Evaluating a BiPV sun shading system with various software and methods

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Abstract

This paper aims to explore the attractiveness of a BiPV (building integrated photovoltaic) fixed façade shading systems in view of a deep retrofit of the residential building envelope. While doing so is necessary to access the confidence and differences among optimization and simulation tools. A facade equipped with a fixed BiPV shading system is simulated with different methods, software and modelling assumptions. The output of the simulations is compared and discussed, underlining the strong and weak points of each considered method. The performance of the BiPV façade is accessed by comparison with a more traditional one without BiPV.

The traditional façade is characterized by a lower WWR (window to wall ratio) compared to the BiPV one because they have the same DF (daylight factor) by design. The BiPV façade is characterized by a better behavior toward annual radiative solar gain, while the traditional façade relies on lower thermal conductivity. Both the façade solutions are the result of a performance optimization method developed at EURAC and described in the paper. The method is based on the use of genetic optimization algorithms to find the parameters, WWR tilt angle and distance from the window, that maximize target performance indicators.

Aims of the study are to evaluate the BiPV impact on the façade (i.e. whether it ensures an improved annual thermal performance or only better energy balance thanks to energy production) and to compare the results obtained with different simulation methods (i.e. by evaluating the results coherency and discrepancy).

The comparison between these two facades performance and the consequent BiPV impact assessment, is carried out with different methods by coupling different software tools (e.g. PVGIS + COMFEN, Archsym + postprocessing). The software tools capabilities, the relative errors and the simplifying assumptions that can be considered safe in a performance-driven design perspective are discussed in the paper.

Keywords: BiPV, optimization, software, genetic algorithms, daylight, heating and cooling.

1. Introduction

The value of BIPV (building integrated photovoltaics) and its benefits have been recognized by the industry and by the scientific community since more than a decade [1]. Apparently the known benefits of BiPV are not sufficient to make it a ubiquitous or at least a widespread technology. This is due, at least in part, to the difficulty of integration in the complex system of a building [2]. The lack of BiPV market may be due to scarcity or inadequacy of products [3] [4]. Nonetheless, a large number of products are available on the market that are cheap, known and functional which could give a large added value to the building if used in a clever and creative way. In this paper, we show a type of integration that does not require any special product, indeed the PV technology is integrated in the energy concept of the building. In the architectural practice building features are often described in a conceptual statement [5]. In many countries, especially in Europe, Asia and the Middle East, designers look at historical buildings as examples of clever and sound environmental design, and these buildings are analysed in a conceptual way [6]. Optimization is a key tool to enable a number of different architectural systems including BiPV. Despite this, architectural design tools and practices analysis shows that optimization is still not relevant [7]. Optimization is a change of perspective compared to simulation because it does not require precise features as an input. In most of the available tools a specific area and orientation is required to insert where to place PV, and the software will provide the electric output. Architectural systems such as ventilated facades, shading systems, complex fenestrations and others are characterized by a set of parameters and a precise physical interaction with the building. Window overhangs could be characterized by the angle respect to the façade and the distance from the window, the main physical interaction involves the

annual solar gain. In previous studies [8] [9], the effect of window overhangs was evaluated at a city block scale in a situation where the window dimensions and positions were already decided. In [8] and [9] tough, the daylight aspects were not taken into account, and the optimization was not repeated changing some input affected by uncertainty such as weather files, occupancy or level of ACH (air changes per hour). Furthermore, once found an optimal configuration, it was not confronted against a real case to access the benefit. Given the difficulty and costs to verify the goodness of an optimized solution in a built example, the optimized configuration is here tested with different software and assumption. The example chosen for the experiment is a single room facing south and surrounded in all the other 5 faces by adiabatic walls. The orientation was chosen for the high effectiveness of the window overhang in the south façade, the single room hypothesis was forced by the inability of one of the tools to simulate more zones. This single zone is an approximation of a zone embedded in a building with an ample south facing façade.

2. Methodology

In this study the consequences of using BiPV window overhangs are assessed by comparison of a bare façade against one with the BiPV overhang. The method is repeated for both the solutions and consists in two distinct parts, which are optimization phase and evaluation phase. The optimization phase finds the optimal way to configure the BiPV overhang considering the required WWR (window to wall ratio), whereas the evaluation phase simulates the performance and shows electricity production and energy savings. In This paper the evaluation phase is repeated with different assumptions and compilers to have an idea of the uncertainty level and of the scale of real possible benefits. The two compilers of EnegryPlus used for the evaluation are ARCHSIM and COMFEN [2.4.1].

