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Assessment of thermal and electrical performance of BIPV façades using simplified simulations

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Abstract. Building integrated photovoltaic (BIPV) facades are a solution to consider when it comes to electricity generation on the building site. One of the main challenges attributes to this technology is finding the best trade-off between the electrical efficiency of BIPVs and the energy use of the building. This study aims to identify a scenario that yields the optimized results for electrical and thermal performance in a test building. Among the scenarios, the original wooden cladding in the test building is either replaced with PV panels or the PV modules are added to the existing facade. Rhinoceros 3D CAD software and its visual programming plugin Grasshopper are used to perform various simulations for both east-oriented and west-oriented façades with low and high thermal inertia wall structures. Although a complex flow phenomenon behind BIPVs is simplified in the 3D heat transfer model, relatively reliable results are obtained using the chosen simulation tool. It is observed that the east-faced BIPV facade in the test building has higher electrical efficiency. This could be attributed to the lower inertia of the east wall that allows easier propagation of heat through the structure.

1. Introduction

Nowadays, energy production in the building sector has become an important issue. Indeed, fossil resources are not infinite, and it is necessary to think about their replacement by renewable resources. As a renewable energy source, solar energy could be converted into electricity by employing photovoltaic systems. Due to the lack of available area in a dense urban space, Building Integrated Photovoltaic (BIPV) technology, incorporating photovoltaic (PV) modules into the elements of the building envelopes such as façades, has been shown to play an essential role in the on-site production of electricity [1].

This study aims to analyse the thermal and electrical performance of the BIPV façade implemented in a building prototype. Eight scenarios of different façade compositions are studied for two representative days of summer and winter in a test reference year. The solution that yields the trade-off between the energy used and the energy generated throughout the year is provided. In the first section of this paper, different simulated scenarios are introduced. Thereafter, the methodology for the calculations is explained. Finally, the results are presented and compared.

1.1. The test building

The building that is used for the simulations is a shared research facility building prototype in the Smart Living Lab named *Controlled Environment for Living Lab Studies* (CELLS) located in Fribourg (Switzerland) [2]. The building is composed of two identical rooms with different thermal inertia walls.

The low inertia room (room 1) is east-oriented, and the high inertia room (room 2) is west-oriented. The high inertia room has an extra layer of compressed earth bricks compared to the low inertia room. The original facade is a wooden cladding. The external cladding is separated from the wall core incorporating a ventilated air-space that creates an airflow typically entering from the bottom and leaving from the top openings when buoyancy forces exceed the wind-driven pressure. The composition of the building elements and the physical properties of the materials are listed in Table 1.

Table 1. Description of the wall layers with thermal properties of the modelled materials [2-4]

	Materials	**Thickness [mm]**	**Conductivity [W/m K]**	**Density [kg/m^3]**	**Heat capacity [J/kg K]**
Roof	Gravel	50	2	2000	900
	Bitum elastometric membrane	4	0.2	875	4500
	Insulation polyurethane	180	0.031	15	1116
	Vapour barrier	0.22	0.4	500	1800
	OSB panels	25	0.13	600	2150
Floor	Linoleum	3	0.17	1200	1470
	Cement screed	50	0.8	1400	1000
	Acoustic insulation	9	0.15	556	1700
	OSB panels	25	0.13	600	2150
	Insulation glass wool	350	0.032	28	1030
	Wooden panels	60	0.047	250	2100
Walls	Wooden cladding	24	0.15	450	1800
	Air Layer	70	-	-	-
	Permeable membrane	0.45	0.17	900	1800
	Insulation polyurethane	180	0.031	15	1116
	Vapour barrier	0.22	0.4	500	1800
	Wooden structure	140	0.13	471	1600
(Extra layer in the high inertia wall)	Compressed earth bricks	50	0.79	1900	1100

2. Methodology

2.1. Simulated scenarios

Eight scenarios are considered to analyze the impact of different external cladding compositions on the electrical and thermal performance of the wall assemblies (Figure 1).

