Interdisciplinary Laboratory
of Performance-Integrated Design **LIPID**

Semester project

Master
Energy Management and sustainability

Photovoltaics integration in the Solar Decathlon pavilion :

Assessing the implication of transparent BIPV with Graetzel technology on the indoor comfort and energy performance

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1 Introduction

The reduction of wild land areas in already-densely populated regions is an increasing matter related to the never-ending growth of the human population and activities. The urban consolidation appears to raise more attention as a potential effective approach to find solutions to this issue. As a consequence, new ways of using surfaces for energy production emerged in the last decades, one of them being the large implementation of photovoltaic panels (PV) on buildings' roofs and facades. However, the standard silicon PV technologies are not always appreciated due to their lack of aesthetic value. To respond to this demand, Building-Integrated Photovoltaic devices (BIPV) appeared on the market. These products are designed to be more accepted on an aesthetic basis. A very promising BIPV technology is the Graetzel cell: a transparent photovoltaic device that wants to imitate photosynthesis. This dye-sensitized solar cell (DSSC) has the advantage to possibly be fully building-integrated.

The purpose of this research is to examine the daylight and thermal comforts and energetic performance of a room when such Graetzel cells are implemented as window pane components. Furthermore, it is wished to assess the utility of implementing such technology on north-oriented facades to see if south-oriented PV are not always the only solution. This study focuses more specifically for the international Solar Decathlon competition of the year 2017.

The Solar Decathlon competition
The Solar Decathlon Competition is an international competition. In order to win, students from universities around the globe have to design and build the best life-size scale, fully operational, solar-powered only pavilion. Through the Swiss Living Challenge, the Ecole polytechnique fédérale de Lausanne is actually part of this competition. Among a large quantity of models, the one chosen for this research is the one presented on Figure 1 : the Facettes model. This model has been made using a Voronoï algorithm.

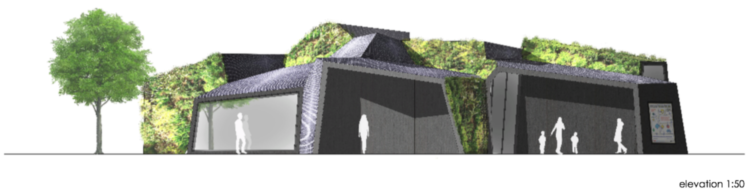


Figure 1: Facettes pavilion for the Solar Decathlon

Facettes actually has the main objective of having a 100% productive building envelope. This wish comes from the issue of urban consolidation that appears to affect Switzerland, just like many other European countries. In the context of the Solar Decathlon competition, the actual issues brought by such highly dense regions was wished to be a key concept of the pavilion thematic.

Graetzel technologies

In the same objective, it was decided to implemented Graetzel cells as a window component in the pavilion. To reach this purpose, two different BIPV with Graetzel technology have been studied (see Figure 2) : the glass2energy red module and the SBskin green module.

Figure 2: G2E (right) and SBskin (left) technology

This research won't expose specific results but indications to give to the architects. It should adapted to every shape of pavilion and every design that might be chosen by the architects. This research take into consideration the decisions that have already been made by the different teams of the Solar Decathlon but also strives to stay as general as possible.

2 Working method

The object of the analysis is a single room (the kitchen) chosen out of the different modules from the pavilion “Facettes”. Its layout can be seen on Figure 3. It has one fully glazed facade (thin section on the upper left wall), which will be the focus of the different proposed variants of Graetzel panels’ implementation.

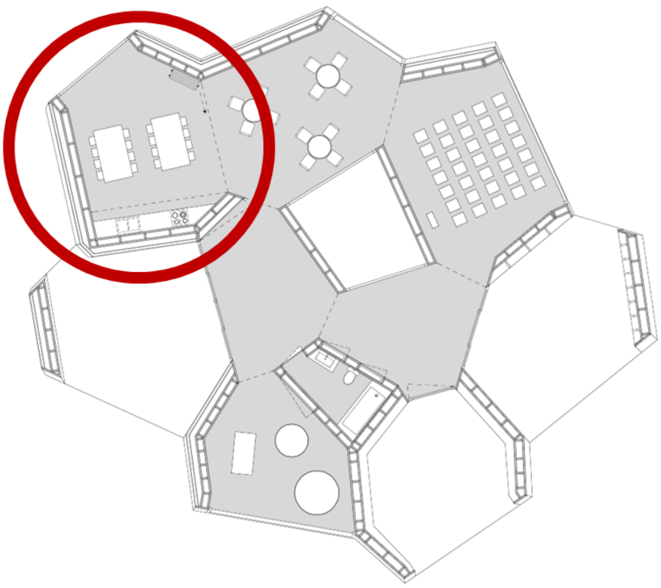


Figure 3: PAVILION’S FLOOR PLAN: the kitchen is highlighted by the red circle

A preliminary stage was to set the different possible variants. As the idea is to replace a percentage of the glazed area by Graetzel modules, calculation of the different possible layouts of those modules was assessed. The only constraint considered for this is the dimensions of a G2E module 100x60 cm as the dimension of the SBskin module is a fraction of the latter one (20x20 cm[1]). Given the dimensions of the facade, it was roughly cut to approximate the panel’s size[2]. The results of the cuts can be seen on Figure 4. Two options are available, vertical or horizontal panels, respectively giving a grid of 4x4 and 2x6. Because the Graetzel panels and the standard glazed window are separated by their own frame, it was decided not to use random configurations of the Graetzel panels, but only the possibility to have them filling entire rows or columns (not both at the same time). The facade remains fully glazed in every variant, but the number of Graetzel

[1] 19x19 cm in reality for the glass block. However, such accuracy is not required as the purpose of this study is to give general behavior of the assessed technologies.

[2] See note 1

panels to replace a standard window changes. To sum up, the horizontal split allows the implementation of 0; 25; 50; 75; 100 percents of Graetzel cover on the facade, which is referred as the Graetzel ratio. The vertical split gives Graetzel ratios of 0; 16.7; 33.3; 50; 66.7; 83.3; 100 percents. For instance, if 50% is the optimal Graetzel ratio, a possible configuration would be the upper half of the facade for Greatzel, the lower half for the standard window, the other wa round, or 25% respectively at the top and the bottom of the window (if the window was vertically separated, it could be Greatzel on the left side and standard window for the right side).