2.1 Setting and boundary conditions

A 36 m² south-oriented room (6 m deep and 6 m wide) of a generic residential building has been considered as reference for the simulations. This corresponds to the representative area for one person in a single room dwelling. The choice of using a single room space confined by adiabatic walls comes for a limit in modelling capabilities of COMFEN

Name	MU	Optimisation	Simulation	Reference
Climate location	[-]	Bolzano		Meteonorm
ROOM GEOMETRY				
Room internal height	[m]	3		
Room width	[m]	6		
Room depth	[m]	6		
Room net heated floor	[m²]	36		
Room net heated air volume	[m³]	108		
ROOM USE AND SYSTEMS				
Number of people	[person]	1		
Equipment electric consumption	[W/m²]	2		SIA2024, 2006
Lighting electric consumption	[W/m²]	9.4		SIA2024, 2006
Shading system type	[-]	No	Movable external venetian blinds	
Shading system control	[-]	N.A.	Always on	
Mechanical ventilation Fresh hygienic air changes	[l/s/person]	0.011		EN 15251
Mechanical ventilation heat recovery	[-]	No		
Mechanical ventilation control	[-]	Always on		
Outdoor air infiltration rate	[1/h]	0.2		COMFEN
Cooling setpoint on indoor air temperature	[°C]	25.5	23.9	COMFEN
Heating setpoint on indoor air temperature	[°C]	20.5	21.1	COMFEN
ROOM CONSTRUCTION				
Opaque wall U-value	[W/m²K]	0.34		DGL59/09

Glazing reference U-value	[W/m²K]	1.651		COMFEN
Glazing reference g-value	[-]	0.382		COMFEN
Window frame conductance	[W/m²K]	2.86		COMFEN
External shading: tilt angle from hor	[°]	N.A.	0°	
External shading: tau	[-]	0	0	
External shading: rho_front	[-]	N.A.	0.7	
External shading: rho_back	[-]	N.A.	0.7	

Table 1:boundary conditions

2.2 Optimization

The optimization of the system is obtained by creating a pool of different possibilities and testing them through simulation to access their performance. The possibilities represent different combination of parameters in a parametric description of the geometry. Every specific combination of parameters is an individual, the whole system can be described by three parameters (φ, L, WWR)[Figure 1].
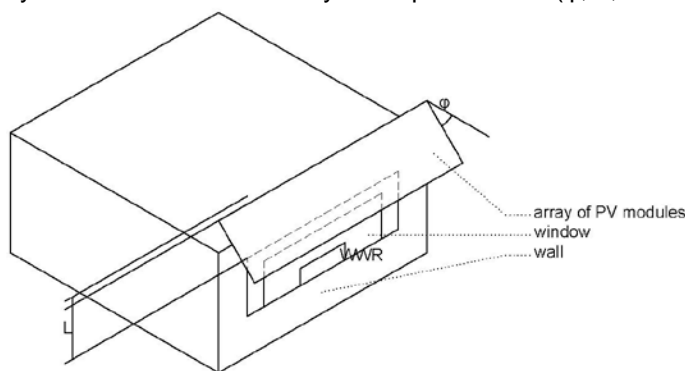

Figure 1: schematic representation showing the parameters in the model

φ is the angle between the plane of the PV array and the normal to the façade $0 ≤ φ ≤ 90°$. L is the distance of the PV array from the border of the window $0 ≤ L_l ≤ 1$ and represent the proportion between the distance of the module in the combination and the maximum distance allowed. WWR is the window to wall ratio ca. $0.007 ≤ WWR ≤ 0.67$. Note that the L parameter is dependent on WWR as the lower bound is the upper frame of the window. The single room is meant to be part of a building consisting in a repetition of similar rooms, therefore the maximum value for the parameter, L, is limited by the presence of the window in the upper floor.

Every single individual is evaluated in terms of energy produced by the photovoltaics and in terms of consumption for heating and cooling. The presence of the overhang have an impact on the solar heat gain throughout the year but also on the quantity of natural light that the building can harvest. Having a smaller window can be considered as an advantage because the glass material has a lower thermal resistance. Ff daylight is not taken into account the result of the optimization would surely be the smallest possible window, and this is obviously not a meaningful solution. A lower limit to the area of the window was given so that it could not be lower than 1/8 of the internal floor area (considered as minimum in the Italian national regulation). To guarantee the same quantity of incoming light in both the facades (with and without the overhangs), the DF (daylight factor) of the façade without BiPV having the smallest allowed window area was measured, and every individual with a lower DF was discarded by the optimization. In this step the DF was calculated assuming a transparency of the glass of 100%, this was done because the importance was the capacity to allow light comparatively to the traditional façade, was therefore a purely geometrical characteristic. Later, in the Evaluation phase, real transmittance values were used. GA (genetic algorithm) [10] were used as search algorithm to find the optimal solution, these algorithms are based on the evaluation of each individual according to one or more values called "fitness values". The set of parameter values of each individual is treated as a genome. The idea imitates the natural selection process by keeping only the best performing individual in a given set of randomly generated ones, the following generation will be made by recombination of the best genomes. In this example two fitness values were used, the annual ideal demand for heating and cooling energy and the yield of the photovoltaic overhangs. Each individual is evaluated through these two values, and a Pareto front is formed. The Pareto front is the set of better performing individuals, No individual among the simulated ones had surpassed all the performance values of any point in the Pareto front. All the individuals in the Pareto front are better in at least one fitness value than their neighbors [Figure 2](i.e. the individuals with a similar performance).