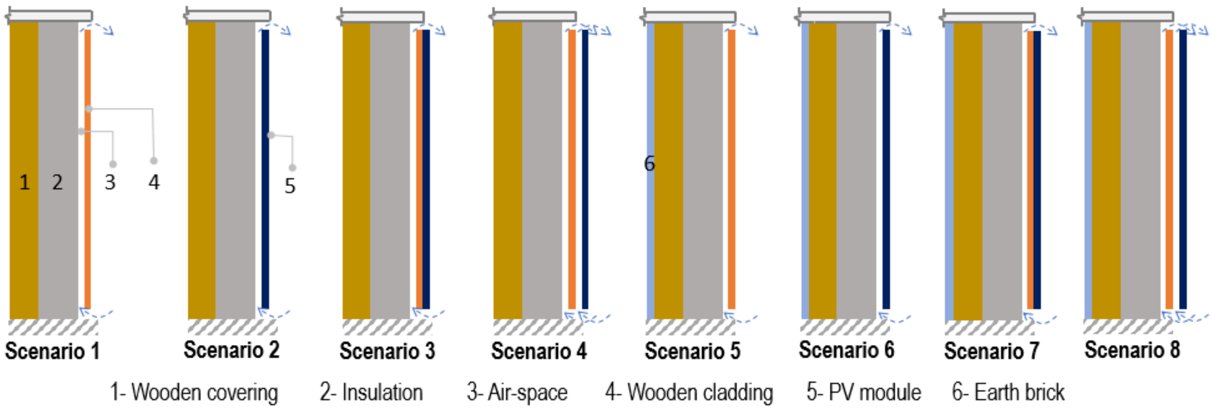

Figure 1. Schematic representation of the eight scenarios analysed (scenarios 1-4 on the east wall and scenarios 5-8 on the west wall)

The air cavity behind the external cladding is ventilated in all cases; the external cladding is changed in different scenarios. Scenarios 1 to 4 are similar to scenarios 5 to 8 but applied to the east facade with a lower inertia wall. Only the first scenarios in each wall (scenarios 1 and 5) have the original wooden cladding. The original cladding is replaced with a polycrystalline photovoltaic panel in scenarios 2 and 6. The PV modules are attached to the wooden cladding in scenarios 3 and 7, in which there is no air-space behind the PV panels. In scenarios 4 and 8, the PV panels are added to the façade such that one ventilated cavity is created behind the PV modules and another air gap presents behind the wooden cladding. The Si-based PV panel consists of tempered glass, photovoltaic cells encapsulating between EVA layers, a polymer back sheet, and a final structural frame used for framing the module. The physical properties of each layer are taken from [5]. The electrical efficiency of the PV panel is assumed to have a linear dependence on the PV temperature and solar flux with a nominal efficiency equal to 12 %. The height of the panels is assumed to be equal to 1.64 m [5].

2.2. Analysis period
The sol-air temperature is calculated considering the daily outdoor temperature and solar radiation. Thereafter, the typical winter and summer days in 2005, as a test reference year, are determined as December 8th and August 14th using the cumulative frequency of the sol-air temperature [6]. In the first step, hourly simulations of typical summer and winter days are performed. Then monthly simulations are done for the entire year.

2.3. Simulation tool
The 3D geometry of the building prototype is modelled in Rhino. To perform energy analysis, the '*Honeybee'*, *'Ladybug'*, and *Butterfly'* plugins from the '*Ladybug Tools* library are used in Grasshopper [7]. Grasshopper 3D is connected to EnergyPlus/OpenStudio to run energy simulations (Figure 2). To run a CFD analysis of the air cavity, the Butterfly plugin is used. The input values of the butterfly components are the output values obtained with Honeybee. The daily simulations are performed considering a 1-hour time step. The complex flow phenomenon behind BIPVs is simplified using a 3D heat transfer model in Grasshopper. The ventilated air cavity is modelled as an unheated plenum zone with natural ventilation with two openings and without an insect screen. Appropriate wind pressure and heat transfer coefficients are applied to model the wind and stack effects. The wooden slats inside the air cavity are neglected. The physical properties of the outer layer of the PV panel are approximated as the average physical properties between the EVA layer and the tempered glass.

