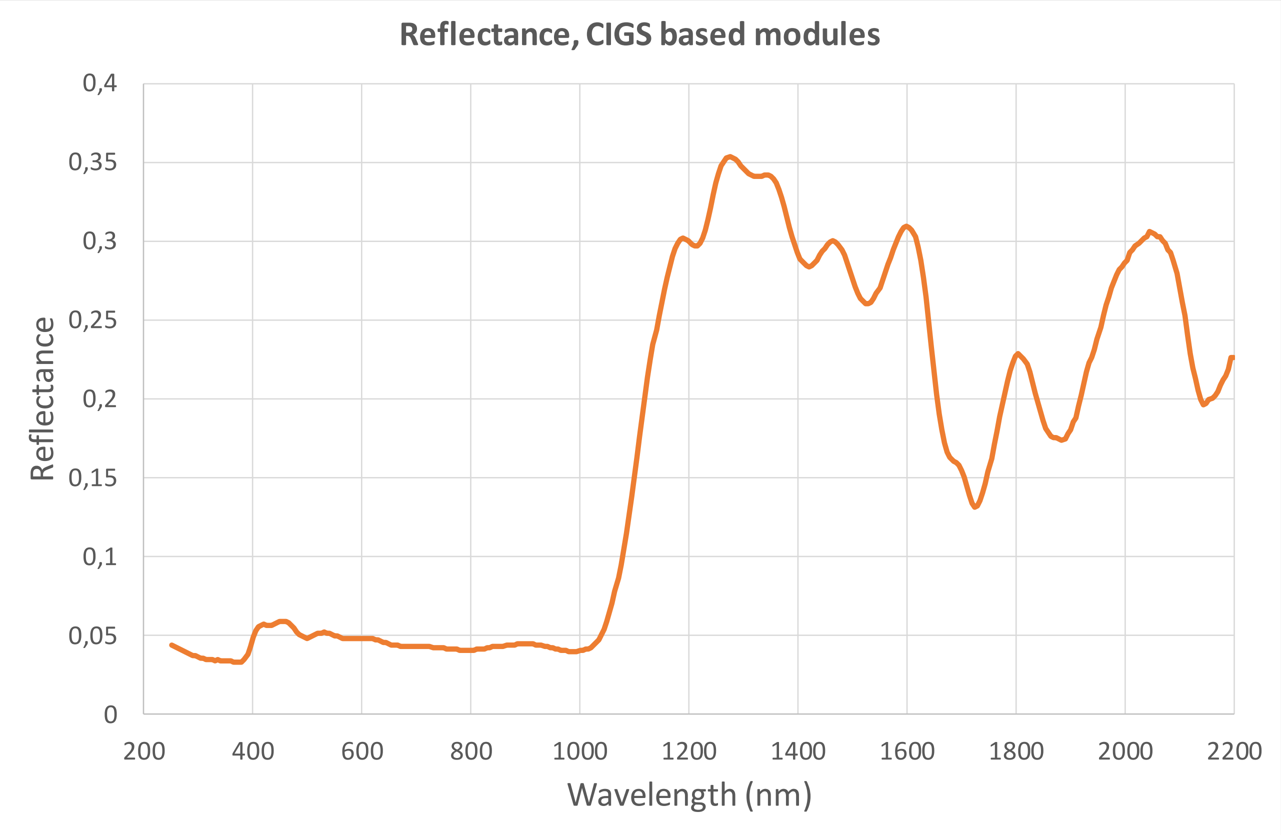

Figure 4.1. Experimental spectral reflectance of CIGS based modules

The spectral curves for reflectance are fully compatible with the wavelength range in which CIGS cells are active (300-1300 nm approx.).

4.2 Thermal calculation at element level

A thermal study of the roofing shingle integration in the Belgium residential single dwelling demo site has been performed, because it was identified as necessary for the design process. The thermal behaviour of this solution is especially interesting due to the gap created between the roof and the modules and its potential stack effect.

The main aims are to analyse the temperatures of modules and the behaviour of the air gap in STC conditions (that also correspond to average maximum summer temperatures) and in heat extreme conditions. The following paragraphs describe the details of this model, the results and conclusions.

4.2.1 Thermal modelling

Numerical steady state thermal analyses were conducted in order to compare different boundary conditions, regarding natural convection to environment and ambient temperature. A unique load case is considered, which will be later defined.

Simulations were carried out with NX from Siemens PLM. The analysis type was a coupled thermal/flow analysis, in which air is the fluid involved in the model.

The design analysed is shown in Figure 4.2 and corresponds to the final integration design of the demo site system.

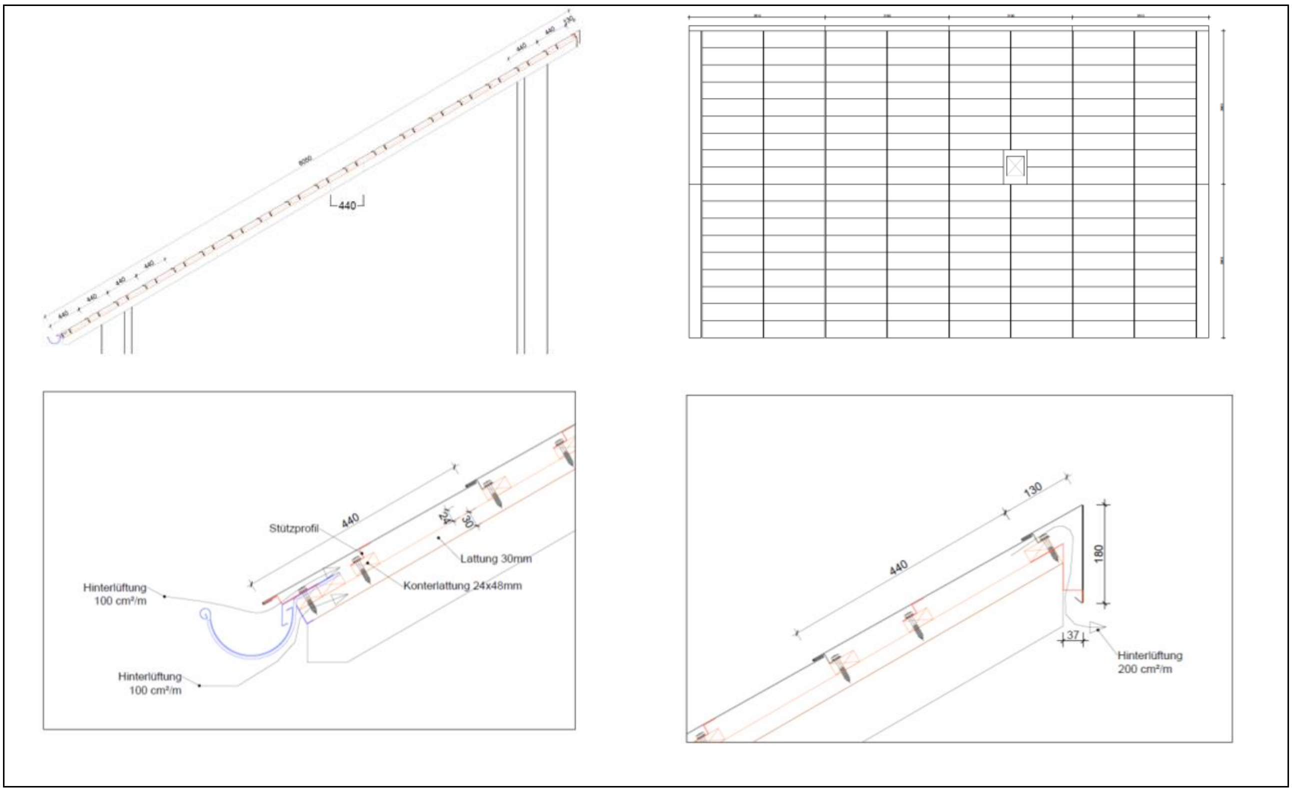

Figure 4.2. Roofing system drawings

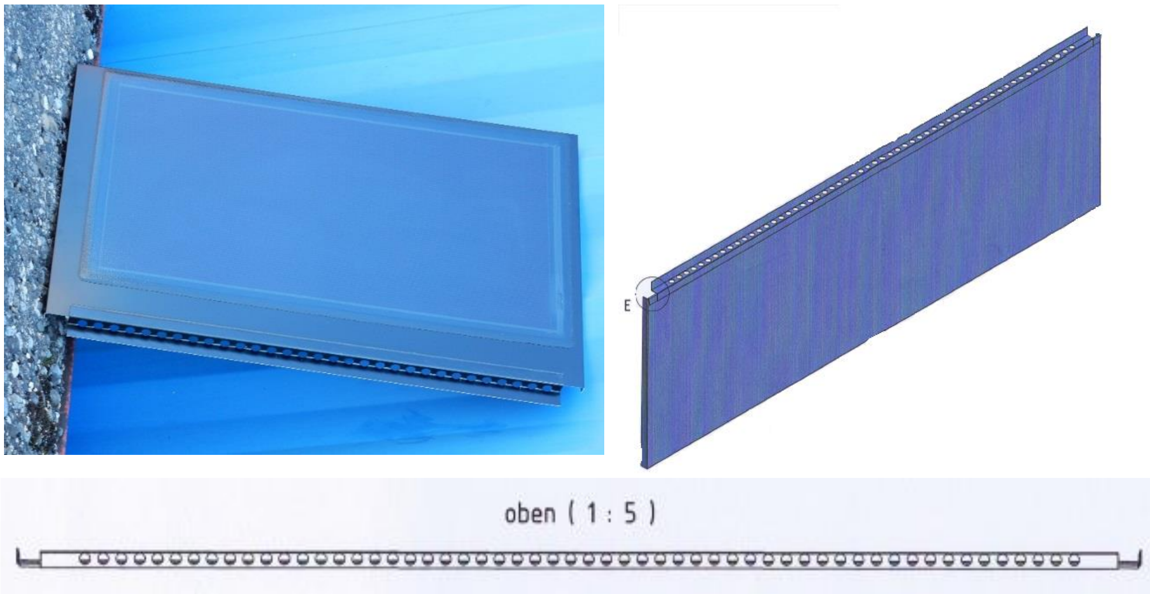

Figure 4.3. CIGS on steel roofing shingle

A first attempt to simulate the whole roof was done but the model was so huge that an enormous amount of time and computing resources were necessary, resulting in an unaffordable simulation. Therefore, the roof model was simplified taking advantage of its longitudinal symmetry. Boundary conditions aside, the roof can be considered to be a repetition of a basic unit which comprises a width of 25 mm of the roof. The basic unit comprises one complete hole in the module tray, so that this basic unit, by repetition, forms the whole roof assembly.

Then, several tests were done to adjust the FEM mesh and get accurate results while maintaining affordable computing time. Finally, 3 mm size tetrahedral nodes configuration was used in modules, beams and fluid.

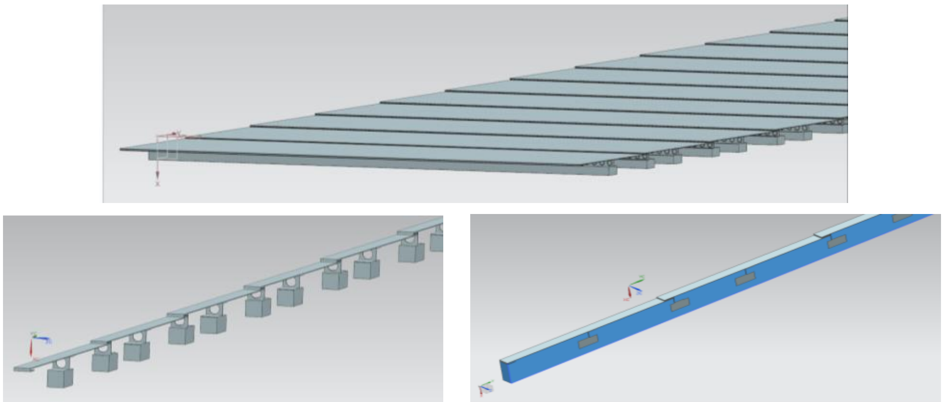

Figure 4.4. Roof structure. Top: 3D view. Down left: basic unit for the simulations. Down right: Basic unit with air volume modelling

Regarding materials, the modules are made of aluminium and the structural beams are made of wood. Since all the simulations are for a steady state, the only thermal property involved is the conductivity. Considered values are 0.1 W/m/K for wood, 0.026 W/m/K for air and temperature dependent behaviour for aluminium.