2.3   Optimization results

The optimization was launched at first with the weather file from the U.S. DOE (department of energy) [11], the optimization generated a Pareto front of solutions [Figure 2].
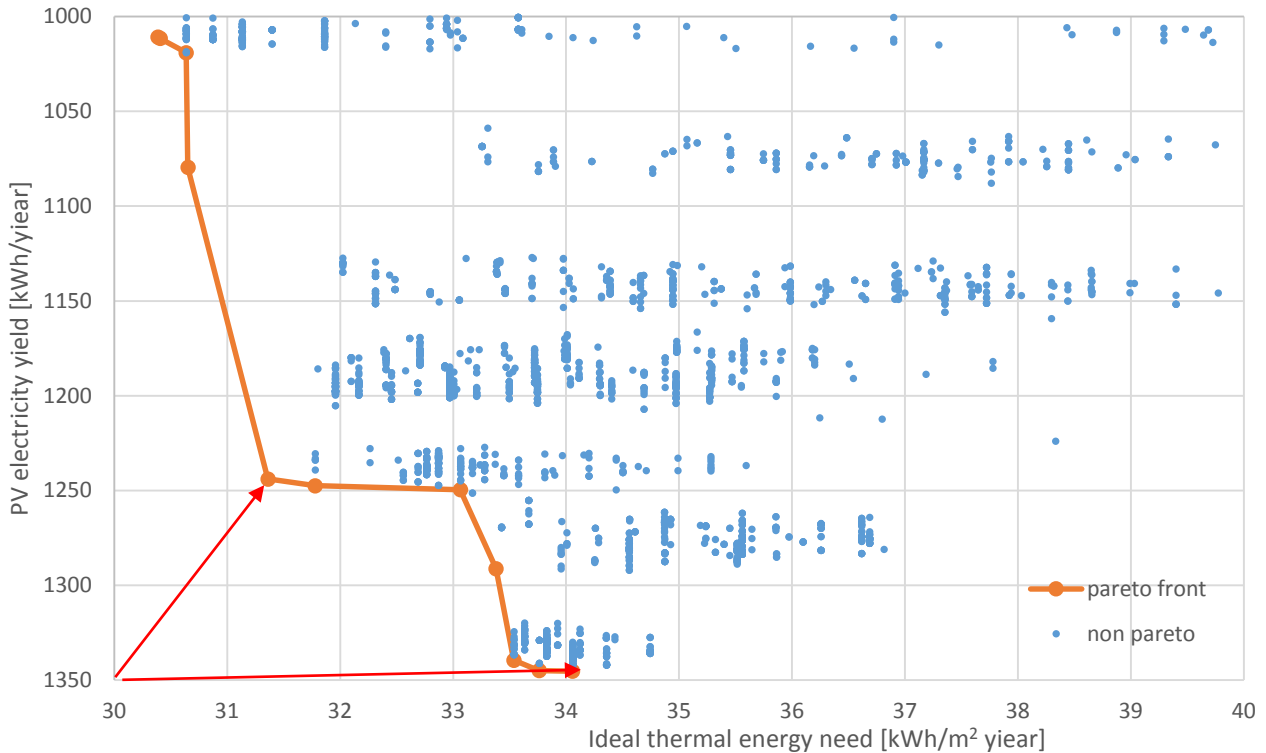

Figure 2: representation of all the individuals simulated according to their fitness values

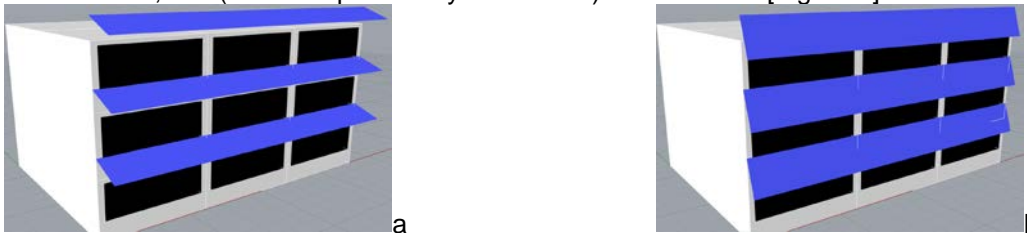Among these solutions, two (the ones pointed by the arrows) are shown in [Figure 3].