2.4. Simulations
The methodology used to perform the CFD simulation is based on the work of Ahmar et al. [8]. The energy used in the building is determined by employing the EnergyPlus tool. The Honeybee tool calculates the heating and cooling demands of the building for a predetermined time duration.

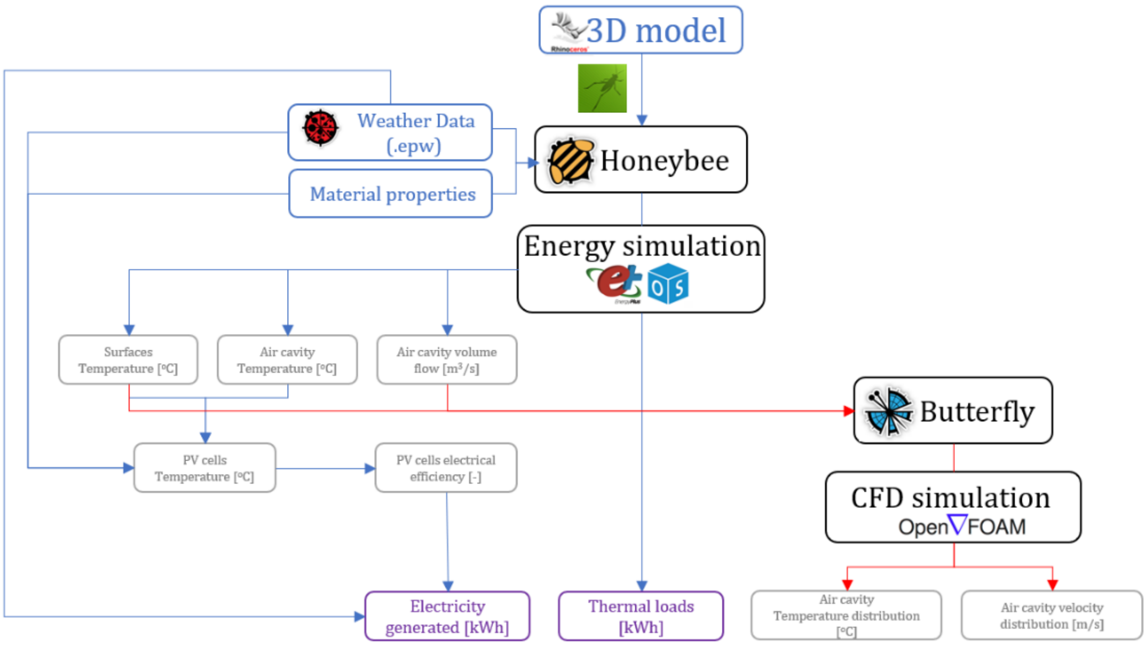

Figure 2. Analysis workflow

3. Results and discussion

3.1. Air cavity and PV panels

The presence of the air cavity behind the external claddings in the traditional wall assemblies has been shown to have an impact on the thermal performance of the entire structure [9,10]. In the BIPV façade, this can also affect the electrical efficiency of the PV panels. The variation of the air temperature inside the air cavity and the electrical efficiency of the PV panels are presented in Figure 3 and Figure 4.