Since a simplified model is used, considering a basic unit, symmetry conditions are needed at the symmetry planes, so these planes are considered adiabatic and no perpendicular thermal or mass fluxes are allowed through them.

4.2.2 Operating and boundary conditions

Thermal flow is calculated according to the absorptance of the modules.

$$Q = Q_{solar} \cdot \alpha \ ,$$

where α=0,93 is the absorptance.

For STC conditions, where Q_{solar}= 1000 W/m^2, thus Q = 930 W/m^2. The model assume that PV system is in open circuit conditions i.e. no radiation is transformed into electricity.

Two working temperatures have been considered, one corresponding to STC conditions (T_{STC} = 25 °C) and the other corresponding to the maximum historic temperature measured at the location of the pilot site (T_{max} = 37 ºC).

Specific values of convection have been set for the upper side of the modules while for the inner air chamber the air flows according to the convective flow stablished by the thermal gradients in the model.

The natural external convection coefficients correspond to very low values of wind speed. 5 W/m^{2}K is an extreme minimum value with complete absence of wind and caused just by the temperature differences. 10 W/m^{2}K correspond to very low wind speed. As a reference, the external natural convection considered in EN 673 for glass thermal transmittance calculation is 25 W/m^{2}K.

Table 4.1 Operating conditions.

Inner fluid flow	kg/s	Natural
Fluid inlet temperature	ºC	25/37
Solar flow	W/m^2	930
Natural convection on upper side	W/m^{2}K	5/10
Ambient temperature	ºC	25/37

Finally, radiation to ambient has also been considered, considered a clear sky as the radiative exchanging environment. Clear sky temperatures have been calculated according to the Swinbank expression.

$$T_{sky} = 0{,}0552 \cdot T_{ambient}^{1.5}$$

4.2.3 Results

Numerical results obtained for each operating condition (hereinafter referred to as OC) assessed are presented below. Main input model parameters are the ambient temperature (25 ºC – 37 ºC) and convection coefficient at module external surface (5 W/m^{2}K - 10 W/m^{2}K). Every case assumes incidence radiation of 1000 W/m^2, of which 93% is absorbed by the modules and transformed into heat.

OC 1: $T_{ambient}$ = 25°C / h = 5 W/m^{2}K

Table 4.2 Main results. OC 1.

Results	OC 1
Max/Min temperatures [ºC]	
• **Modules**	47,6 / 95,6
• **Fluid**	25 / 95,5
Max. fluid velocity [mm/s]	620,78

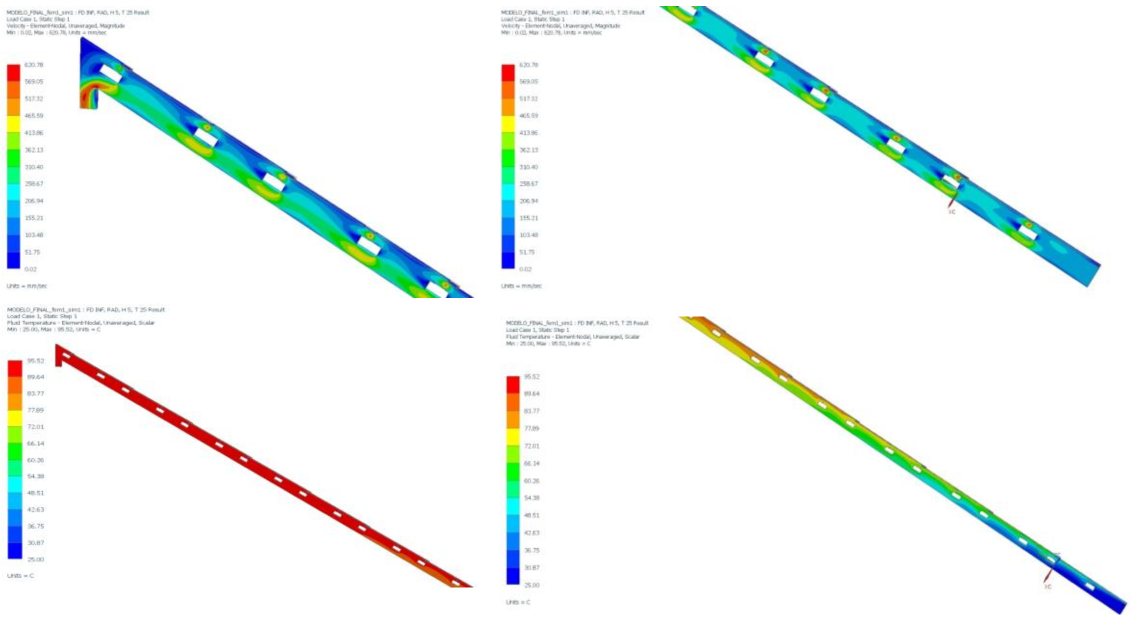

Figure 4.5. OC 1. CFD results. Top-left: air velocity in upper side. Top-right: air velocity in lower side. Down-left: internal air temperature in upper side. Down-right: internal air temperature in lower side.

OC 2: $T_{ambient}$ = 25°C / h = 10 W/m^{2}K

Table 4.3 Main results. OC 2.

Results	OC 2
Max/Min temperatures [ºC]	
• **Modules**	44,8 / 77,2
• **Fluid**	25 / 77,1
Max. fluid velocity [mm/s]	529,94

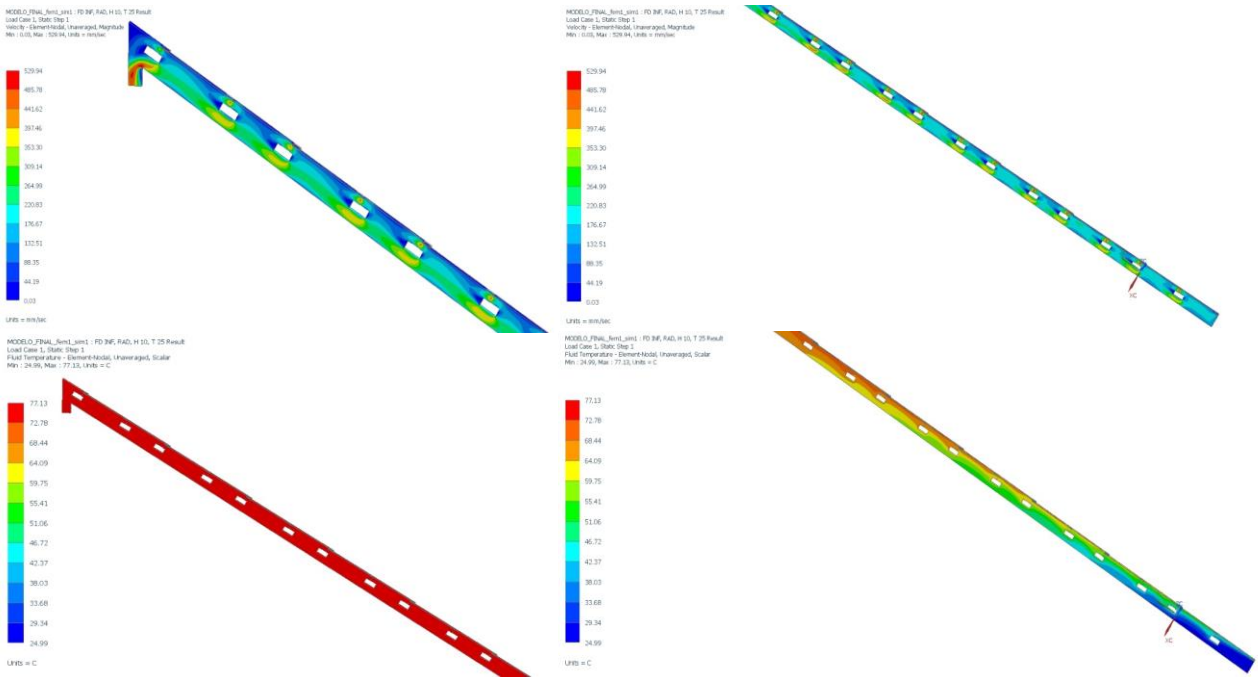

Figure 4.6. OC 2. CFD results. Top-left: air velocity in upper side. Top-right: air velocity in lower side. Down-left: internal air temperature in upper side. Down-right: internal air temperature in lower side.

OC 3: $T_{ambient}$ = 37°C / h = 5 W/m^{2}K

Table 4.4 Main results. OC 3.

Results	OC 3
Max/Min temperatures [ºC]	
• **Modules**	60 / 105,3
• **Fluid**	37 / 105,3
Max. fluid velocity [mm/s]	608,4

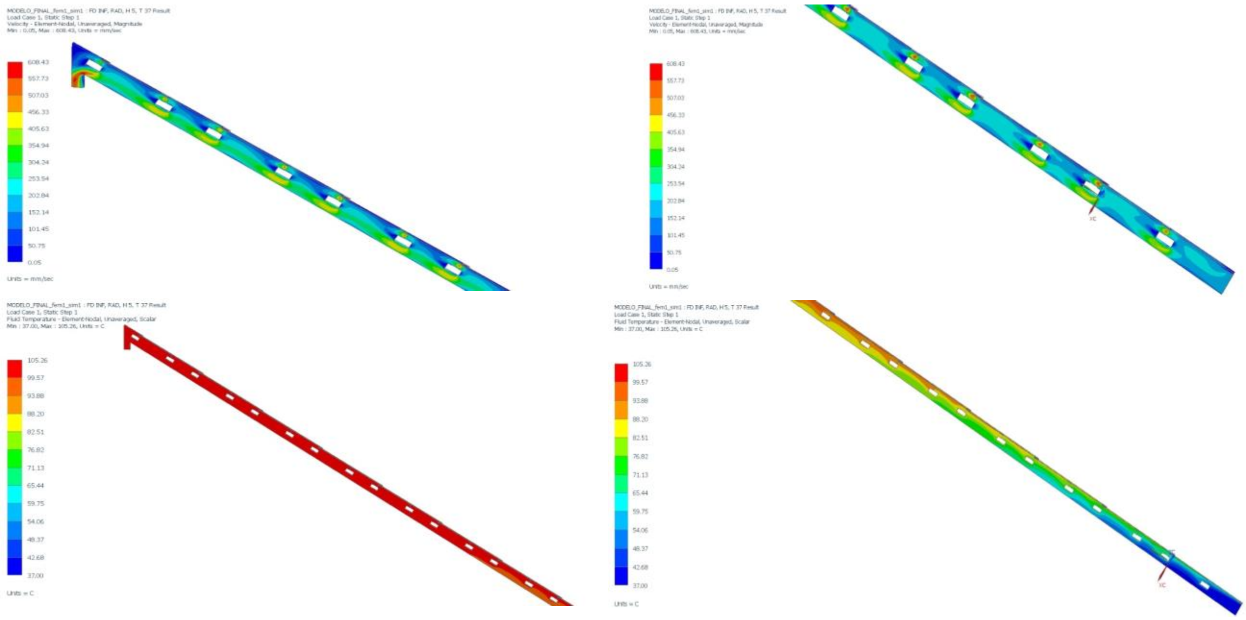

Figure 4.7. OC 3. CFD results. Top-left: air velocity in upper side. Top-right: air velocity in lower side. Down-left: internal air temperature in upper side. Down-right: internal air temperature in lower side.