Figure 3: two example individual from the first optimization, the PV overhang is represented in blue, the glazed surface in black. The room is represented inside an example building. A is a solution picked from the middle of the Pareto curve, b is the solution found to have the best PV production.

This optimization session was then repeated because the solar radiation in the weather file from the DOE was found to be strongly underestimated in comparison to the ones retrieved from Meteonorm [12]. From this examples is possible to understand the workings of the algorithm, both the solutions in fact are equipped with large windows ("a" 9.5 m^2 "b" 9.9 m^2) to harvest the most of the daylight. It ss not possible for a solution to be evaluated if its DF is lower than the DF from the traditional window, and the overhang surely reduces it. The angle of the shading system also stands out, the highest solar irradiation is found for an angle of 72° degree from the horizontal. This angle, which is far from the best free field south oriented (39° degree)[13], outperforms smaller angles thanks to the lower self shading of the arrays. Launching the optimization session a second time with the weather data retrieved from Meteonorm no Pareto curve was generated, the front was in fact really narrow and one particular solution dominated both the two performance indicators.
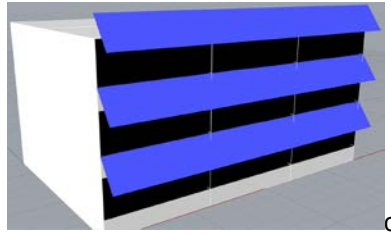
Figure 4: best solution generated by the optimization with the new weather file.

This solution, compared with "a", is more focused on preventing the overheating. The solution "b", being the PV production end of the Pareto does not deal with reducing thermal energy demand. The solution "a" has a low angle that do not provide any shading during the winter months while the solution "c" is characterized by a very effective shading, this may be due to a higher solar irradiation in the weather file used in the second optimization. In solution "c" the overhang, blocking more light, forced the algorithm to put the highest WWR possible. The overhang's angle in this solution provides an irradiation value really close to the one of the solution "b" because of the higher irradiation despite the higher self shading. The similarity of this solution with "b" is the cause for the narrowness of the Pareto front.

2.4   Evaluation

The result of the optimization consists in an overall improvement of performance made up by both electricity production from the PV and reduction in heating and cooling demands, nevertheless the simulation is susceptible of the characteristics of the model. To access in major depth the impact of the BiPV system the two solutions, with and without BiPV were evaluated using three different models. All the models are based on the use of the software Energy plus [14], but they are built with the aid of three different compilers, i.e. COMFEN, ARCHSIM and Ladybug for grasshopper. A set of generic BC (boundary conditions) were imposed, and all the three models, each according to its possibilities, reproduced them. A special attention was given to the electricity production and the daylight analysis, these two aspects cannot be evaluated with the features offered in the three compilers, therefore different methods are implemented and compared.

2.4.1 Thermal simulations

The thermal simulations in the evaluation phase are put in place to check the performance of the optimized configurations, and to measure whether different methods agree in considering the overhangs a benefit. The two tools used are both compilers for EnergyPlus, but have very different characteristics. None of the tool is more advanced than the other, indeed they differ in their scope and have different strength and weaknesses. Their differences are enough to consider the optimized overhang once an improving, once a pejorative addition.

COMFEN simulations

COMFEN is a free tool developed by the LBNL as support for the design of fenestration systems. It generates an input file and it runs the EnergyPlus (v. 7.2 is implemented in COMFEN 5) calculation routines. It allows a deep assessment of the energy performances and both thermal and visual comfort levels. In order to compare different fenestration scenarios, it allows changing all façade-related parameters and input, while it keeps fixed some element of the building physics and energy-plant related settings. In particular, for example, the infiltration rate, the heating and cooling setpoint temperatures, the schedules (mid-residential, office and school are available as main usage categories), heating and cooling distribution and generation systems, cannot be set differently from the default configurations. Furthermore COMFEN does not allow the creation of multi-zone models limiting the modelling possibility to a single zone surrounded by five adiabatic surfaces and one externally exposed one.

ARCHSIM simulations

ARCHSIM is a EnergyPlus (v. 8.2) compiler which works in the GrassHopper 3d parametric environment. The main focus of the tool is the early stage design, it can write and execute multi zone IDF EnergyPlus files, allows freedom in choosing materials, geometries, boundary conditions, schedules, inputs and outputs. ARCHSIM do not force you to use certain technologies, indeed it allows for free floating temperature and ideal heating and cooling demand as an output. From a technological perspective is limited compared to COMFEN as it goes not in any detail about the building elements or the technological systems. Stands out as an example the lack of description of the window frame, the window is in fact only composed by the glass material.