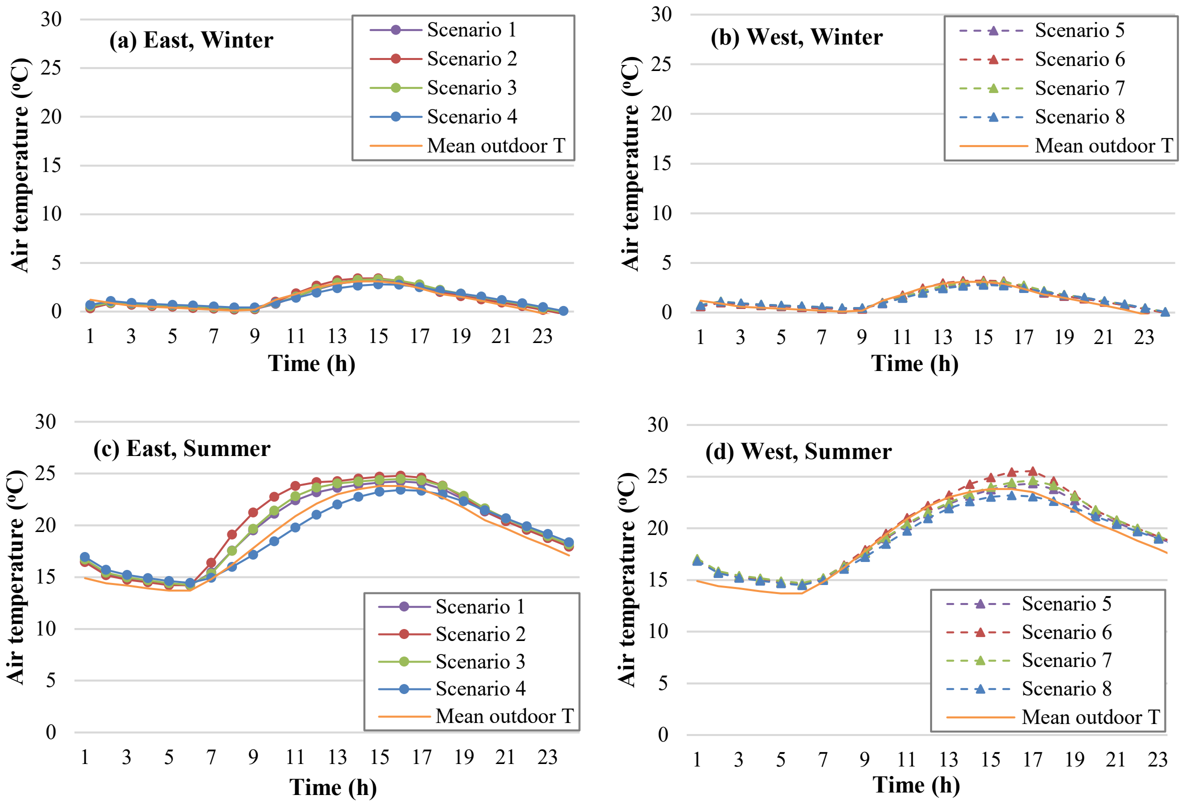

Figure 3. Comparison of air temperature inside the air cavity for a typical winter day (a), (b) and summer day (c), (d)

As shown in the plots in Figure 3, there is a time shift of 5 hours in the temperature profile in summer conditions comparing the high inertia (West) and low inertia (East) walls. In contrast to summer, the orientation doesn't have a remarkable influence on the electrical efficiency in winter. Moreover, the results show that the air temperature inside the cavity in scenario 2 and scenario 6, where the original wooden cladding is replaced by PV modules, is higher compared to the other scenarios. This is mainly due to the higher solar absorption of the PV module compared to the original wooden cladding, which consequently increases the air temperature behind the panels. As shown in Figure 4, the electrical efficiency of the PV modules is higher in scenario 4 and scenario 8 compared to the other cases. The presence of two air gaps in the wall composition results in a higher ventilation rate that reduces the temperature of the PV panels and subsequently increases the electrical efficiency.