OC 4: $T_{ambient}$ = 37°C / h = 10 W/m^{2}K

Table 4.5 Main results. OC 4.

Results	OC 4
Max/Min temperatures [ºC]	
• **Modules**	57,2 / 88,1
• **Fluid**	37 / 88,1
Max. fluid velocity [mm/s]	522,3

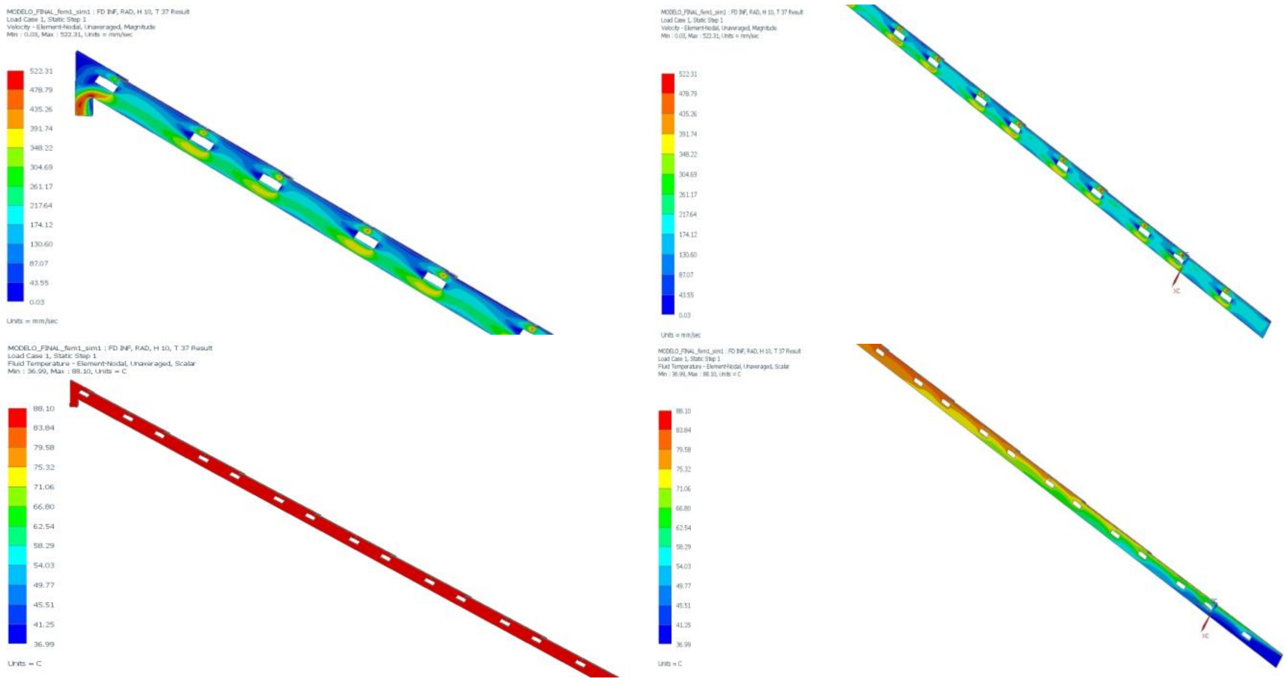

Figure 4.8. OC 4. CFD results. Top-left: air velocity in upper side. Top-right: air velocity in lower side. Down-left: internal air temperature in upper side. Down-right: internal air temperature in lower side.

4.2.4 Conclusions

The operating conditions considered are quite extreme in terms of high temperature, high radiation and very low natural convection values. Thus, the results should be considered as maximum values of temperatures and air velocity in the gap between the modules and the building roof.

As expected, the upper side of the roof shows the higher module temperatures while the lower part shows the minimum temperatures. The OC 2 correspond to conditions that may be reached every summer and this case shows module temperatures up to 77-78 ºC. On the other hand, OC 3 correspond to most extreme conditions for location site in which maximum module temperatures can reach 105 ºC.

The results show that slight differences in the external convection coefficient influence significantly in the maximum temperatures of modules. For instance, the maximum temperature between OC 1 and OC 2 goes from 95.6 ºC to 77.2 ºC respectively. Conversely, the minimum module temperatures are almost the same in both cases. Thus, the real maximum temperature of modules is very difficult to predict as it strongly depends on wind conditions.

The temperatures differences between the modules located at the lower and the upper side of the roof can be about 30 ºC and may reach up to 45 ºC. This are significant differences that can affect electrical parameters of modules and cause mismatch effects.

4.3 Electrical calculations

With the aim to simulate the electrical production and characteristics of CIGS products, two cases have been selected to be modelled and analyzed: The EHG demo installation and a curved façade based on curved CIGS products. Both cases have been analyzed with BIMSolar software tool.

The goal of this work is not only to get the PV production results, but also to test the software tool and its suitability to model the CIGS products developed in the framework of WP4 from the electrical point of view.

4.3.1 CIGS Façade: EHG case

The analysis of EHG demo started with the building and environment modelling and finally described with an IDF file (files used by EnergyPlus). Then, the file was loaded in BIMSolar software. The demonstrative installation will include two façades, one located in West building (facing East) and another located in East building (facing West). Figure 4.9 shows how the model looks like in BIMSolar under radiation analysis tool. More details and images can be found in section 5.4.2.

This simulation will be later repeated with a more accurate modeling of the environment and systems, so this work should be considered as an initial test of the software to simulate the technologies developed in WP4. The results of new simulation will be included in D8.2.

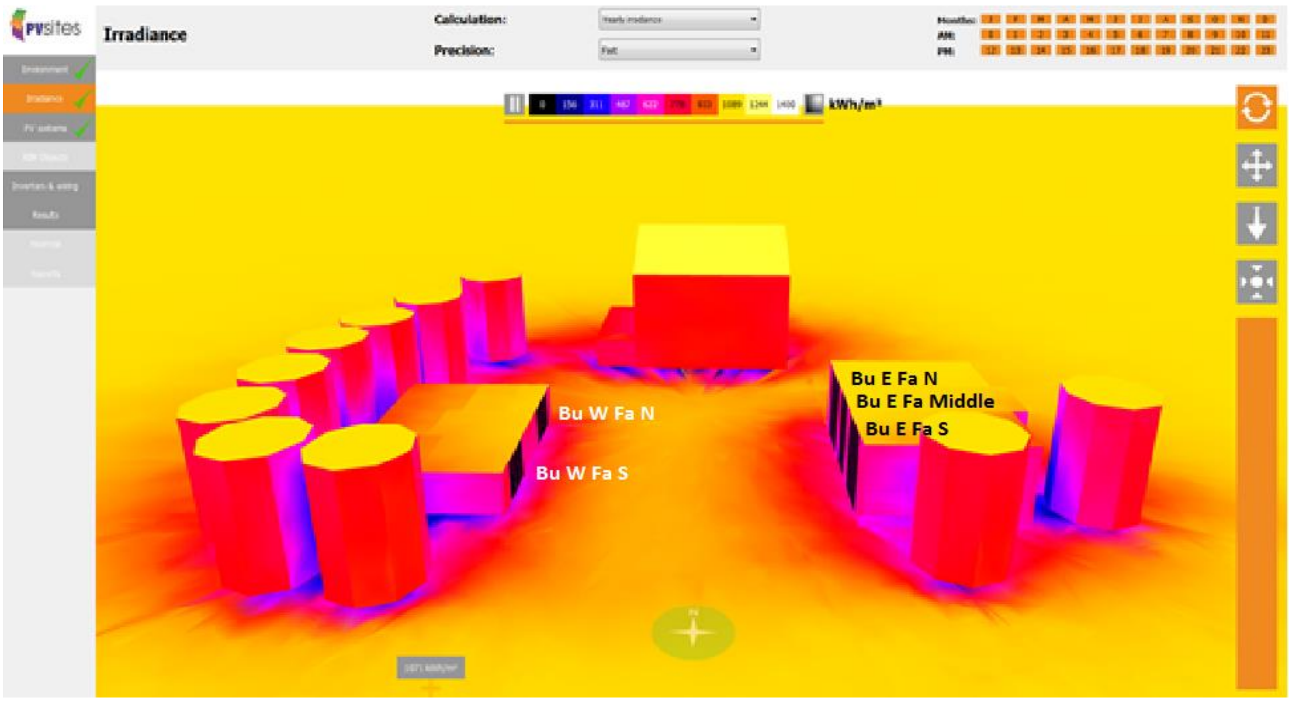

Figure 4.9: Radiation analysis of EHG model in BIMSolar software

The thin-film modules, including CIGS modules, have an internal electrical connection based on several cells created by laser patterning. This means that the common scheme used in BIMSolar to describe c-Si cells and modules should be reinterpreted for the thin-film modules.

For the CIGS modules description, the "opaque BIPV" mode was selected, and the module parameters were described directly in "cell editor", so the whole module is assumed to be like one big solar cell. In terms of calculation, this will mean that a partially shadowed module will behave as if it were fully shadowed which, according to module and installation dimensions, is an acceptable approximation. Thus, a specific solar cell and module were created in the software to describe the CIGS product. The electrical characteristics described in the model are the ones from the 50 Wp module that is the worst case, as Flisom modules go from 50 to 60 Wp.

The EHG demo shows another modelling challenge related to the BOS. It is not planned to use a common inverter system but to use a combined system of inverters and MPPT optimizers. According to current demo information, two inverters are planned to be installed, one for each façade, these are SE2200H and SE6000H from SolarEdge. Additionally, 6 P405 optimizers have been considered for small façade (facing East) and 15 P405 optimizers have been considered for big façade (facing West). Thus, two new inverter models have been described in BIMSolar using the “inverter editor” tool, describing main parameters of SE2200H plus 6 MPPTs with P405 electrical characteristics, and the same has been done for SE6000H but including 15 MPPTs.

The monthly production results are shown in Table 4.6. The results are specified for East and West buildings (E Build, W Build respectively) and different set of modules composing each façade (Figure 4.9). Figure 4.10 compares monthly results in both buildings as well.