2.4.2 Photovoltaic assessment

Using PVGis

The first method is based on PVGIS [13], as it is one of the most commonly used tools by designers to quickly predict PV energy production.

The PVGIS-CMSAF database, instead than the Classic PVGIS, is used for the calculation since its irradiation data are in good agreement with the ones of the epw. file used in the second method "Energy plus and grasshopper" (the global irradiation on horizontal is respectively of 1430 kWh/m^2 y and 1428 kWh/m^2 y).

The classic PVGIS database is underestimating the global irradiation of 16% with respect to the epw. file retrieved from Meteonorm software [12].

As an input for the PVGIS calculation, a value of 12.5% is given for estimated system losses, which include losses in cables, power inverters and dirt on modules.

The losses estimated from PVGIS for the 21.6° and 54° tilted modules are respectively:
- 9.3% and 9.4% due to temperature and low irradiance;
- 2.9% and 2.7% due to angular reflectance effects.

Using Energy plus and grasshopper

The second method used is based on the use of Energy plus to retrieve the solar irradiation on the surface of the shadings, some post processing was then performed with Grasshopper to take into account the effects related to the bypass diode and the temperature. In order to consider the effects caused by the partial shading on the array the single PV collectors were divided in strings according to their internal disposition of cells [Figure 5].

Figure 5: disposition of the strings inside the PV collector, each module is formed by 3 strings in series, each string is equipped with bypass diode.

The hourly irradiation on each string was retrieved starting from the radiation data contained in the Epw file, the same used in the thermal simulations with Archsim and Comfen. The Energy plus model is based on the Perez [15] sky function as explained in [2], the output is a matrix **P$_{i,j}$** containing the power [W/m^2] hitting each photovoltaic string (i) in every hour (j). every element of the matrix is transformed to take into account the effect of the bypass diode

$$p^1_{i,j} = p_{i,j} \ \forall \ p > p_{max,j} \cdot \kappa,$$
$$p^1_{i,j} = 0 \quad \forall \ p \leq p_{max,j} \cdot \kappa.$$

Equation 1: condition for the bypassing of the ith string in the jth hour of the year

A new matrix **P$^1_{i,j}$** is generated in this transformation Where: p$_{i,j}$ is an element in the matrix (i.e. a string in an hour of the yiear), p$_{max,j}$ is the highest string irradiation value in the jth hour of the year and κ is a coefficient that represents the fraction of incident light below which a string is bypassed. The new matrix represent the part of the irradiation that can be harvested by the photovoltaic collector, all the strings that are shadowed above a threshold are supposed completely shadowed. The matrix is then collapsed in a single list of 8760 values by calculating the gross power hitting the solar collector that is not discarded by the bypass diode. Every value in the list is therefore calculated by

$$p_j = \sum_{i=1}^{n_{string}} p^1{}_{i,j},$$

Equation 2:incident solar radiation that can be harvested in the jth hour of the year

Where: p_j is the gross power hitting the solar collector that is not discarded by the bypass diode and n_{string} is the number of strings in the collector. To extract the power produced by the system El_j in every hour of the year every p_j is multiplied by the efficiency at module level and the area of a string. To take into account the temperature effect on the collector the module temperature was calculated using the Ross coefficient [16]

$$T_{m,j} = T_{amb,j} + k_r \cdot G,$$

Where: $T_{m,j}$ is the temperature of the module, $T_{amb,j}$ is the ambient temperature, k_r is the ross coefficient assumed 0.035 [16] and G is the irradiation over the collector in that hour retrieved from the matrix **$P_{i,j}$**. Once the module temperature is known the power of the whole collector is modified by

$$El^t{}_j = El_j + 0.005 \cdot El_j \cdot (25 - T_{m,j}),$$

Where: **$El^t{}_j$** is the electricity produced in the **j^{th}** hour taking into account the effects of temperature.

To evaluate the electricity production at system level $El^t{}_j$ was then multiplied by a P.R. (0.875) taking into account soiling, AC-DC losses and reflection losses (12.5%)[17]

2.4.3 Daylight assessment

The metric used in the optimization phase (DF) does not take into account the position of the sun throughout the year and the deployment of movable shading device from the user, because of this the facades were evaluated using a different metric, the SDA (spatial daylight autonomy). This method consists of simulating the deployment of movable shadings when more than 2% of a space floor area is covered by 1000 lx of illuminance from direct sunlight (as in a 0 'ambient bounce' lighting calculation). Considering the movable shading system (having light transmittance 0.5) according to the hours of the year in which the preceding condition is met, the illuminance levels on a grid of points is calculated. The value of the $SDA_{300/50\%}$ represents the percentage of the floor area where the minimum threshold of 300 lx is met during more than 50% of the occupied hours.