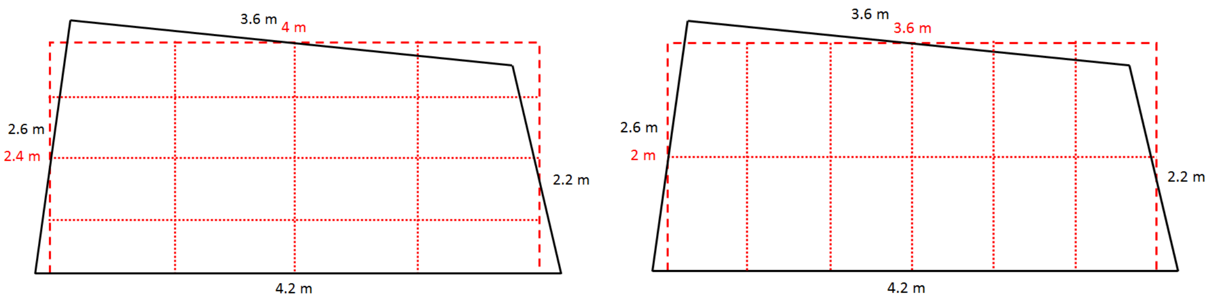


Figure 4: Graetzel modules cuts: horizontal and vertical cuts of the glazed facade, corresponding to the Graetzel module's dimensions

The methodology works on a two-steps simulation process. In a first time, the thermal performance of the different technologies are simulated using the software DesignBuilder. The results of the different Graetzel ratios are reviewed, and the most effective one is kept as the one to be assessed in the second step. This latter step is the daylight performance analysis, which is assessed with the DIVA and GRASSHOPPER plugins of the software Rhinoceros 3D. The full methodology is performed for each of the following orientations of the variants (north, south, east and west) and for both technologies (G2E and SBskin).

3 Performance assessment

3.1 Materials Implementation

The construction materials of the pavilion were chosen by a team from Solar Decathlon, based on a life-cycle analysis to use materials with low embodied energy. Walls, roofs and floors mainly consist of plywood panels with wood insulation. The windows are triple glazed whose cavities are filled with argon and both exterior and interior panes have a low-emissivity coating. The frames are made of wood.

To model the windows incorporating Graetzel cells in DesignBuilder and Rhinoceros, their thermal and optical properties were gathered. Table 1 recapitulates the input values used in DesignBuilder to create windows with the properties of the two Graetzel technologies. The SBskin glass block properties (see Figure 35 in Appendix) provided are values for the whole module. Thus, the window was modeled as a single glass layer with the properties found in Table 1. As DesignBuilder doesn't accept a glass layer with a thickness larger than 50 mm, the input thickness was set to 50 instead of 80 mm. To keep consistency with the real material properties, the conductivity was changed from 0.167 to 0.1044 W/mK so that the intrinsic conductivity remains 0.2088 W/m^{2}K.

Table 1: Optical and thermal properties of the SBskin and G2E products.
* Due to the lack of optical and thermal properties, the values are assumed to be the same as Generic CLEAR 3MM glass from the DesignBuilder database

	SBskin	G2E red
Thickness [mm]	50	6.5
Conductivity [W/m-K]	0.1044	0.9*
Solar Transmittance [-]	0.1936	0.33
Outside Solar Reflectance [-]	0.1114	0.08
Inside Solar Reflectance [-]	0.2558	0.08
Visible Transmittance [-]	0.2935	0.15
Outside Visible Reflectance [-]	0.07	0.07*
Inside Visible Reflectance [-]	0.1603	0.07*
Infrared Transmittance [-]	0	0*
Outside Emissivity [-] (IR)	0.837	0.837*
Inside Emissivity [-] (IR)	0.837	0.837*

The second column of Table 1 refers to a red DSC module from G2E [1]. This module is added to a triple glazed window with two configurations: w1 and w2. w1 is created by simply replacing the first window pane by the G2E module, while w2 is made by inserting the Graetzel module behind the first window pane. By doing so, the first window pane loses its low-emissivity coating. Thus, the middle pane of the triple glazed window is further changed for a low-emissivity one. Figure 5 shows the original and two variants windows built with the G2E module.

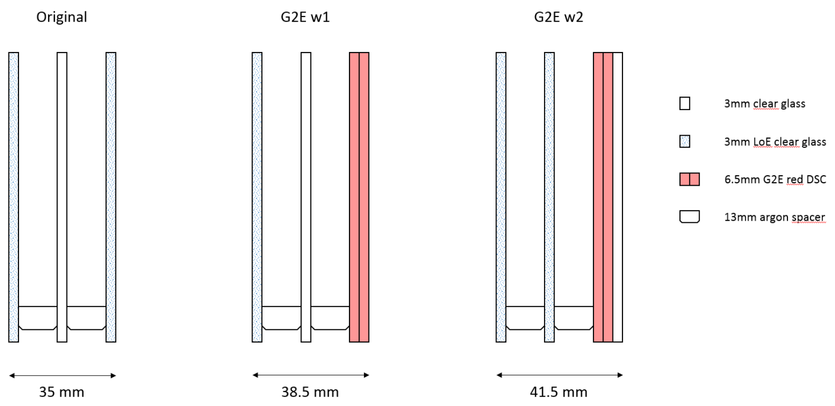


Figure 5: Scheme of the triple glazed windows: from left to right: Original, G2E w1 and G2E w2

The properties of the whole windows are calculated by DesignBuilder and described in Table 2. As expected, the direct solar and light transmissions are lower for the three DSC windows than the standard one. Because the U-Value of a transparent material like a window is mostly driven by the radiation heat transfer [3], the variants G2E w1 and w2 have a higher U-Value than the original window.

Table 2: Main thermal and optic properties of the four windows configurations

	Original	SBskin[3]	G2E w1	G2E w2
SHGC [-]	0.474	0.508	0.267	0.225
Direct solar transmission [-]	0.358	0.194	0.181	0.142
Light transmission [-]	0.661	0.295	0.116	0.110
U-Value [W/m2K]	0.780	1.528	1.053	0.985

As a matter of consistency, the same optical properties are applied for DesignBuilder and Rhinoceros. It was decided not to look at the colors while modeling the windows in Rhinoceros. Thus, the windows were created as Glass materials, whose main properties are the light transmission calculated by DesignBuilder (Table 2) and the refractive index, which was kept as the default value (1.52) for a window.

[3]The SHGC and U-Value calculated by DesignBuilder are actually different than the one measured by the start-up. This is surely due to the DesignBuilder model that was created as a single layer, erasing all radiation properties and interactions of the multiple layers.