Table 4.6 Estimation of electricity production thanks to BIPV installation in EHG buildings. Results are detailed for the different set of modules (South and North in West building; South, middle and North in East building)

Production (kWh)								
Month	**W Build S Fac**	**W Build N Fac**	**Total West Building**	**E Build S Fac**	**E Build N Fac**	**E Build Mid Fac**	**Total East Building**	**Both Buildings**
January	19	19	**38**	31	31	20	**82**	**120**
February	30	28	**58**	54	54	36	**144**	**202**
March	57	58	**115**	103	105	68	**277**	**392**
April	70	72	**142**	116	116	77	**309**	**451**
May	92	93	**185**	151	152	100	**403**	**588**
June	105	104	**209**	155	155	103	**412**	**621**
July	102	104	**206**	166	167	110	**443**	**649**
August	86	88	**174**	139	140	93	**372**	**546**
Sept.	58	58	**115**	105	106	70	**282**	**397**
October	35	34	**70**	65	65	43	**173**	**243**
November	20	18	**38**	35	35	23	**93**	**131**
December	13	13	**26**	27	28	18	**73**	**100**
Annual	**688**	**689**	**1377**	**1148**	**1153**	**762**	**3063**	**4440**

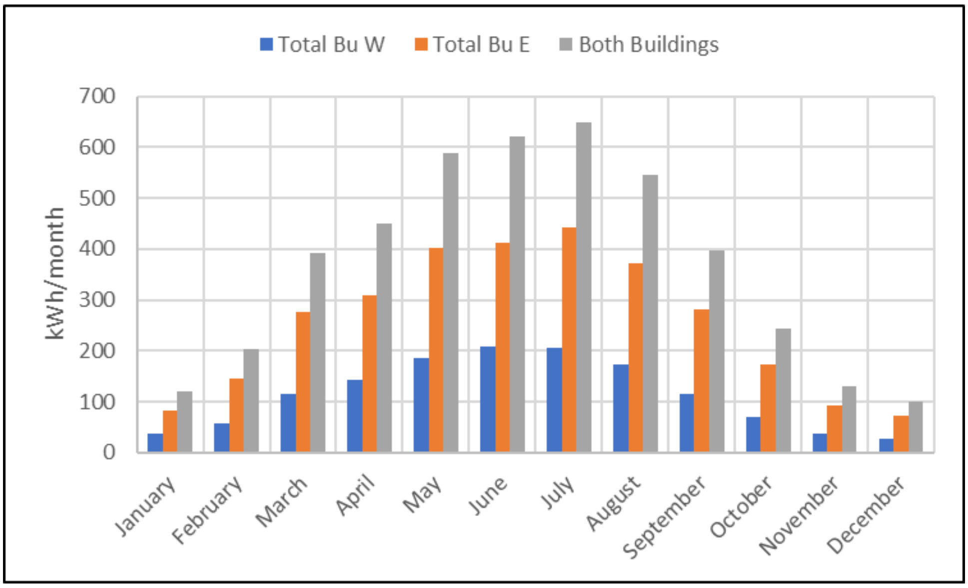

Figure 4.10: Estimation of monthly electricity production of BIPV installation in EHG buildings

In addition to monthly estimated production, the daily production profile has been analysed (Figure 4.11). This result may be interesting depending on connection or energy management scheme. As expected due to East-West orientations, the production varies significantly from sunrise to sunset.

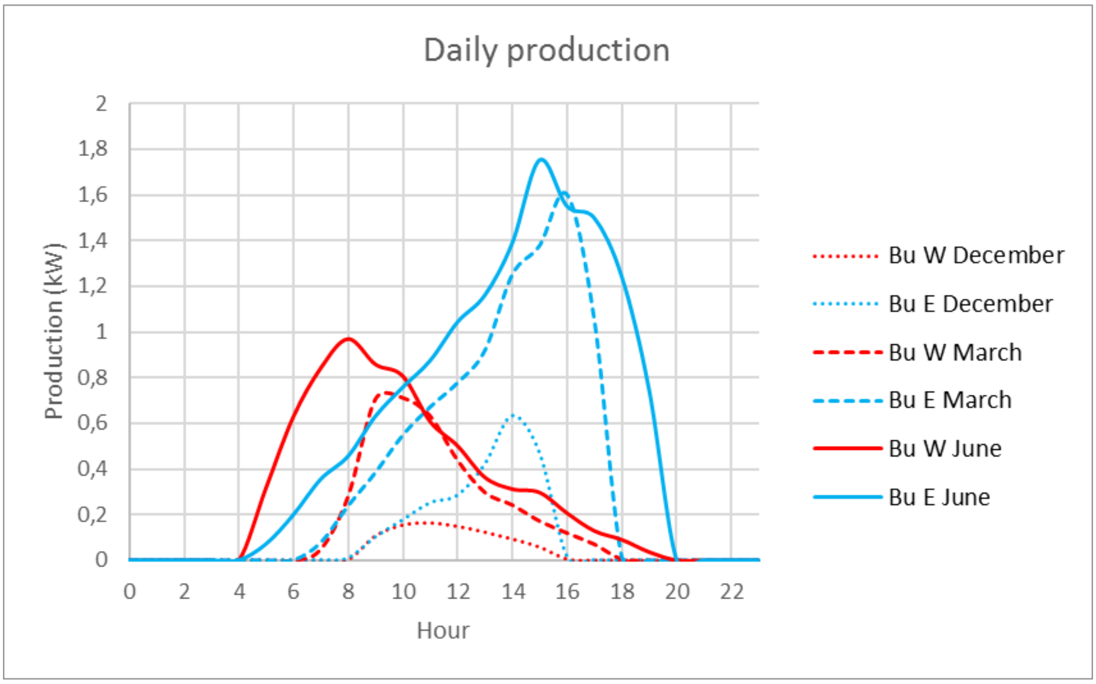

Figure 4.11: Daily production profile

4.3.1 Curved CIGS

Within the framework of task 4.2 “Flexible CIGS module technology to curved BIPV solutions”, curved CIGS modules have been developed using laminated glass and cold bending technologies. This product was described in D4.3 “Curved CIGS glass elements”, consisting in laminated glass modules with a permanent slight curvature with embedded CIGS submodules. The final permanent displacement at module centre compared to edges was 15 mm, while the modules were 1475 mm long.

One of the potential applications of these modules is their use in curved façades, where the orientation of each module will be different. According to bending dimensions measured in the product prototypes, the radius of curvature has been calculated to be about 18 m (approximate).

With this information, a model has been prepared in BIMSolar in order to compare the production potential of a curved façade with that of its equivalent flat façade. For this purpose, the previous CIGS modules description has been used. As the curvature of each real module is very low, it was found that the differences in electrical behaviour at module level are not significant and flat modules can be used in the software. On the other hand, the curvature of façade has been considered by rotating each module according with the radius of curvature. Figure 4.12 shows a top view of curved and flat façades and the connection scheme to inverter. Each is composed by 9 modules and main orientation is South. The chosen location is Lyon.

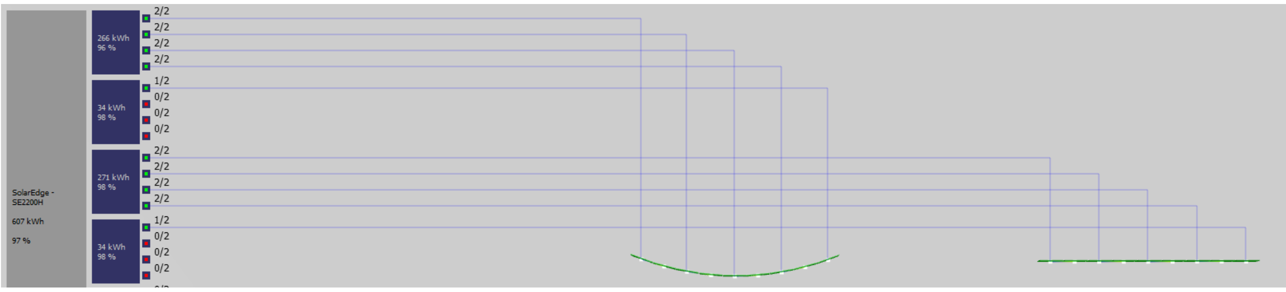

Figure 4.12: Connection scheme of curved façade and flat façade. Top view.

An important fact of CIGS technology should be considered herein: as other thin film technologies, the modules present high voltage and low intensity compared to common c-Si, and the number of modules that are normally connected in series is very low (2 in our model). This feature contributes to minimize losses caused by different irradiation levels in the modules connected in series (mismatch effect).

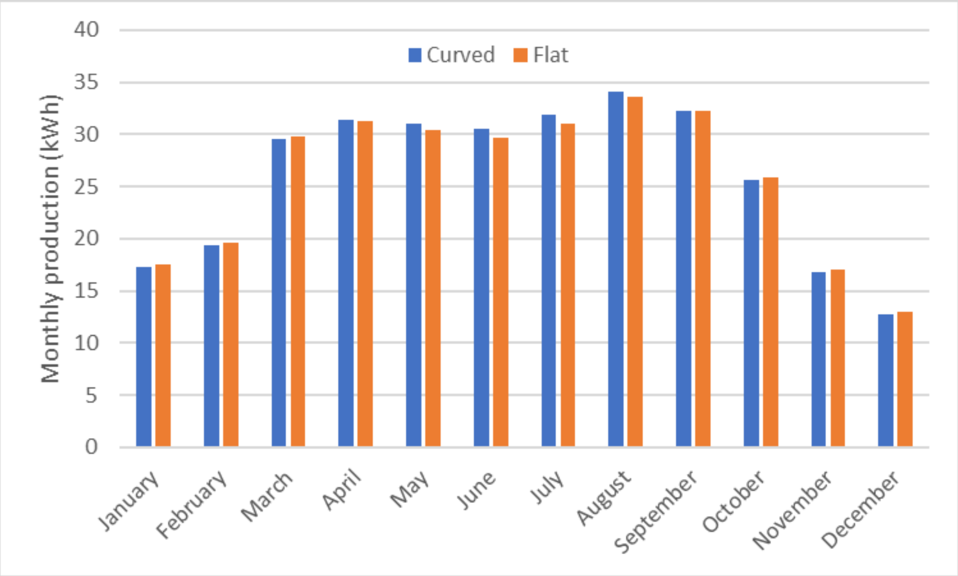

Figure 4.13: Estimation of monthly electricity production of curved CIGS façade and flat CIGS façade. Both South oriented.

The estimated production is depicted in Figure 4.13. There are slight differences in the range of -2% to +3% between the production of curved façade compared to flat façade. Mainly, the curved façade production seems to be slightly higher from April to August, while in autumn and winter months its production seems to be slightly lower. Nevertheless, the yearly estimated production difference is below 1%, so it can be concluded that both façades will have almost the same yearly production.

The final conclusions from the work described in this section are not only the production results obtained from BIMSolar, but also its suitability to model the new CIGS products developed under WP4 framework and their associated demonstration installations.

5 Optical and thermal modelling of thin film CIGS products at building level

5.1 BIPV EnergyPlus model

Depending on the integration method, FLISOM products can be modelled in two ways:

- If BIPV elements are integrated as covers, or are in direct contact with the envelope, they can be modelled as an additional layer in the wall composition. Given that the heat capacity of the product is not relevant at building scale, a massless layer can be declared and configured with the following inputs:

Table 5.1 EnergyPlus Material: NoMass configuration [1]

Roughness	[-]	From "very rough" to "very smooth". This input influences the convection coefficient. FLISOM BIPV can be considered to be smooth.
Thermal resistance	[m².K/W]	Product thermal resistance
Thermal absorptance	[-]	Fraction of long wave radiation absorbed by the material. For long wave radiant exchange, thermal emissivity and thermal emittance are equal to thermal absorptance. Values must be between 0.0 and 1.0.
Solar absorptance	[-]	Fraction of incident solar radiation that is absorbed by the material. Solar radiation (0.3 to 2.537 microns) includes the visible spectrum as well as infrared and ultraviolet wavelengths. Values must be between 0.0 and 1.0.
Visible absorptance	[-]	The visible absorptance field in the Material input syntax represents the fraction of incident visible wavelength radiation that is absorbed by the material. Visible wavelength radiation (0.38 to 0.78 microns weighted by photopic response) is slightly different than solar radiation in that the visible band of wavelengths is much narrower while solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths. Values must be between 0.0 and 1.0.

- BIPV integrated as cladding or ventilated façade needs to be modelled in a more complex way to simulate the heat transfer due to the air flow in the air gap. An appropriate model called "VentedCavity" can be used in EnergyPlus. The equation and its configuration is not described in this deliverable as it has already been presented in the deliverable 3.7 related to ONYX products simulation at element and building level.

5.2 Reminder on the results obtained for FD2 and EHG demo sites

The impact of PVSITES BIPV modules on the thermal behaviour of the demo sites has been assessed through simulations in the chapter "Demo system and building simulation using EnergyPlus" in deliverable D8.2.