3. Results

The conbinations of parameters which came out from the optimization phase are summarised in [Table 2]

	Window area [m²]	Overhang angle [°deg]	Overhang distance [%]
traditional	4.5	--	--
"a"	9.5	21.6	100
"b"	9.9	72	100
"c"	11.8	54	100

Table 2: synthetic scheme of the parameters of the solutions

3.1 Ideal Heating and Cooling Demand

Focusing on the ideal heating and cooling energy demand three of the four configuration in [Table 2] were evaluated as shown in [Figure 6]. Looking at the ideal heating and cooling demand the first aspect that becomes apparent is that with both the simulation tools the energy demand is largely predominated by cooling loads with every configuration. From the simulations carried out with ARCHSIM both the configurations are slightly pejorative of the traditional wall, while according to COMFEN the configuration "c" outperforms the others by a significant margin. With both the tools, the "c" configuration is in general better than the "b". This could be due to the fact that "b" is optimized with a different weather file where the cooling load is less extreme.
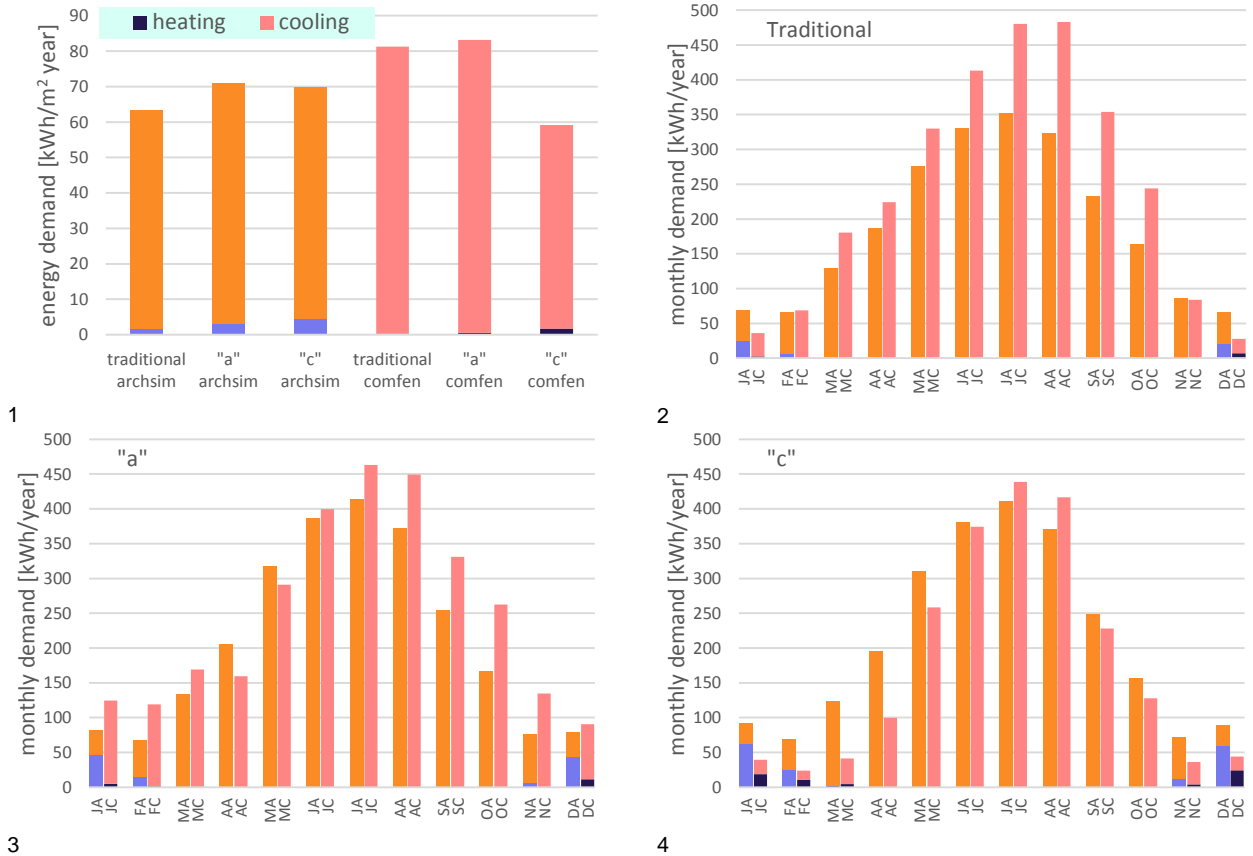
Figure 6: ideal heating and cooling demand for two configurations calculated with ARCHSIM and COMFEN. 1) annual cumulative specific ideal energy demand for three configurations.2) monthly cumulative energy demand for the traditional case.3) monthly cumulative energy demand for the "a" case. 4) monthly cumulative energy demand for the "c" case.