3.2 Energy analysis

3.2.1 Introduction and objectives

A team from Solar Decathlon run multiple optimisation simulations to find the best fitting parameters of the DesignBuilder model that would fulfill the contest's regulations. The main parameters, in addition to the materials already mentioned in section 3.1, are the following. The occupancy schedule and people density of the whole building were chosen to fit the "museum" function of the pavilion during the contest. The temperature must stay within the range of 20-23°C and the relative humidity between 35 and 60% in every room, as stipulated by Solar Decathlon. Thus, the energetic performance of the room is an indicator of the thermal performance with a broader sense. Heat gains from appliances were taken into account for every room. The target illuminance of every room is 300 lux, as required from Solar Decathlon's regulations. It means that the lights turn on when the natural daylight illuminance is lower than this amount, and thus the lighting load is affected. The sensor that verifies the illuminance level is set at the middle of the room, which is the location of the real captor device that will be used during the contest. Finally, the HVAC system consists of an air to water heat pump and natural ventilation with the possibility to use air conditioning.

Despite the different configurations possible with the cuts seen on Figure 4, for simplification purposes, in the DesignBuilder 3D models, the windows were implemented only by looking at the Graetzel ratio and not the real configuration of the Greatzel window on the glazed façade. This can be done in DesignBuilder because this software is only used for energetic assessment. Thus, putting the correct configuration don't affect the results consequently : all different configurations can be sum up to one with the same Greatzel ratio.

3.2.2 Simulations and results

The criterion used to tell whether a solution is better than another is the energy consumed to keep the room within the comfort requirements range. The variants having different SHGCs and U-Values, the heating and cooling loads will change without doubt for each case. Moreover, the light transmission being much lower for the three proposed windows using Graetzel technology, the lighting load is expected to increase along with the Graetzel ratio, as the illuminance should remain above 300 lux. Any other load on the system is not taken into account for the optimality assessment as they are completely independent from the window performance (e.g. appliances). Figures 6 and 7 represent the three energy loads for a simulation run from September 1^{st} to October 30^{th} for an east orientation with the three products. The contest has been planned to occur during all September

2017. However, the average September month has a climate such that there is no need for heating. To stay on the safe side and to prevent the pavilion's performance to fail due to a potential early cold season, it was decided to include October as the heating loads are higher than the cooling loads for this month. It should be noted that the observed lighting load curve on the graphs is not the absolute one, but the difference between the current Graetzel ratio and the model without any use of this latter technology. The reason is because the lighting load is not available at the room level but only at the building scale. The Graetzel windows affecting the illuminance in the subjected room only, the lighting loads from the other rooms stay identical for each Greatzel ratio. Thus the difference between two states is the same at the building and room levels.

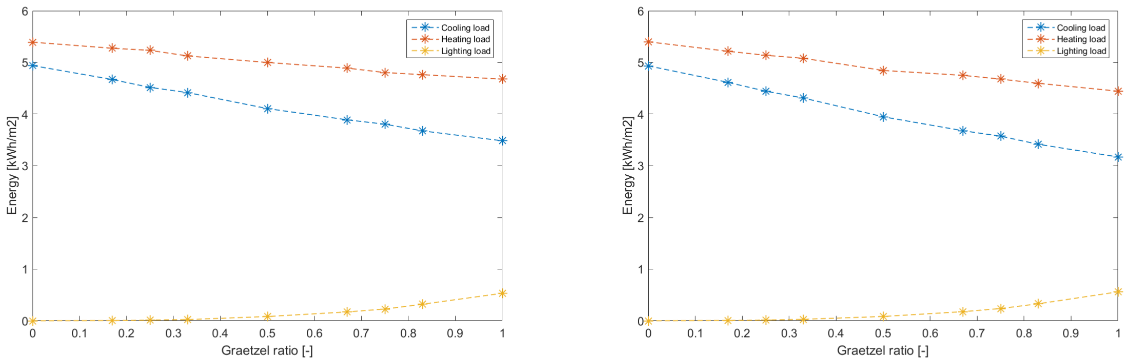


Figure 6: ROOM ENERGY LOADS FOR THE EAST ORIENTATION: From left to right: G2E w1 and G2E w2

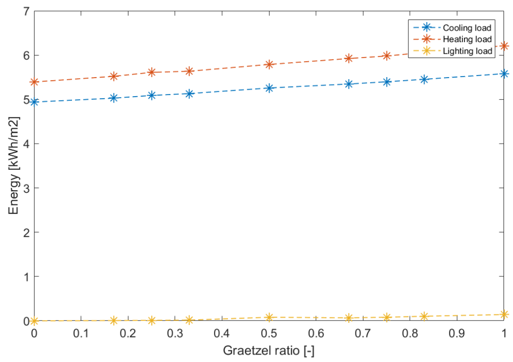


Figure 7: ROOM ENERGY LOADS FOR THE EAST ORIENTATION: SBskin

Figures 6 and 7 show that the heating and cooling loads follow the same trend: both decreasing or increasing with the Graetzel ratio. The lighting load always increases with the Graetzel ratio. The three variants demonstrate a higher heating load than the cooling one. All those statements are identical for every orientation of the room. The only exception is a higher cooling load than heating load for the SBskin product for the west orientation.

To see if a difference of behaviour in the room performance could be observed between a hot and cold month, the results were also analysed separately for September and October. Figure 8 is an example of the results for an east orientation with the G2E w2 product.

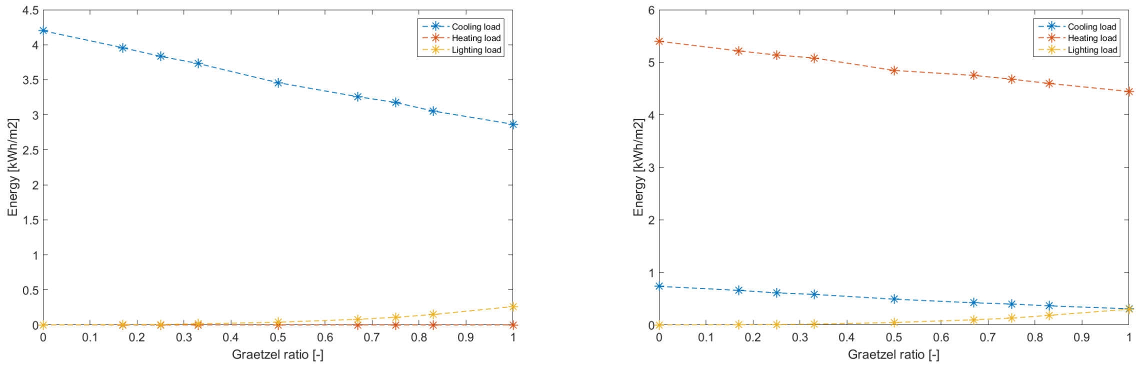


Figure 8: MODEL: **Facettes** modelling using Rhinoceros 3D software

Figure 8 depicts the same trends in the three load curves as seen in Figure **??** for both months. September requires cooling only and October mostly requires heating. Once more, those statements are the same for every orientation of the room and for the three products. As the trends are the same for both months, the results are presented only for the two months merged together from this point in the analysis.