FLISOM modules are used in 5 demo sites (3 buildings, 2 carports). Among these demo installations, 2 buildings have been simulated. The first one is a Belgian house located near Brussels on which the X1 products are used to replace the roof tiles. The second one is the “Ecole Hôtelière de Genève” (EHG) building located in Geneva Switzerland. For this demonstration site, the X1 modules are used as cladding system. For the third demo site located in Barcelona (Spain) and in which FLISOM technology (X1 CIGS roofing shingle on metal product) is planned to be installed as well, a “classic” building thermal simulation is not adapted (see reasons provided in D8.2). This is why this case is not considered here.

5.2.1 Format D2 house

The FD2 house is a 219m² building that hosts a residential and an office space. The building has a highly insulated enveloped that complies with the passive house level. Ventilation is achieved through a double flux air handling unit with an 84% efficient heat exchanger. Internal gains such as occupant, appliance and lighting are set according to on site measurement. During the winter period heating temperature set point is set to 21°C and set back is set to 17°C.

In D8.2, a baseline using standard roof tiles is simulated and compared to a version that uses FLISOM PV roof tiles. The setup is defined according to the following schemes:

Figure 5.1: FD2 panel location

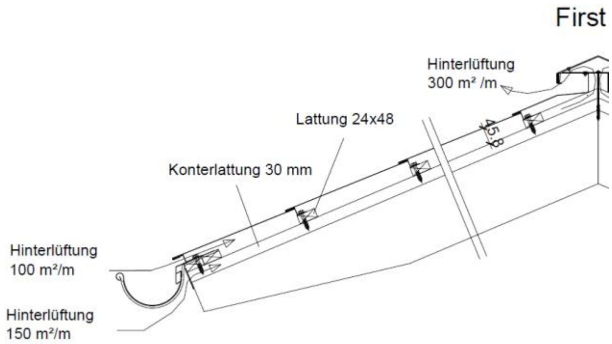

Figure 5.2: FD2 panel mounting system

Regarding the PV modules impact on the building heat needs, the simulations show a very small difference (around 4%) between both configurations.

Concerning thermal comfort, the PV has a very small impact on the Givoni indicator that is used to assess occupant summer thermal comfort. In the occupied rooms, the maximum temperature does not increase by more than 0.17°C, and the mean temperature increases by 0.14 to 0.16°C.

Considering these very low variations, the PV installation seems to have nearly no impact on the building behavior in terms of heating needs as well as comfort conditions.

5.2.2 EHG

This demonstration site is composed of two buildings. The opaque surfaces of the building envelopes have a heat transfer coefficient ranging from 0.2-0.6 W/m².K, the windows have a heat transfer coefficient ranging from 2.0 to 3.1 W/m².K with a Solar Heat Gain Coefficient (SHGC) of 0.40. The PV modules will be installed on two façades facing East and West. Ideal HVAC systems are considered for heating and ventilation. Temperature set point and air renewal rate are set according to French labour code recommendations.

Figure 5.3: One of the buildings in EHG site involved in the demonstration (right side of the photo)

FLISOM PV modules are considered to be integrated as a standard vertical cladding system with a 5cm air gap between the PV modules and the building façade.

At building level, the simulations show a heat need difference of 1% between the baseline and the configuration integrating FLISOM BIPV system. Regarding thermal comfort, the Givoni comfort index value does not vary by more than 4% and the maximum temperature in the adjacent rooms do not exceed 0.24°C.

5.3 Objectives of simulations at building level

Considering the above results, it appears that the effect of the PV modules on the building thermal performance is low. In order to better quantify the effects and to understand which parameter or which physical phenomena will be predominant, a Sensitivity Analysis (SA) is carried out on the PV model input for the EHG building. The impact of the BIPV model on the adjacent room is observed through heat needs and thermal comfort indicators. Three different SA are carried out:

- Characterization of the impact of the vented cavity model for the full range of each parameter on the adjacent room.
- Characterization of the impact of the uncertainty parameters on the two main BIPV properties: solar absorption and solar reflectance. It also quantifies the impact of the thickness of the airgap and of the airflow in the cavity.
- Characterization of the impact of a solar cladding with regard to the building envelope, internal gain, and HVAC uncertainty.

5.4 Sensitivity analysis

5.4.1 Methodology

In the past years, Sensitivity Analysis (SA) and Uncertainty Analysis (UA) have been widely used in Building thermal simulation to identify the parameters that affect the building thermal performances. Tian et al [] provided an extensive review of the most used SA methods in the building domain. According to this review, ranked regression methods such as Partial Ranked

Correlation Coefficient (PRCC), and variance-based methods such as Sobol are well adapted to non-linear models. This makes these methods good candidates for building analysis.

NOBATEK has developed an EnergyPlus based sensitivity analysis library in Python featuring several SA methods, using from linear regression to variance. In this study, the number of uncertain parameters is reduced (<10), so the Sobol method can be used with a reduced number of simulations. From a sample of simulation, a meta-model is built using the chaos polynomial method. Its accuracy is validated during the construction process, using Mean Average Error (MAE) and Root Mean Square Error (RMSE). The polynomial is used to compute an approximation of the Sobol index using its coefficient. Also, its fast execution allows to perform uncertainty analysis.

5.4.2 Reminder on EHG model hypothesis

The demo site is composed of 2 buildings located in the city of Genève (Switzerland). The BIPV modules are integrated as cladding on these buildings. Their location is displayed on the following figure:

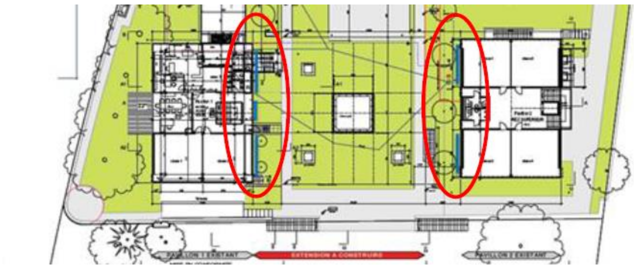

Figure 5.4: FLISOM PV modules location

The buildings shading environment and thermal zones separation are displayed below:

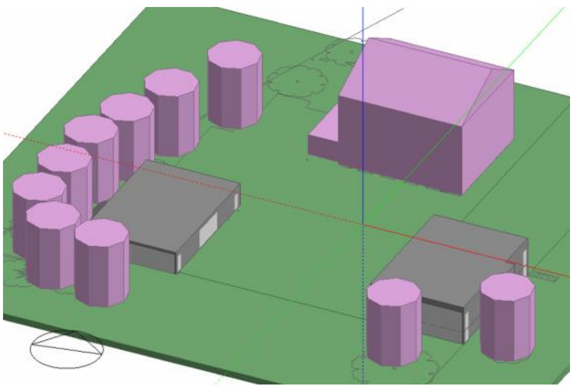

Figure 5.5: 3D model view

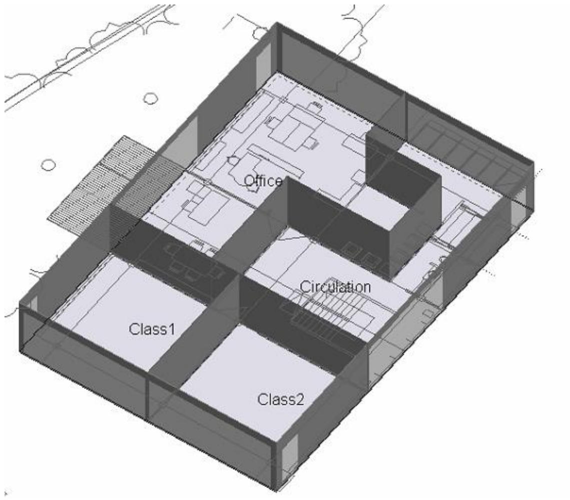

Figure 5.6: Pavilion 1 - Ground floor

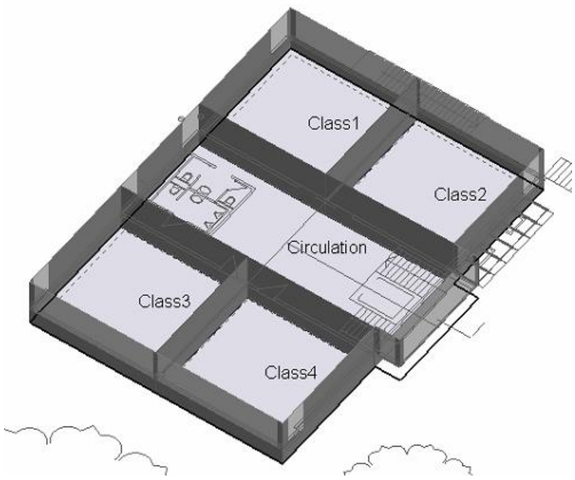

Figure 5.7: Pavilion 1 - Ground floor (partially buried)

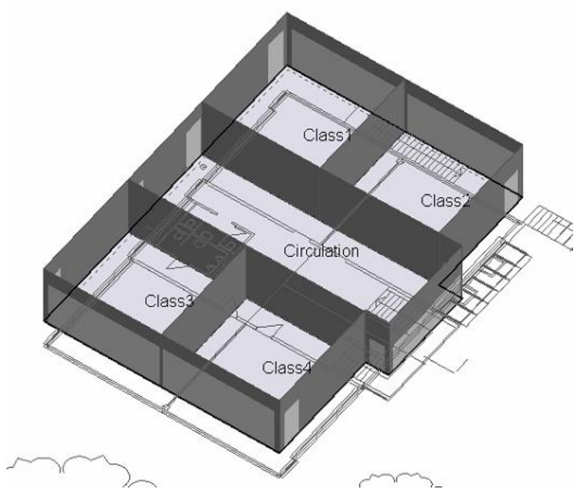

Figure 5.8: Pavilion 1 - 1st floor

- Building envelope thermal performance is uncertain with heat transfer coefficient ranging from 0.4 to 0.6 W/m².K for pavilion 1 and from 0.2 to 0.4 W/m².K for pavilion 2.
- Windows properties are unknown. Given the year of construction, assumptions are made. Heat transfer coefficient is 3.10 W/m².K for pavilion 1 and 2W/m².K for pavilion 2. Solar Heat Gain Coefficient is assumed to be 0.4.
- Infiltration level is assumed to be 2.37 Vol/h.m² @50Pa.
- Regarding internal heat gain, hypothetic schedule and level of heat power are derived from the French thermal mandatory calculation (RT2012) []. A density of 0.45 pers/m² is assumed in the classroom with a heat gain of 80W/pers. Appliance heat gain is 5 W/m².
- HVAC equipment are modelled as ideal system. Heating temperature set-point is 20°C, set-back is 17°C. In summer the office part is cooled to 24°C. Regarding mechanical ventilation, a fresh air supply of 18m^3/h.people in the classroom and 25 m^3/h.people in the office part is assumed.

5.4.3 Impact of the vented cavity model on building thermal behaviour

The first sensitivity analysis study aims at characterizing the impact of the vented cavity model on the building heating/cooling needs and summer thermal comfort. The baffle models inputs are considered as uncertain parameters. Their probability density functions are considered uniform and bounded by the minimum and the maximum allowable values (except for the gap thickness). This way the results will show the impact of each input on its full range of variation:

Table 5.2 Vented cavity impact uncertain parameter

Vented cavity model – Parameters		
Thermal Emissivity of Exterior Baffle Material [-]	0 - 1	Baffle material emissivity
Solar Absorptivity of Exterior Baffle [-]	0 - 1	Baffle material solar absorption
Effective Thickness of Cavity Behind Exterior Baffle [m]	0.02 – 0.1	Air gap thickness
Effectiveness for Perforations with Respect to Wind	0 - 1	Coefficient related to wind driven air gap ACH
Discharge Coefficient for Openings with Respect to Buoyancy Driven Flow	0 - 1	Coefficient related to buoyancy driven air gap ACH

A 1000 simulations sample is generated with uncertain parameters values randomly selected from their pdf. From this result, meta-models are generated and validated for each room and each indicator. The relative RMS errors are around 0.02% and the relative maximum error does not exceed 0.16% which makes the meta-models very accurate. It is used to:

- Compute a Sobol index approximation,
- Perform an Uncertainty study: the meta model is used to cast 10 000 simulations.