3.2   Photovoltaic electricity production

The electricity produced by the overhangs present a strong difference between the two methods adopted, especially during the summer months. PVGIS produces the result based on the tilt and azimuth angle, not considering the shading determined by the array overhead and the losses due to the bypass diode [Figure 7]. If the shading system overhead is removed there is good agreement between the two methods in the summer months, but GH, based on EnergyPlus, tends to overestimate the production in the winter months.
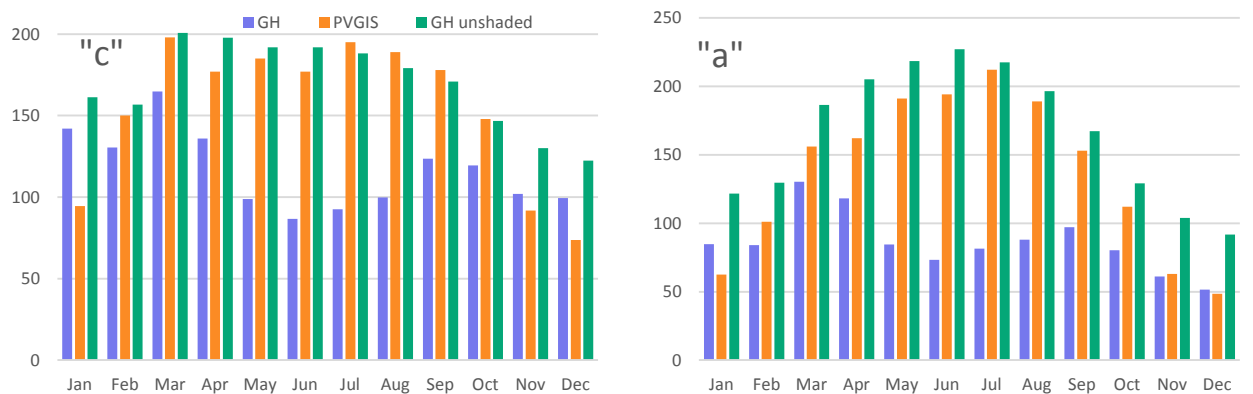

Figure 7: monthly cumulative electricity production calculated with GrassHopper (full model), PVGIS online and GrassHopper (without array of shaders above)

3.3 Cumulative energy balance

The aggregated result from the energy perspective consists of a balance between the electricity produced and the electric energy consumption for heating and cooling (in the case of a heating/cooling system using electricity). The electricity demand was evaluated assuming an heat pump with COP 3 in both the cycles. In this case as well there are significant differences considering the evaluation method in [Figure 8] two extreme cases for the configuration "c" are presented. Considering the production from PVGIS (overestimated) and the demand from ARCHSIM (low) the balance is positive every month. Considering the most conservative assumptions (COMFEN+GH) the balance is negative during the summer months. The simulation does not take into account any form of electric or thermal storage.
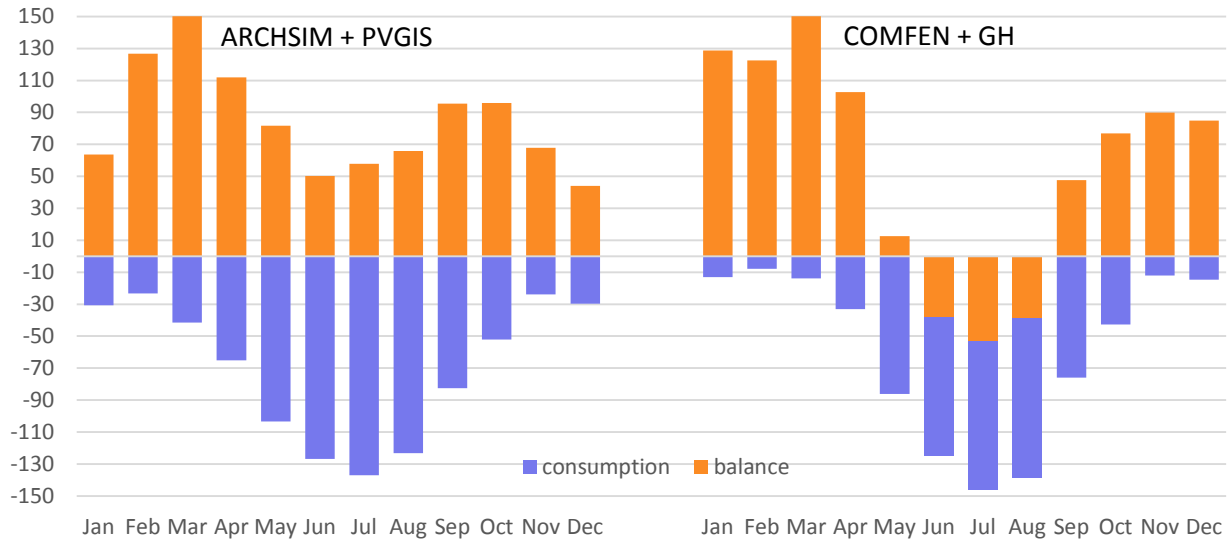