Finally, the energy produced by the photovoltaic cells is deduced from the accumulated previous three energy demands to have the global energy performance affected by the Graetzel technology. To find out the amount of produced electricity for each room orientation and Graetzel ratio, solar irradiation were simulated with Rhinoceros for the four facade orientations. As the irradiation was homogeneous for the whole facade (there is no surroundings or self-obstruction from the pavilion), the energy production was calculated with the following formula for each Graetzel ratio at a given orientation:

$$E_{el} = \sum_i I_i * \eta(I) * \mathrm{A} * G_{ratio} \tag{1}$$

With I_i the irradiation at a time i, $\eta(I)$ the efficiency as a function of the irradiation, A the façade surface and G_{ratio} the Graetzel ratio.

The timescale of the simulation is hourly-based and the values are indeed sum up from September 1^{st} to October 30^{th}. The efficiency curve as a function of the irradiation for a

G2E red panel is given on Figure 36 in Appendix. It was assumed that the SBskin product uses the same technology. Thereby the same efficiency properties are used. Finally, the light reflections occurring inside the first glass layer of the SBskin and G2E w2 products (the Graetzel module is inserted behind a thin glass layer) are assumed to be negligible, and the irradiation used for the calculations are the one hitting the outermost window layer. Figure 9 shows the results of the three products for each orientation. Despite their higher U-Value, the two G2E products induce a better energy performance with a Graetzel ratio of 100% for the east, south and west orientations. This is surely due to their lower Solar Heat Gain Coefficients (SHGC) value which is very helpful for such overheated orientations to reduce the cooling load during daytime. It was seen that the heating load of the G2E products were also decreasing, this might be because of the higher thermal inertia of the Graetzel windows (bigger absorption coefficient), which gives back the heat at the end of the day, when heating is required. For the north oriented room, the optimum is at 50% Graetzel ratio for both G2E products. The increasing lighting load catches up with the decreasing heating and cooling loads. Finally, the SBskin product appears to always lead to more energy consumption (cooling and heating) due to a very high U-Value.

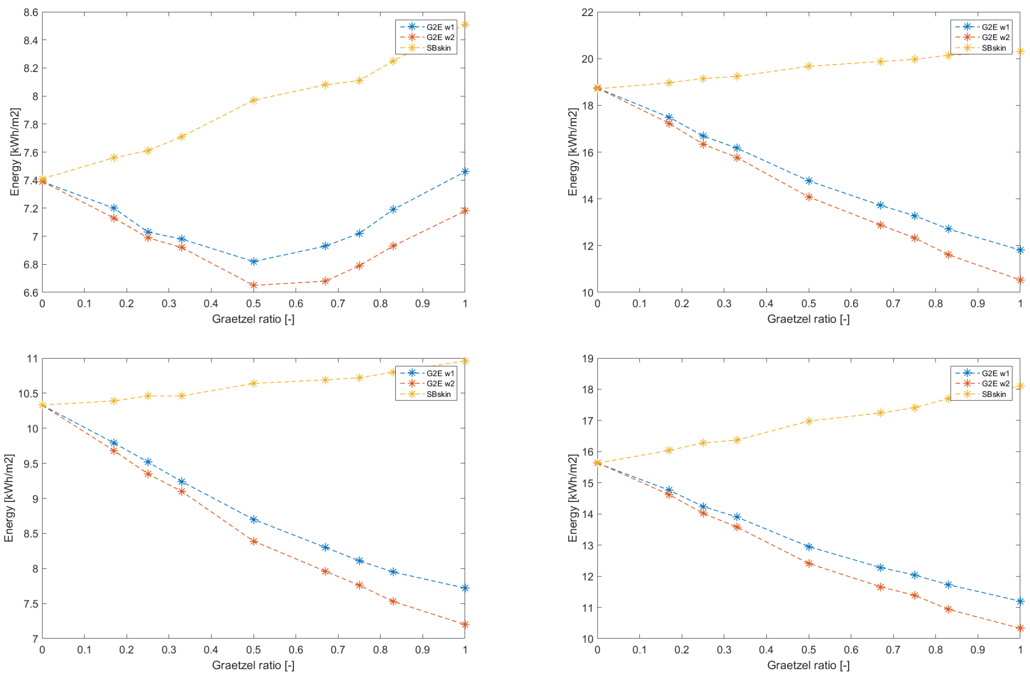


Figure 9: Room energy consumption: From right-left and up-down: north, south, east and west

3.3 Daylight analysis

3.3.1 Introduction and objectives

Previously, an energetic optimization of the Graetzel cells has been made to evaluate an approximate ideal percentage to respect thermal comfort and energy consumption regarding the Solar Decathlon rules. The second important step in this comfort analysis is the natural daylight optimization. Indeed, knowing the behavior of the pavilion including an amount of Graetzel will have an important impact on its assessment. This indication added to the thermal optimization constraints will give to the architects approximate directions to follow while assessing the Graetzel cells on the pavilion.

The purpose of this section is to evaluate the Graetzel's implementation respecting the minimum daylight needed. Taking into consideration the percentage given by the energetic assessment, the objective is to find the best way to use it. For this analysis, the software Rhinoceros was used helped by the GRASSHOPPER and DIVA pluggin. GRASSHOPPER was chosen for its ability to perform a high amount of simulations by only changing an input parameter (Graetzel ratio). DIVA for Rhino was helpful for its daylight modeling performances.

In this project, the different input parameters are first presented. Then, daylight analysis is made for each orientation (north, east, south and west) comparing the selected products. For each orientation, different configurations are tested for every Graetzel ratio.

3.3.2 Modelling "Facettes" with a Daylight analysis software

The **Facettes** model is represented on Figure 10. The kitchen and the studied glazed surface are located in the foreground of the Figure.