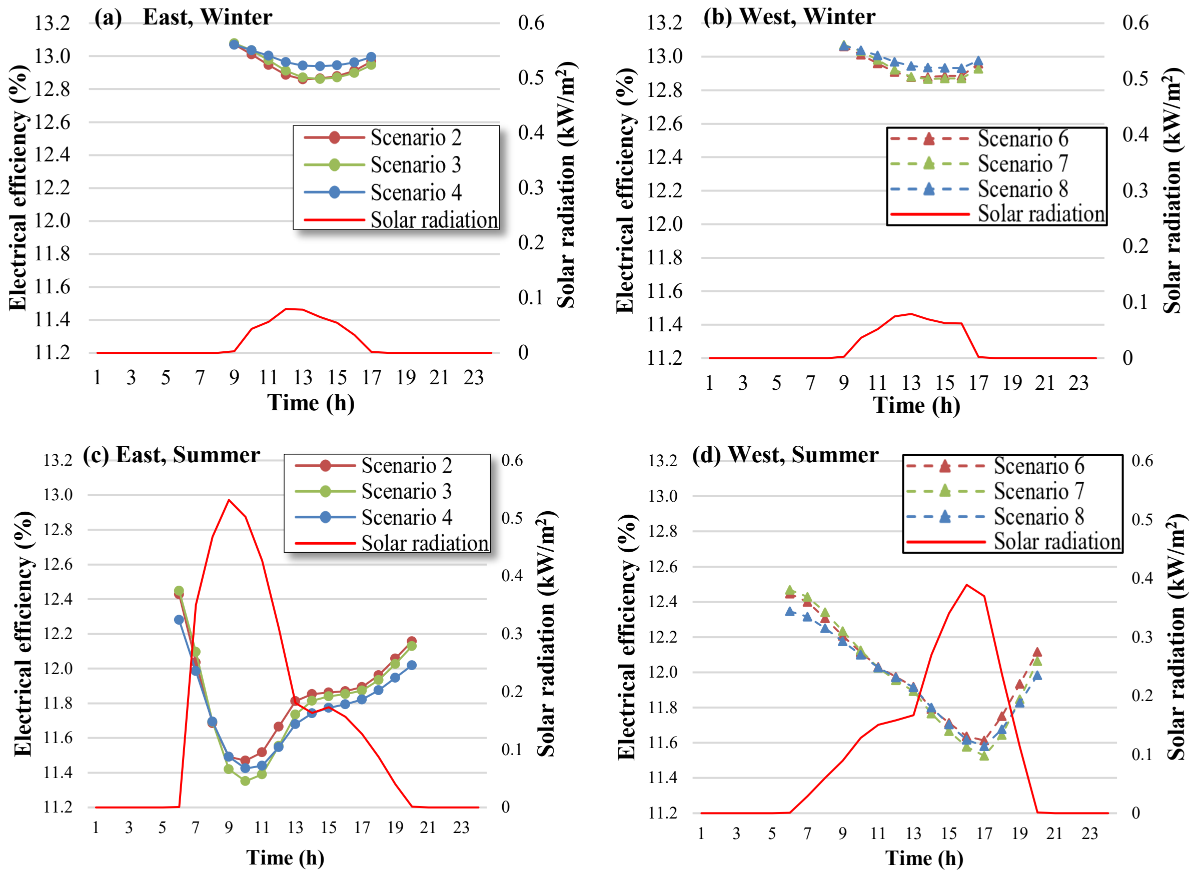

Figure 4. Comparison of the electrical efficiency for a typical winter day (a), (b), and summer day (c), (d)

3.2. *Electricity generated and energy used*

Table 2 and Table 3 present the values obtained for the electrical efficiency, electricity generated, and energy used in different scenarios. The cases with the best performance are highlighted in the Tables.

Table 2. Electricity generated and energy used for both the typical winter and summer day

	Electrical efficiency		**Electricity generated [kWh]**		**Energy demand [kWh]**	
	Winter	Summer	Winter	Summer	Winter	Summer
Base scenario	-	-	-	-	20.00	12.10
Scenario 1	-	-	-	-	18.92	12.06
Scenario 2	13.01%	12.04%	0.73	**5.60**	18.91	12.10
Scenario 3	13.01%	12.01%	0.71	5.43	18.90	12.08
Scenario 4	13.03%	11.93%	0.73	5.57	18.88	**12.06**
Scenario 5	-	-	-	-	18.87	12.22
Scenario 6	13.01%	**12.12%**	0.78	4.03	18.87	12.24
Scenario 7	13.01%	12.11%	0.76	3.91	18.85	12.23
Scenario 8	**13.03%**	12.05%	**0.78**	4.02	**18.84**	12.19

The results show that no scenario has better performance than the other, and the scenario with a balance between the electrical and thermal performances varies depending on the time of the year. It can be observed that the second scenario has the best annual trade-off between electrical energy generated and the thermal energy demand. The monthly data are presented in Figure 5, and it can be seen that the electricity generated by the PV panels meets the energy use of the test building during spring (April and May) and autumn (Sept. and Oct). It should be mentioned that the building prototype uses the heat pump with the COP > 3; therefore, the electricity need of the heat pump is 3 times less than the heat values shown in the plot. This, alternatively, means that the electricity generated by the BIPV façade could cover the energy required most of the time through the year.