Figure 8: electric energy balance for two limit cases about the configuration "c" (ARCHSIM + PVGIS vs COMFEN + GH).The chart shows the monthly cumulative balance between electric energy demand for heating and cooling and the production from the PV. The orange bar represent the balance, the blue represent the demand.

3.4 Daylight situation

The benefit of this optimization is uncertain on the thermal balance but is visible in terms of daylight situation. By design the two solutions should have the same DF, but as it is known the DF do not take into account the direction from which the direct light comes throughout the year. By applying a more complete metrics the benefit of the window overhang become apparent. The minimum $SDA_{300/50\%}$ (Spatial Daylight Autonomy) [18] to get 3 daylight point in the LEED certificate is in fact 75%, [Figure 8] shows the percentages for three configurations, both the optimized configurations are well above the threshold.
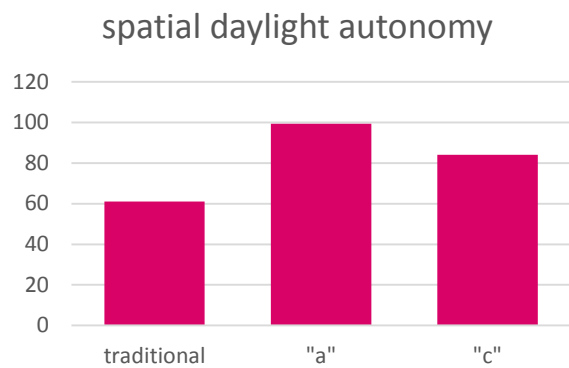

Figure 9: SDA 300/50% percentages for three configurations.

4. Conclusions

The Paper deals with the optimization and evaluation of a BiPV window overhang system used in a continuous south facing façade. The model is simplified by considering a single room exposed to sun, wind and external temperatures from south while insulated from the other 5 surfaces by perfectly adiabatic walls. Optimization using GA was deployed to find out the proper way to use the overhang. The optimization phase was repeated changing some aleatory input values and it gave different output. The traditional solution and two of the output were evaluated using ARCHSIM and COMFEN. These software are both compiler for EnergyPlus but are meant for different scopes and have different profiles and capabilities. The electricity production was as well evaluated with different methods to access the entity of the errors that can be done during the planning phase, and the uncertainty level of the benefit of the BiPV electricity. From the point of view of the ideal heating and cooling demand the impact of the shading system is unclear, one optimization is a significant advantage for COMFEN while both the optimized solutions are slightly pejorative according to ARCHSIM. On the other hand from the point of view of the daylight both the configurations are strongly improving the baseline. This result suggest that the algorithm was possibly too demanding on the DF. By design in fact all the solutions that performed below the DF of the traditional south facing window (which had the smallest allowed window area) were discarded, being the traditional façade unshaded by external object its DF was really high. Introducing a smaller DF (ex 3) as a minimum threshold for a solution to be evaluated would have given more freedom for the algorithm to browse among more shaded facades improving the thermal behavior and, possibly, without harming the SDA, which is poorly related to the DF. It is unpractical to perform the SDA for each individual of an optimization phase because is far more computationally intensive than the DF, it would render the calculation significantly slower.

Is notable that, despite being generated by optimizations based on different inputs the solution "b" and "c" are fairly similar in terms of parameters and behavior. Although there are not sufficient cases to establish a rule, exist the possibility that the characters in these solutions give more resilience to the configuration. This aspect suggests that is possible to repeat the optimization phase changing aleatory aspects to find which optimized configurations are more frequent therefore intrinsically better. This suggest that the optimization should be much faster, one way of doing it is to launch energy plus only in the beginning (for every set of inputs), find the free floating temperatures and the thermal capacity of the whole building, and evaluate only the solar gain with every configuration. Given the uncertainties in the input many simplifications in the physical model are possibly allowed to make the simulation faster. The evaluation phase as well can be subject of improvements as the energy balance is now done without taking into account any thermal or electric storage behavior. In conclusion the difference in accuracy and computing resource use between optimization and simulation phase should be widened even more to have a fast and clever optimization and a reliable and meaningful evaluation.

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