Materials The materials definition is equivalent to the one used in the energetic assessment. In this model, different materials have been used to define every surfaces of the pavilion. Internal and external wall surfaces were defined as oak wood as the initial wish of the Solar Decathlon team was to build this pavilion entirely with wood, and thus to let the surfaces as bare as possible. The G2E module is assessed with the properties of the w2 window. Indeed, in the energetic analysis of the pavilion (section(3.2), the results showed that it was a better alternative regarding the thermal comfort. The optical properties of this G2E module, the SBskin module and the standard window are presented in Table 2.

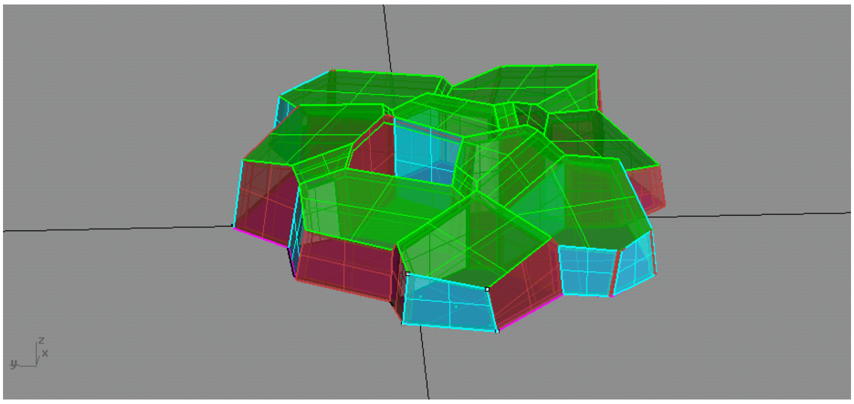


Figure 10: Model: **Facettes** modelling using Rhinoceros 3D software

Days for analysis To make this research relevant, it was wished to test this pavilion in the solar decathlon context. The best and worst days of the assessed period were selected, respectively September 15 and October 8, to perform the daylight analysis.

Figure 11 shows this radiance extracted from the EnergyPlus typical weather file of Denver.

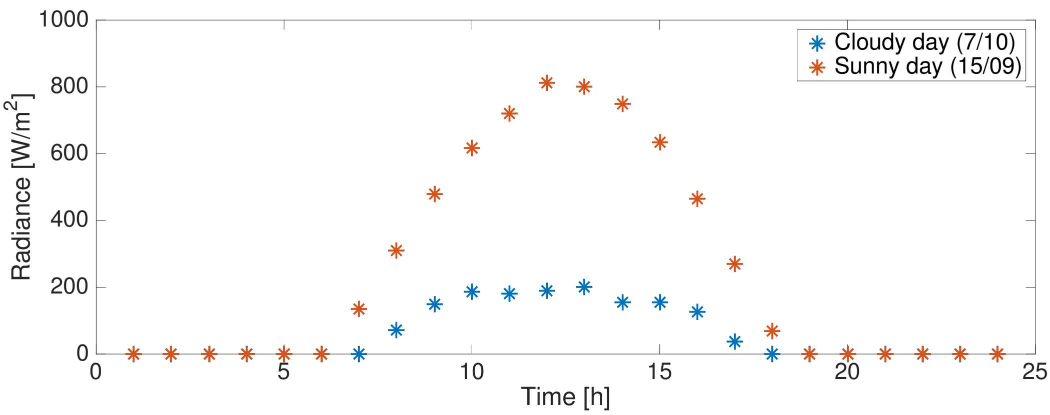


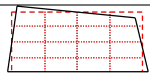
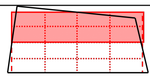
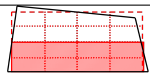
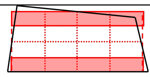
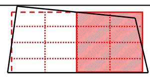
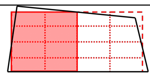
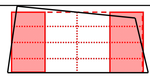
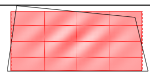
Figure 11: Days for analysis: Radiance for a sunny day (15th of September) and for a cloudy day (8th of October)

As we can see on Figure 11 the radiance on the 15th of September is almost four times more important than the radiance of the 8th of October.

Configurations Using the optimum found in the thermal analysis, different configurations are set to observe their influence on the daylight performance. The same percentages were evaluated for both technology. Thus, for the north, the following percentages were evaluated: 50% and 0% are the respective optimum of the G2E and SBskin products, and 100% for comparison. Similarly for the south, east and west orientations, the selection was: 100% and 0% are the optimum and 50% is a midpoint.

In the end, only the 4x4 grid cuts is assessed. The different configurations are presented in Table 3.

Table 3: Configurations with G2E and SBskin modules for all orientations: the red part represent the location of the Graetzel product
* For SBskin product there isn't horizontal division due to its physical propreties

Configuration	**% of Graetzel**	**Division**	**Localisation**	**Representation**
1	0	-	-	
2	50	Horizontal*	Top	
3	50	Horizontal*	Bottom	
4	50	Horizontal*	Divided	
5	50	Vertical	Right	
6	50	Vertical	Left	
7	50	Vertical	Divided	
8	100	-	-	

Rhinoceros 3D software parameters for daylight analysis Indoor illuminance was simulated with a grid of 380 captors placed at a distance of 0.9 m from the ground level. Indeed, this height corresponds approximately to the eyes of a seated person. For a more general and simple overview of the results, only 5 points are studied in this research. The repartition of these points is presented in Figure 12.

The ambient bounces parameters of Rhinoceros 3D, which represents the reflectance level of the simulation, has been set to 2.

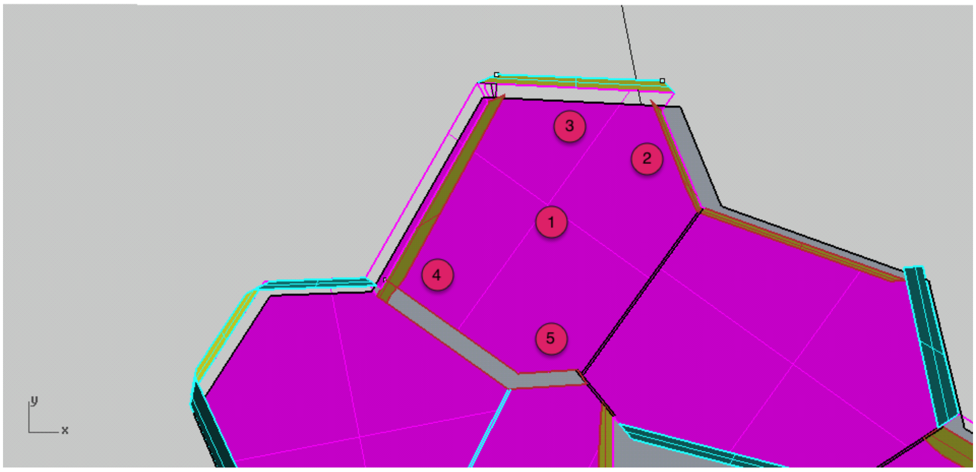


Figure 12: POINTS FOR ANALYSIS: Location of the different points that will be analysed in the daylight analysis (center (1), wall (2), window (3), down left (4) and down right (5))

3.3.3 Simulation and results

The main focus of this part will be the center point but most of the results for the four other points are presented in Appendix.