Table 3. Electricity generated and energy used for the whole year

	Electrical efficiency	Electricity generated [kWh]	Heating demand [kWh]	Cooling demand [kWh]	Total energy demand [kWh]
Base scenario	-	-	2208.3	869.6	3077.9
Scenario 1	-	-	2085.0	**881.6**	2966.6
Scenario 2	**12.53%**	**1289.7**	2082.2	884.4	2966.6
Scenario 3	12.51%	1253.5	2082.2	883.1	**2965.3**
Scenario 4	12.46%	1280.5	2085.0	**882.6**	2967.6
Scenario 5	-	-	2084.5	889.3	2973.8
Scenario 6	12.52%	1266.2	**2081.3**	892.8	2974.1
Scenario 7	12.52%	1231.3	2082.3	890.7	2973.0
Scenario 8	12.46%	1258.2	2085.8	884.9	2970.8

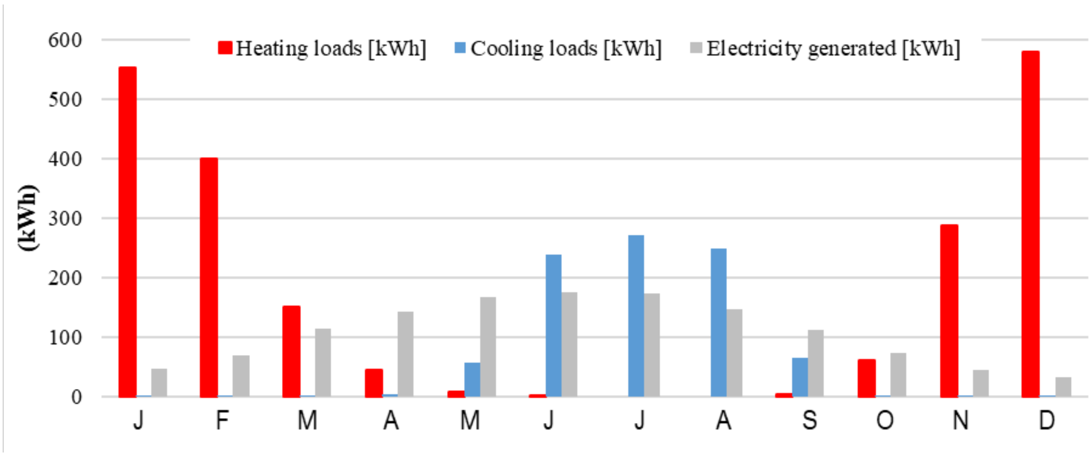

Figure 5. Monthly results of the scenario with the best trade-off

4. Conclusions

The effects of the external cladding type and orientation of the wall in a test building on the electrical energy generated and the thermal energy used are examined in this study. The simulation tools are employed to model different scenarios by replacing or adding PV modules to the original wooden cladding. According to the results, the eastward-oriented BIPV façade in the test building could increase the yearly electricity generated by 1.8% compared to the westward façade. Moreover, it is observed that the variation of cooling energy demand between different scenarios is greater compared to the heating energy demand. It is also found that the scenario with the highest electrical energy generated or the lowest thermal energy demand can vary depending on the period analyzed. The results showed that the influence of changing the composition of the BIPV façade in the energy generated and energy demand is 0.5% and 2.8%, respectively. A similar analysis could be performed in future studies to examine the effect of extreme outdoor conditions on the electrical and thermal efficiency of a BIPV façade.

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