5.4.3.1 Heating needs analysis

Heating needs are observed for the 5 occupied thermal zones that are in contact with the BIPV installation. The following statistical results are obtained from the 10 000 meta model simulations:

Table 5.3 Heating needs calculated for the five thermal zones

	Mean [kWh/m²]	Max [kWh/m²]	Min [kWh/m²]	Uncertainty [%]
GF Pavilion2 Class 1	67	68	66	1.5%
GF Pavilion2 Class 3	55	56	54	1.6%
R1 Pavilion2 Class 1	106	108	103	1.8%
R1 Pavilion2 Class 3	92	94	90	2.0%
GF Pavilion1 Class 2	111	114	108	1.9%

These results indicate that classrooms located in pavilion 1 and on the first floor of pavilion 2 have a greater heat need than the one located at the ground floor (and half buried). Obviously, this is due to a larger surface of external walls in contact with the outside air that increases the heat loss.

Regarding the impact of the vented cavity model on the zone heating needs, the results show that the cladding configuration has a very small impact. No matter the zone or the orientation, the vented cavity doesn’t impact the needs by more than 2% of the mean value. The gap between the minimum and the maximum obtained values is inferior to 5% of the mean value. The following graph displays the heat needs density of probability for the Class 3 of pavilion 2 at the 1st floor:

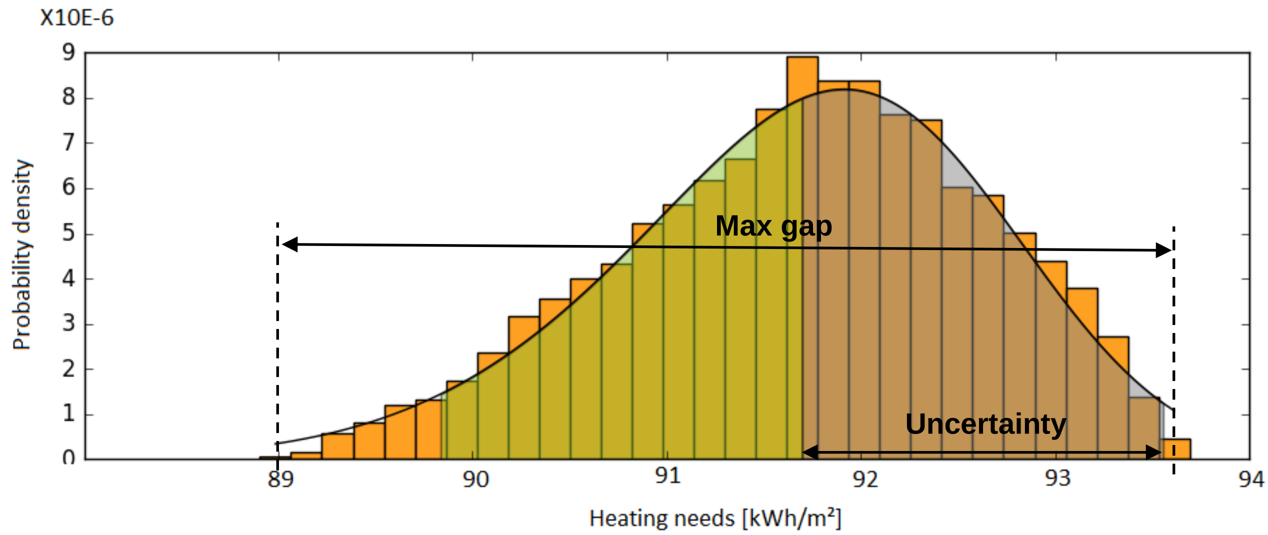

Figure 5.9: Pavilion 2 – Class 3 (GF + 1)

For each classroom, the Sobol index is derived from the meta-model coefficient. The results are presented on the graph below:

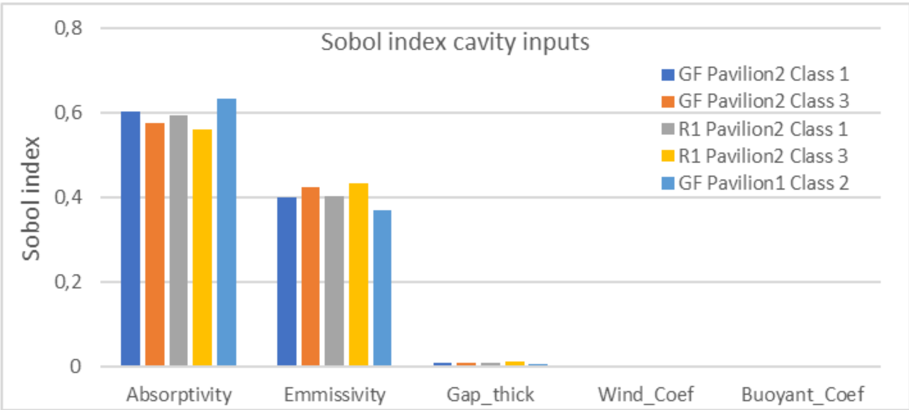

Figure 5.10: Pavilion 1 - Ground floor (partially buried)

The baffle material absorptivity and emissivity account for at least 90% of the heat needs variation. This means that most of the heat transfers are due to long wave radiation. According to the SA, the convective transfers due to air change in the air gap (buoyant and wind effect) do not strongly impact the heat needs.

5.4.3.2 Summer thermal comfort analysis

Givoni comfort indicator and maximum Operative Temperature (OT) are observed for the 5 occupied thermal zones that are in contact with the BIPV installation. The Givoni indicator is explained in D8.2 in the chapter dedicated to simulations and will not be further described here. The following statistical results are obtained from the 10 000 meta model simulations:

Table 5.4 Number of hour when indoor conditions overtake Givoni 0.5m/s zone

	Mean [kWh/m²]	Max [kWh/m²]	Min [kWh/m²]	Uncertainty [%]
GF Pavilion2 Class 1	28	31	27	7%
GF Pavilion2 Class 3	44	55	36	18%
R1 Pavilion2 Class 1	40	54	36	18%
R1 Pavilion2 Class 3	70	90	58	18%
GF Pavilion1 Class 2	66	88	52	24%

Table 5.5 Thermal zones maximum operative temperature

	Mean [kWh/m²]	Max [kWh/m²]	Min [kWh/m²]	Uncertainty [%]
GF Pavilion2 Class 1	32.6	33.2	32.2	0.4
GF Pavilion2 Class 3	32.6	33.2	32.2	0.5
R1 Pavilion2 Class 1	34.3	35.0	33.7	0.6
R1 Pavilion2 Class 3	34.3	35.1	33.7	0.6
GF Pavilion1 Class 2	33.8	34.9	33.0	0.8

The results associated with Givoni thermal comfort indicator show a strong uncertainty no matter the classroom orientation. Except for the “GF Pavilion2 Class 1 » which is a thermal zone that is half buried and North oriented, the uncertainty is superior to 18% for the other rooms. However, the impact on the zones maximum OT is very low, and the uncertainties do not exceed 0.8°C. It means that the vented cavity won’t have a strong impact on the rooms temperatures, but also that considering the number of hours when indoor conditions are overtaking one of Givoni zone may be hazardous due to the high sensitivity of this indicator.

The following graph displays the Sobol index for the maximum OT indicator.

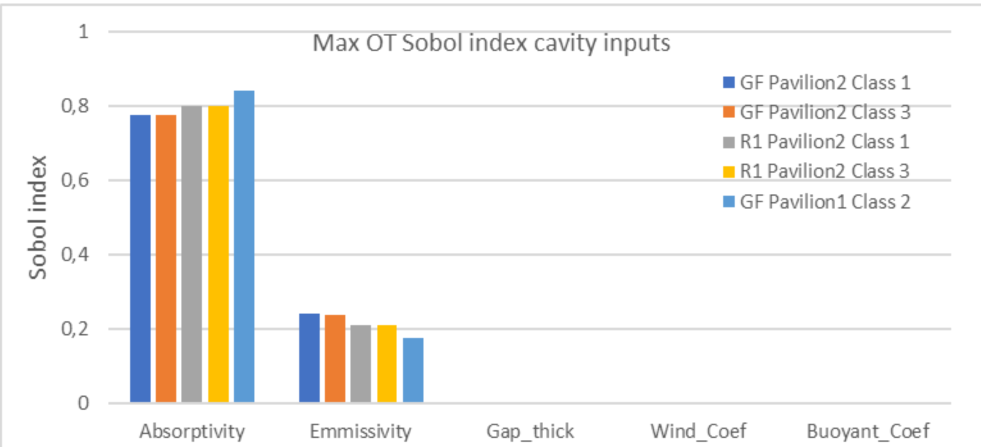

Figure 5.11: Pavilion 1 - Ground floor (partially buried)

The Sobol index calculation confirms the results obtained for the heating needs. The baffle material absorptivity and emissivity account for at least 90% of the OT variance. It means that convective transfers due to air change in the air gap (buoyant and wind effect) do not strongly impact the rooms temperature.

5.4.4 Impact of FLISOM BIPV modules on building thermal behaviour

5.4.4.1 Hypothesis

For this study, the variation interval of the uncertain parameters is reduced to represent the uncertainties linked to the BIPV properties characterisation (absorptivity and emissivity) and to the cladding implementation. Therefore, the new uncertain parameters configuration is as follows:

Table 5.6 Uncertain parameters configuration

Idf input description (EnergyPlus file)	Description	Probability density function
Thermal Emissivity of Exterior Baffle Material [-]	BIPV Emissivity	Normal: mean = 0.84 uncertainty = 10%
Solar Absorptivity of Exterior Baffle [-]	BIPV Solar absorption minus average electric efficiency	Normal: mean = 0.8 uncertainty = 10%
Effective Thickness of Cavity Behind Exterior Baffle [m]	Air gap thickness	Normal: mean = 0.05 m uncertainty = 10%
Effectiveness for Perforations with Respect to Wind	Coefficient related to wind driven air gap ACH	Uniform [0 ; 1]
Discharge Coefficient for Openings with Respect to Buoyancy Driven Flow	Coefficient related to buoyancy driven air gap ACH	Uniform [0 ; 1]

Normal laws are used for BIPV properties and system implementation. It represents the possible errors in the product characterisation process and in the cladding construction. Given that buoyant and wind coefficients are very hard to define, uniform law bounded by minimum and maximum allowed values is used. This way the influence of these parameters will be well taken into account.

A 1000 simulations sample is generated with uncertain parameters values randomly selected from their pdf. From this result, meta-models are generated and validated for each room and each indicator. The relative RMS error are around 0.02% and the relative maximum error do not exceed 0.05% which makes the meta-models very accurate. It is used to:

- Compute a Sobol index approximation,
- Perform an Uncertainty study: the meta model is used to cast 10 000 simulations.

5.4.4.2 Results analysis

For this study, the reduction of the variation interval for the main uncertain parameters and the use of normal laws further reduce the impact of the vented cavity. Regarding the heat needs, the average uncertainty is around 0.2% and the maximum gap between minimum and maximum heat need is around 0.8% of the mean value. At this level, the impact can be considered negligible.