North In section (3.2), an optimum of 50% has been found for the G2E module and 0% have been found for the SBskin. Figures 13 and 14 show the indoor illuminance in September for the center point with every configurations for a G2E and a SBskin module. Figures 15 and 16 show the indoor illuminance for the center point in October for both products. On these Figures can be observed that the center of the room is under illuminated. The lower limit of 300 lux required by the Solar Decathlon rules are not respected. In September and in October this limit is only respected at midday. Thus, artificial lights will be in any case required. However, it is possible to exploit a high quantity of natural light by implementing a 50% of G2E at the bottom of the glazed surface. Indeed, Figures 13 and 15 show that the difference between the 0% Graetzel case and the 50% at the bottom is low. In Appendix 6.2 (Table 5 and 6) are presented the indoor illuminance in September and October for the four other points. The points on the back of the room are under-illuminated and an artificial lights will be necessary for both months. However, the points situated in front of the wall and in front of the window are well illuminated and are self-sufficient during the day. Regarding the indoor daylight comfort, the 50% of G2E module at the bottom of the glazed surface is still the best alternative after the 0% Graetzel case.

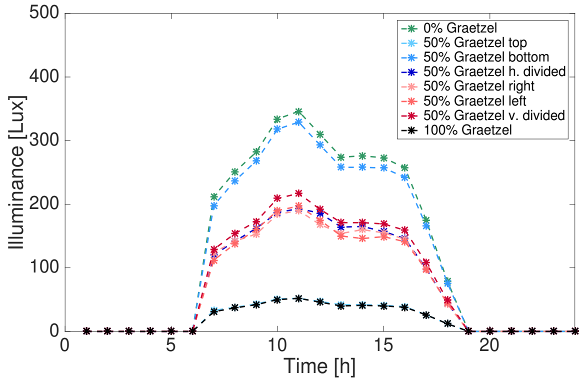


Figure 13: NORTH : September illuminance for G2E module

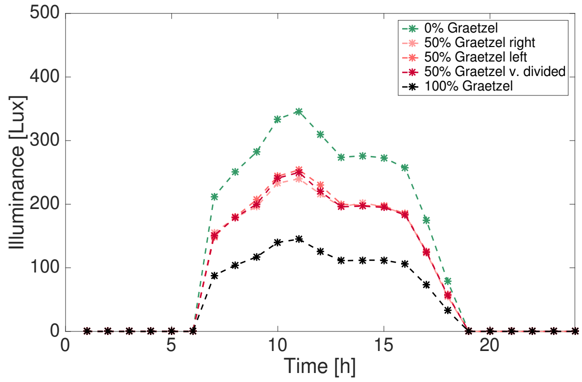


Figure 14: NORTH : September illuminance for SBskin module

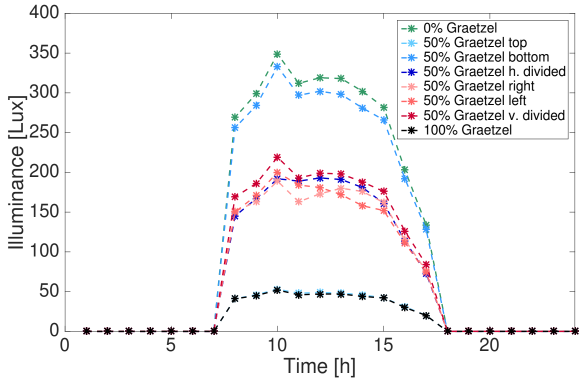


Figure 15: NORTH : October illuminance for G2E module

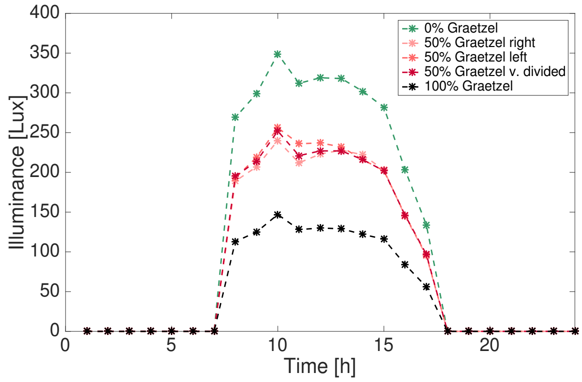


Figure 16: NORTH : October illuminance for SBskin module

East A similar analysis was carried out for the east orientation of the glazed surface. However, as the illuminances are higher than in the north-oriented case and as the differences between each configuration were hardly perceptible, a study of the relative change of the illuminance has been preferred to a simple study of the illuminance. The relative change has been calculating with the 0% of Graetzel configuration as the reference case (higher case of illuminance). Figure 17 and 18 show the magnitude of illuminance that can be reached during the day for both products for the month of September and Figure 19 and 20 the relative changes.

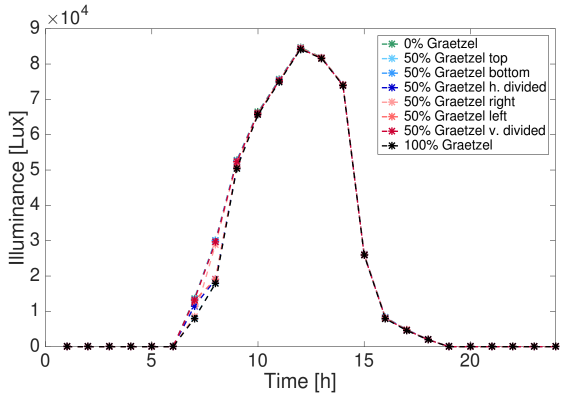


Figure 17: East : September illuminance for G2E module

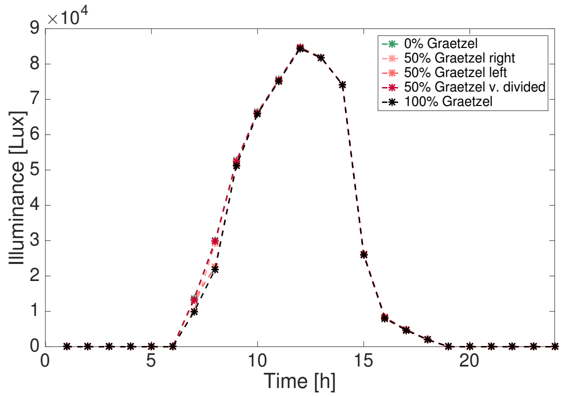


Figure 18: East : September illuminance for SBskin module

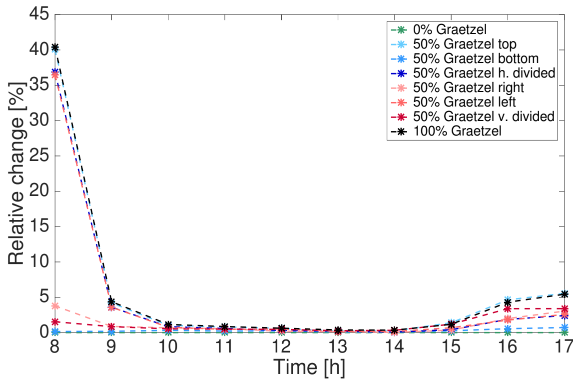


Figure 19: East : September relative change for G2E module

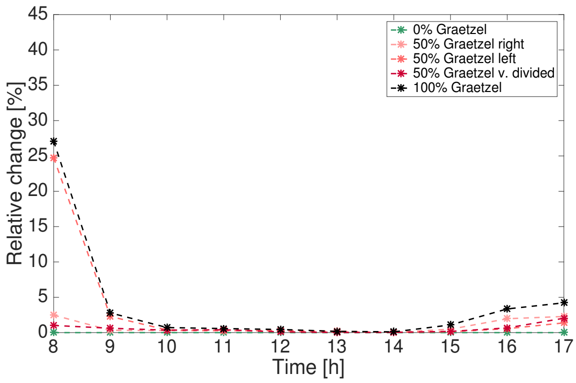


Figure 20: East : September relative change for SBskin module

For the month of October, the illuminance has the same shape as on Figures 17 and 18 with a peak of $8 \cdot 10^4$ lux at 12 pm. The relative changes are expressed in 21 and 22.

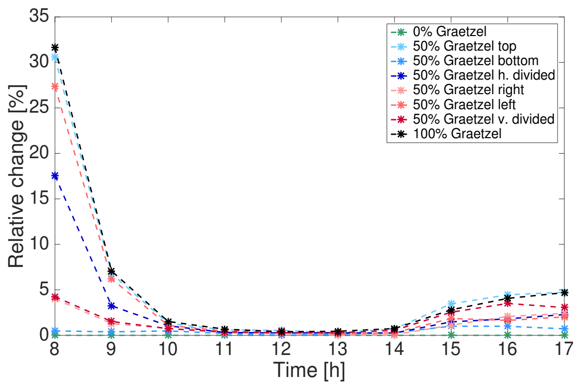


Figure 21: EAST : October relative change for G2E module

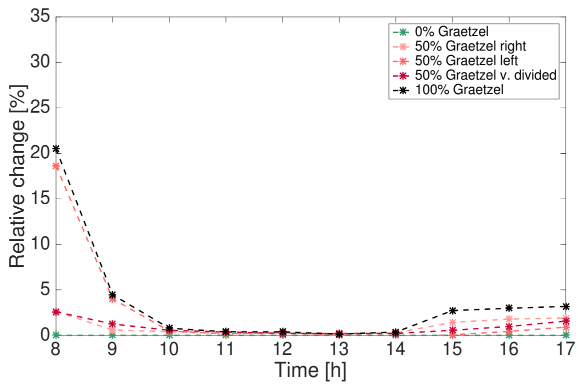


Figure 22: EAST : October relative change for SBskin module

All east-oriented results respect the lower limit of 300 lux. However, the optimal configuration is still the 50% of G2E module at the bottom of the window regarding every existing possibility. If an architect wish to place Graetzel vertically, he shall favour the implementation of SBsking module for its higher transmittance, regarding the daylight performance. For example the 50% of SBskin Graetzel vertically divided seems to be the best alternative regarding vertical division. Indeed, the relative change of the 50% of SBskin Graetzel reaches 2.5% while it reaches almost 5% for the G2E module.

South In the south, the illuminance has a peak of $9 \cdot 10^4$ lux in September and $8 \cdot 10^4$ lux in October. As for the east-oriented glazed facade, the lower limit is respected in all cases. Figures 23, 24, 25 and 24 show that the optimal solution remains 50% of Graetzel at the bottom. However, for a vertical division, the SBskin module allow a higher amount of illuminance than the G2E module.