For thermal comfort, only maximal OT is studied. The results show an uncertainty of 0.1°C for every classroom, and the maximum gap between minimum and maximum value is 0.3°C. For thermal comfort, the impact of the uncertainties on the BIPV modules characterization and installation is nearly null.

To illustrate the results, the following pictures show the heat needs and maximum OT density of probability for the Pavilion 1 classroom (which has the greater uncertainty):

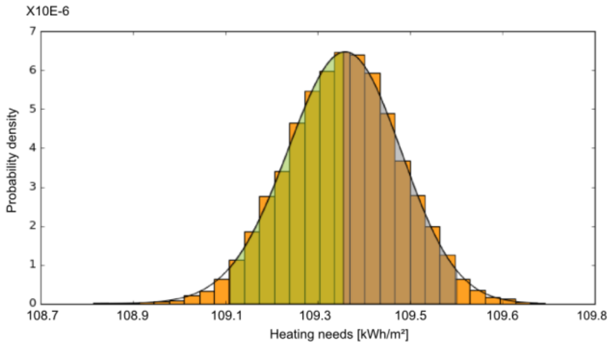

Figure 5.12: Pavilion 1 - Ground floor classroom heating need density of probability

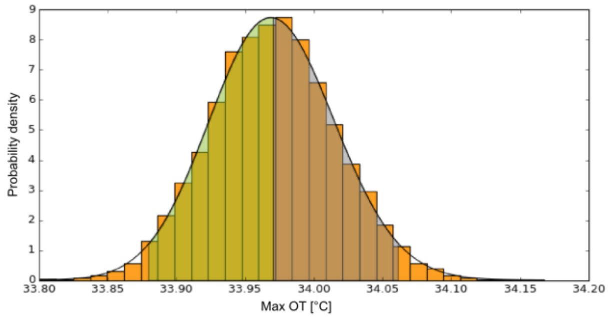

Figure 5.13: Pavilion 1 - Ground floor classroom OT density of probability

The sensitivity analysis results for the classrooms and for the heating need and the maximum operative temperature are displayed on the following graph:

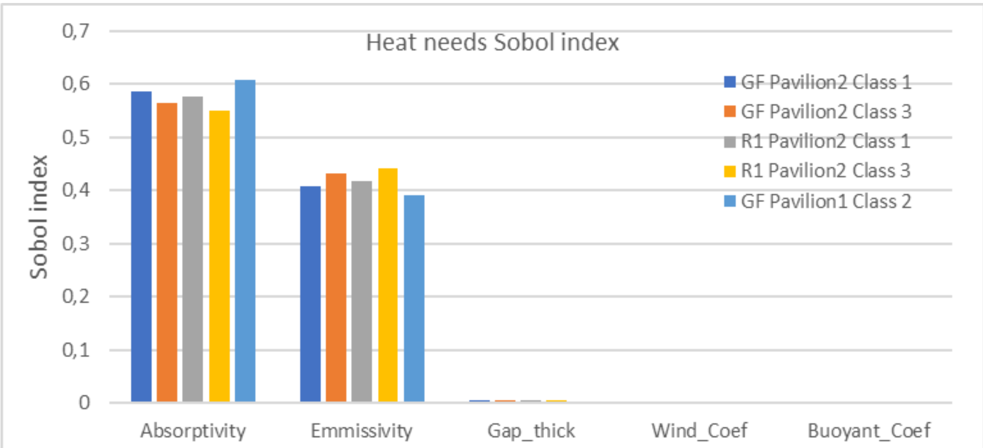

Figure 5.14: Heat needs Sobol index BIPV modules

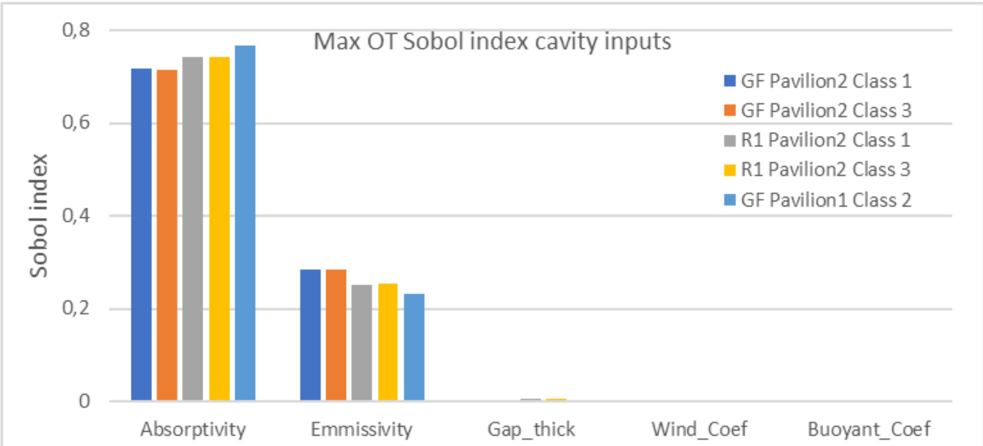

Figure 5.15 Maximum OT Sobol index BIPV modules

The Sobol index calculation confirms the results of the previous sensitivity analysis. The BIPV material absorptivity and emissivity account for at least 95% of the OT variance. Uncertainty related to air changing rate in the cavity does not strongly impact the results.

Overall, this UA demonstrates that according to the building model, the FLISOM BIPV modules used as cladding systems will not strongly affect the building thermal behaviour. Moreover, errors in the BIPV characterization process, or assumption regarding buoyant and wind coefficient are not of great importance.

5.4.5 Impact of a solar cladding with regard to building overall uncertainty

The last analysis includes the previous uncertain parameters configuration and adds 8 other parameters related to internal heat gain, HVAC systems behaviour and building envelop performance. The parameters are gathered and described in the following table:

Table 5.7 Uncertain parameters configuration

Uncertain parameters	Description	Comments
BIPV Emissivity	Normal: mean = 0.84 uncertainty = 10%	
BIPV Solar absorption minus average electric efficiency	Normal: mean = 0.8 uncertainty = 10%	
Air gap thickness	Normal: mean = 0.05m uncertainty = 10%	
Wind driven airflow coefficient	Uniform [0 ; 1]	
Buoyancy driven airflow coefficient	Uniform [0 ; 1]	
External surface heat conductivity	Uniform [67% ; 133%]	According to the energy audit, conductivity of opaque surface is very uncertain. It lies between 0.2 and 0.4 for pavilion 1 and between 0.4 and 0.6 for pavilion 2. This model by material conductivity uniformly varying from 67% to 133% of their nominal value
External windows heat transfer coefficient	Normal mean = 1, uncertainty 15%	The heat transfer coefficient has been guessed based on the building year of construction. An uncertainty of 15% is applied
SHGC	Normal mean = 1, uncertainty 15%	The windows SHGC has been guessed based on the building year of construction. An uncertainty of 15% is applied
Shading solar transmittance	Normal mean = 1, uncertainty 15%	The buildings have external shading device to reduce the solar heat gain. A solar transmission of 0.20 is assumed with an uncertainty of 15%.
Infiltration	Normal mean = 1,	Infiltration is a very uncertain

	uncertainty 25%	parameter. A 25% uncertainty is assumed.
Mechanical ventilation ACH	Normal mean = 1, uncertainty 15%	Mechanical ventilation ACH has been guessed from the occupation hypothesis. An uncertainty of 15% is associated to account for the air vents adjustment.
Heating temperature set point	Normal mean = 1, uncertainty 10%	An uncertainty of 2°C is assumed
Internal gain	Normal mean = 1, uncertainty 15%	An uncertainty of 15% is associated to the internal gain. It corresponds to plus or minus 3 people in each classroom.

A 1000 simulations sample is generated with uncertain parameters values randomly selected from their pdf.

Increasing the number of uncertain parameters while keeping the same simulation sample size reduces the accuracy of the meta-model. While increasing the sample size could have improved the meta-model construction, the errors remain acceptable. For the 3 indicators and for all the studied thermal zones, maximum relative RMS and relative maximum error are displayed in the following table:

Table 5.8 Meta model relative and maximum errors

Indicator	Maximum relative RMS error	Maximum relative Max error
Heating needs	0.8%	5.9%
Givoni, number of hours overtaking 0.5 m/s zone	8.8%	37.7%
Maximum OT	0.2%	1.0%

Excepted for the Givoni indicator, the generated meta-models remain very accurate. They can be used to evaluate the Sobol index and to perform UA. Regarding Givoni indicators, the meta-models are not accurate enough to perform UA. The presented results will be based on a statistical treatment of the simulation sample. However, Sobol index calculation remains accurate.

5.4.5.1 Heating needs analysis

Using the meta-models, UA are performed for each of the 5 classrooms. The following statistical results are based on 10 000 evaluations of the meta-models:

Table 5.9 Heating needs analysis

	Mean [kWh/m²]	Max [kWh/m²]	Min [kWh/m²]	Uncertainty [%]
GF Pavilion2 Class 1	68	120	33	35%
GF Pavilion2 Class 3	56	112	24	39%
R1 Pavilion2 Class 1	107	179	56	31%
R1 Pavilion2 Class 3	93	156	41	33%
GF Pavilion1 Class 2	112	183	56	30%

For all the classrooms, mean heating needs are nearly equal to the ones obtained with the first SA that studied the impact of the vented cavity model. However, the inclusion of uncertain parameters on envelop performance, HVAC system and internal gains add a lot of variability to the results. The uncertainties ranging from 30% to 40% of the mean heating needs indicate that the simulation input parameters are not accurate enough to be confident on the real building heat needs. A graphical representation of the heat need density of probability is shown below for the thermal zone "GF Pavilion2 Class 3":

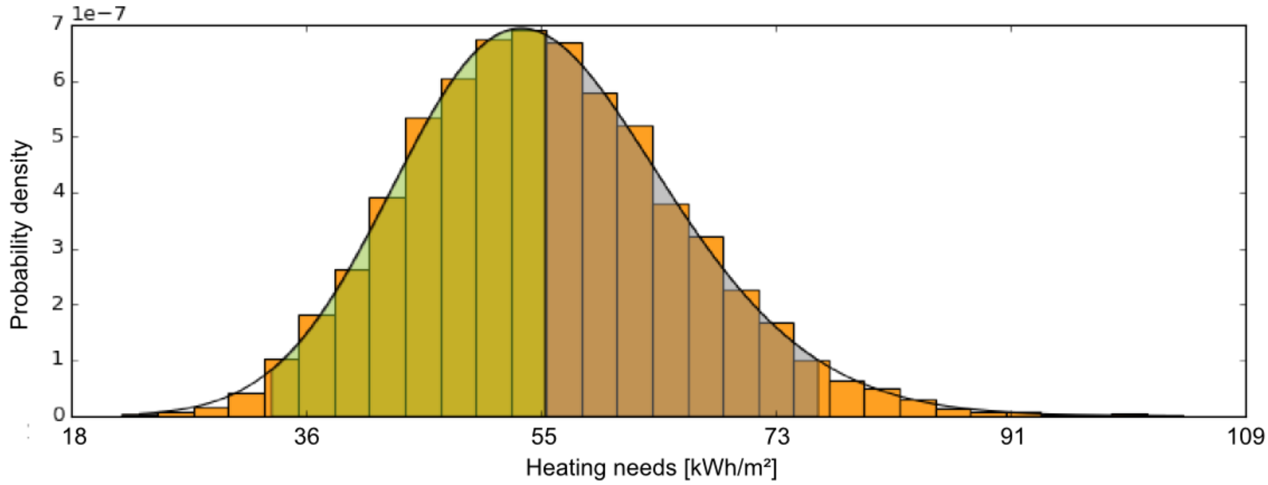

Figure 5.16: Pavilion 2 - Ground floor classroom 3 heating need density of probability

With 95% of the results lying between 34kWh/m² and 78kWh/m² the classroom heat need cannot be accurately estimated.

The use of the sensitivity analysis helps to identify the most impacting parameters. A graphical representation of the Sobol index for every classroom is shown in the figure below:

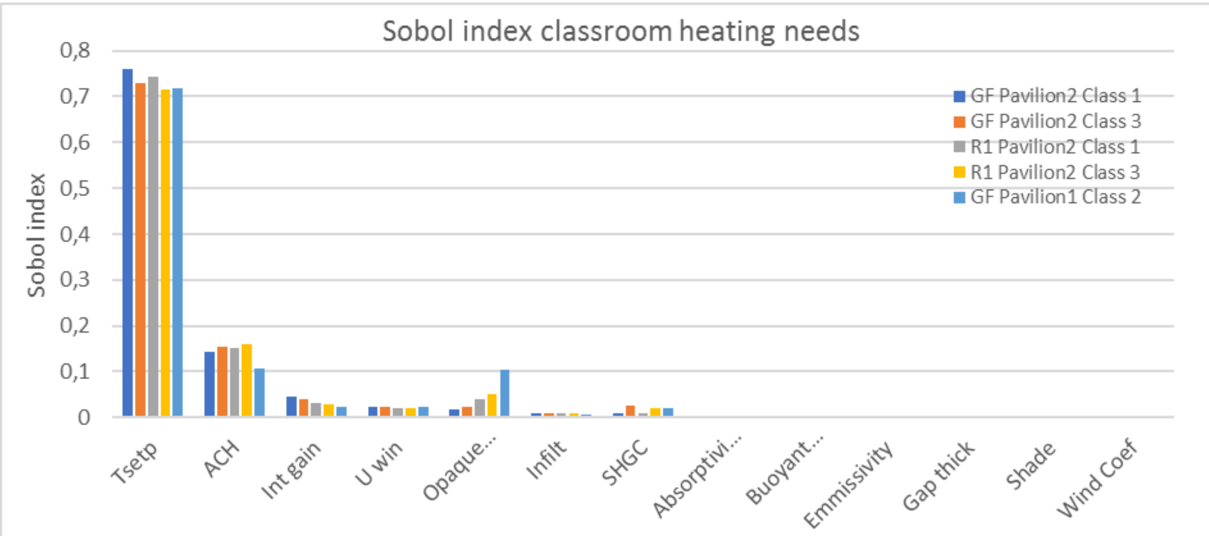

Figure 5.17: Pavilion 2 - Ground floor classroom 3 Sobol index for heating needs

The uncertain parameter ranking is almost similar for every classroom. The temperature set point is the most impacting uncertainty, and account for more than 70% of the variance of the results. Uncertainties related to air changing rates (mechanical ventilation and infiltration) are responsible of around 15% of the heat needs variance. Finally heat gains and parameters related to the envelop performance (windows and opaque surface) have a non-negligible impact on the indicator.

Envelop uncertainties seem to have a greater impact on the pavilion 1 classroom. However, compared to the other parameters, BIPV system properties have a negligible influence on the heating needs.

This last conclusion shows that BIPV impact on building heat demand is negligible. Also, given the amount of uncertainties on the EHG building characteristics, the comparison between experimental (monitored data) and simulation results that is planned within WP8 activities needs to be handled carefully and will be probably more restricted than what was planned initially.

5.4.5.2 Summer thermal comfort analysis

For summer thermal comfort study, two indicators are observed:

- The number of hours when indoor conditions overtake the 0.5m/s Givoni zone,
- The maximum operative temperature reached in each zone.

The statistical results obtained from the simulation for the Givoni results and from the meta-models evaluation for the maximum operative temperature are displayed on the following tables:

Table 5.10 Number of hour when indoor conditions overtake Givoni 0.5m/s zone

	Mean [kWh/m²]	Max [kWh/m²]	Min [kWh/m²]	Uncertainty [%]
GF Pavilion2 Class 1	31	76	13	52%
GF Pavilion2 Class 3	48	128	18	65%
R1 Pavilion2 Class 1	43	92	25	47%
R1 Pavilion2 Class 3	74	136	40	43%
GF Pavilion1 Class 2	72	127	42	39%

Table 5.11 Thermal zones maximum operative temperature

	Mean [kWh/m²]	Max [kWh/m²]	Min [kWh/m²]	Uncertainty [°C]
GF Pavilion2 Class 1	32.7	36.0	30.5	1.3
GF Pavilion2 Class 3	32.7	35.7	30.9	1.3
R1 Pavilion2 Class 1	34.4	37.0	32.1	1.3
R1 Pavilion2 Class 3	34.5	37.2	33.0	1.2
GF Pavilion1 Class 2	34.1	36.8	32.2	1.3

As for the heating needs, the Givoni thermal comfort indicator results show a strong uncertainty no matter the classroom orientation. The impact on the zones maximum OT is also elevated with an uncertainty of 1.3°C. It means that the parameters will have a non-negligible impact on the classroom summer indoor conditions.

The following graph displays the Sobol index for the maximum OT and for the Givoni indicators:

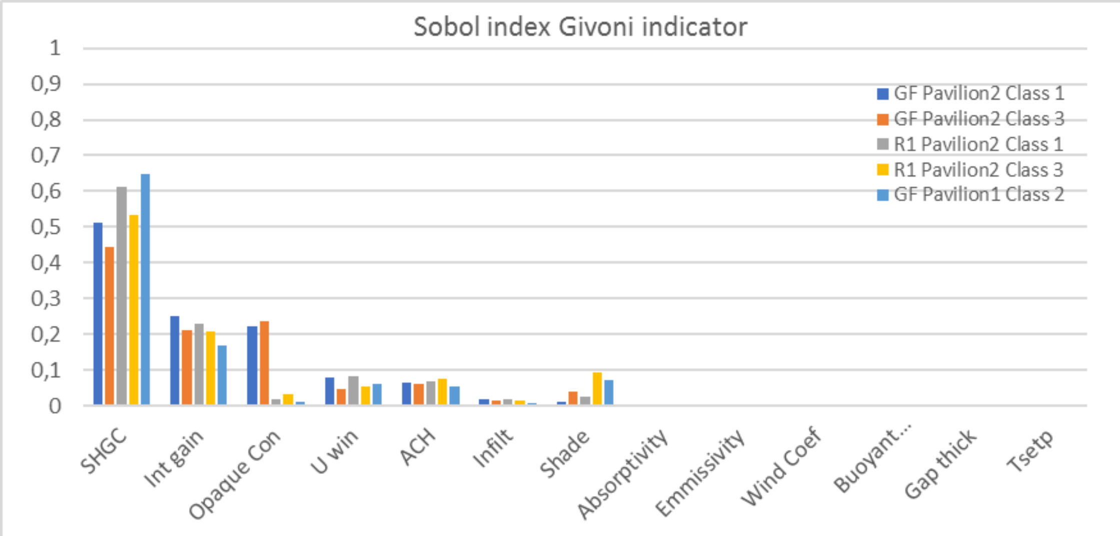

Figure 5.18: Sobol index for Givoni indicator

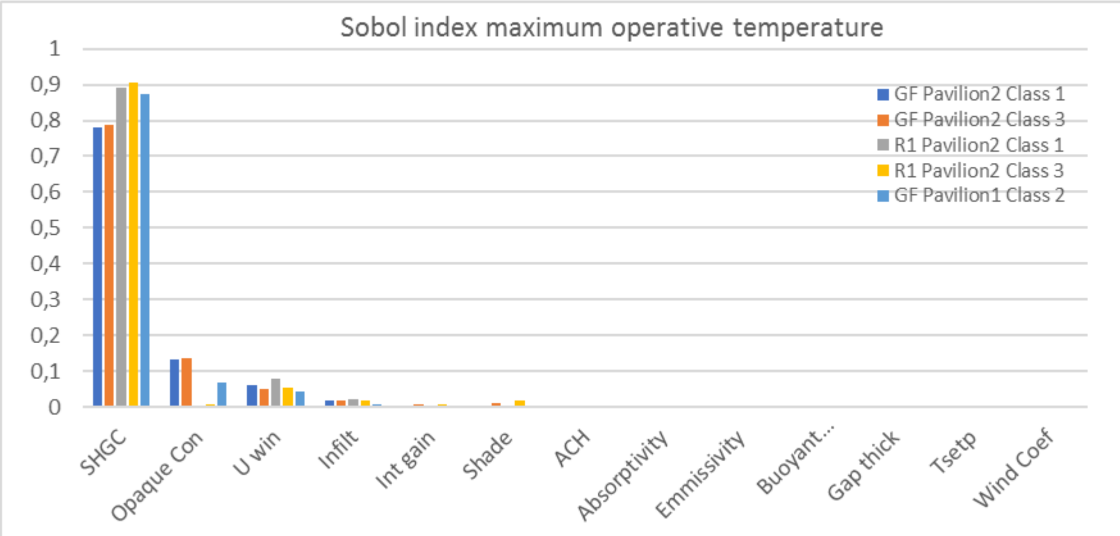

Figure 5.19: Sobol index for maximum OT indicator

Regarding the maximum operative temperature reached in the classroom, the most impacting uncertain parameter is the windows solar heat gain coefficient. It is responsible for nearly 80% of the indicator variance. Envelope heat transfer coefficient (opaque surface plus windows) are responsible for 10% of the variance.

For Givoni indicators, the effects of the uncertain parameters are more distributed. The SHGC is still the most influent parameter, but it only affects 40% to 60% of the indicator variance. When adding the effects of the shading devices, we can conclude that the uncertainties linked to the solar gain have a strong impact on the result variability. Next internal heat gain assumption strongly influences the comfort. Then envelop heat transfer coefficient and air change rate.

Finally, compared to the other parameters, BIPV cladding parameters have a negligible impact on indoor conditions

5.5 Conclusion on thermal modelling of thin film CIGS products at building level

To better understand the impact of FLISOM BIPV modules used as cladding system, 3 sensitivity analyses have been carried out. The aim was to quantify the impact of the system on the building heat needs and on summer thermal comfort and also to better understand how uncertainties in the modules characterization or implementation affect building thermal simulation.

The first SA analysis studied the impact of the vented cavity input parameters varying on their full range. The second restrains the parameter to only account for the BIPV properties and system implementation unknowns.

The results of this study show a very small impact of the system on the building thermal behaviour, both on the heat needs and on the thermal comfort.

The third SA analysis aimed at stepping back from the BIPV model, in order to observe the cladding effects among the other building uncertainties. Uncertain parameters regarding envelop performance, HVAC system, and building occupancy were added.

The obtained results show a strong dispersion of the results both for the heating needs and for the thermal comfort indicators. For heat needs, several parameters such as temperature set point, air change rate and envelop heat transfer coefficient strongly impact the results, leading to uncertainties as high as 40% of the mean heating needs. Regarding thermal comfort uncertainties related to solar heat gains and building envelop performance leads to a strong dispersion of the indicators.

The two main conclusions that can be drawn from these results are:

- When used as cladding system, BIPV modules do not have a strong impact on the building thermal behaviour,
- Uncertainties linked to HVAC configuration, internal heat gain assumption and envelop performance have a strong impact on the simulation results.

This study also raised another issue related with demonstration activities. One of the objective of the project is to compare building thermal simulation results to the monitored data collected on the demo-sites. Given the low impact of the BIPV system, and the strong impact of the other unknown parameters, the comparison will be probably more restricted than expected.

6 REFERENCES

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