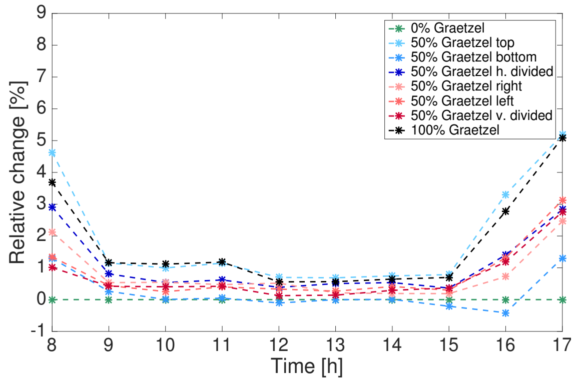


Figure 23: SOUTH : September relative change for G2E module

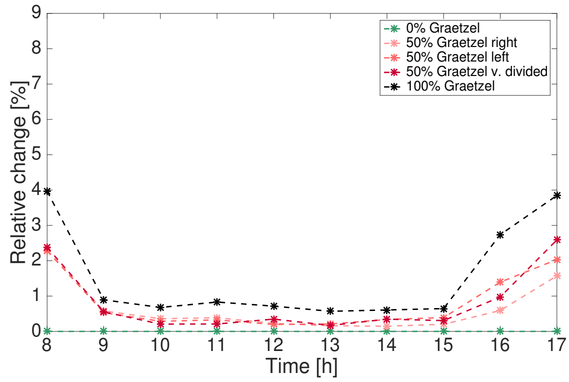


Figure 24: SOUTH : September relative change for SBskin module

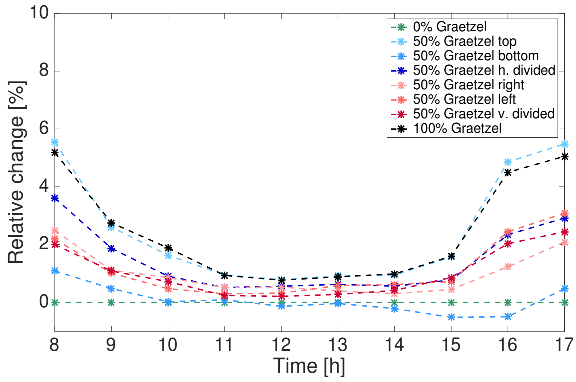


Figure 25: SOUTH : October relative change for G2E module

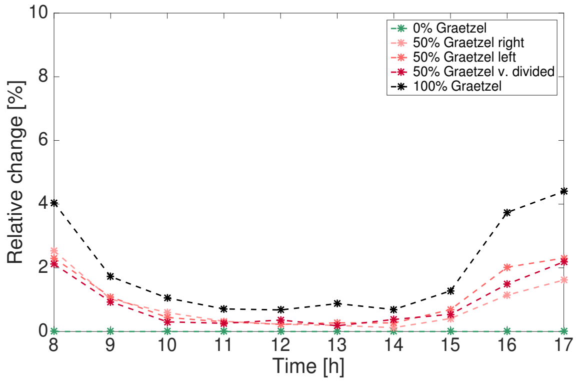


Figure 26: SOUTH : October relative change for SBskin module

West A peak of $9{\cdot}10^4$ lux is seen in September and $8{\cdot}10^4$ lux in October for the west orientation. The illuminance is respected for each configuration. As for the south and east case, the optimal solution is 50% of G2E module at the bottom of the glazed surface even if a vertical division can be considered for a higher transmittance.

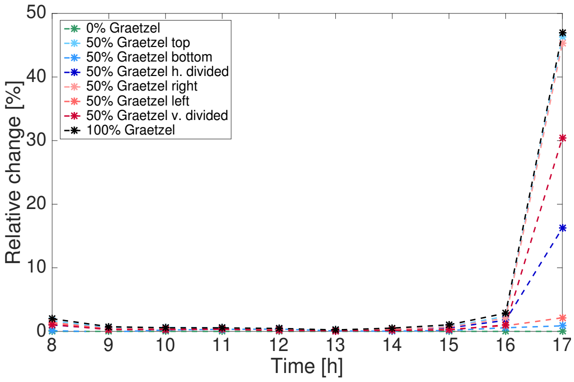


Figure 27: West : September relative change for G2E module

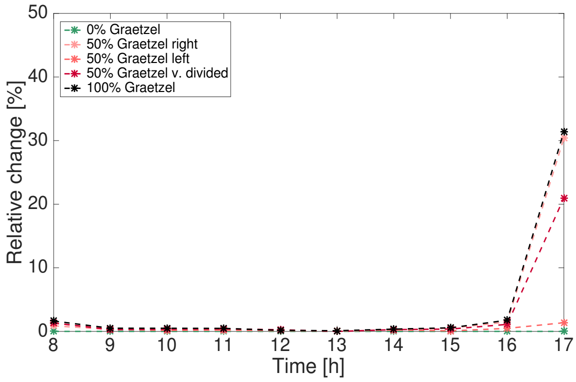


Figure 28: West : September relative change for SBskin module

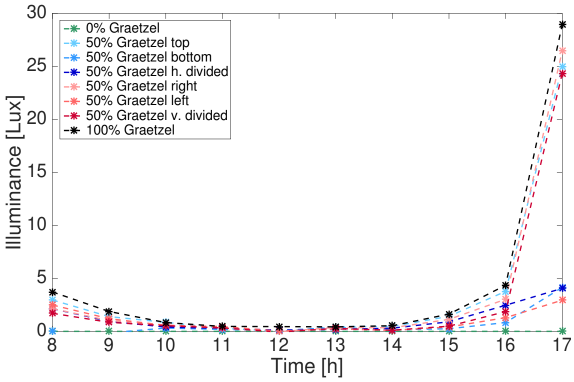


Figure 29: West : October relative change for G2E module

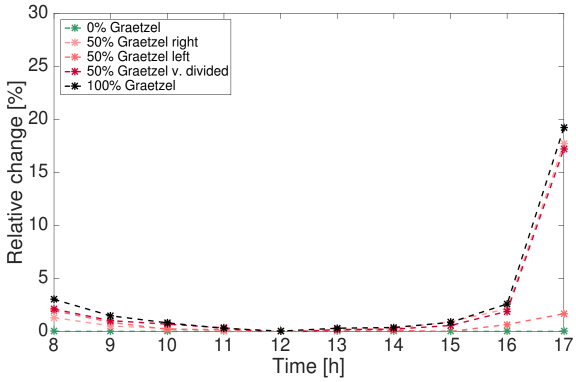


Figure 30: West : October relative change for SBskin module

Glare analysis As a conclusion of the daylight analysis, an important point to make is the benefits that could have the Graetzel technology on the glare.
Glare is actually a representation of visual discomfort. As it is a quite subjective rating, it exists many ways of measuring it. One of them is the calculation of the Daylight Glare Probability (DGP), which is the one evaluated in DIVA for Rhinoceros 3D. To be on a reasonable comfort class, the DGP has to respect the following conditions [2] :

- DGP limit ≤ 0.45
- Average DGP limit withing a 5% band : 0.5

Over these limits, the glare is intolerable [4].
For the glare, the quantity of light is actually an important factors for the glare evaluation and could be studied in conjunction with the daylight analysis.
Without getting into specifics, a glare analysis was made for the south in September at 12pm, which is the higher amount of illuminance seen in the totality of our simulations and thus the case with the higher probability of glare occurrence. The camera was set at the center of the room. The sky condition was set to "Clear sky with Sun" to reproduce the September conditions.
The results are presented on Figure 31, 32 and 33. Figure 31 represents the case of a 0% Graetzel ratio with an intolerable glare. Figure 32 and 33 represents respectively the glare analysis with a 100% of G2E w2 and SBskin products with an imperceptible glare. On these Figures, the DGP is presented along with the glare perception.

Figure 31: GLARE ANALYSIS with a 100 % of standard window

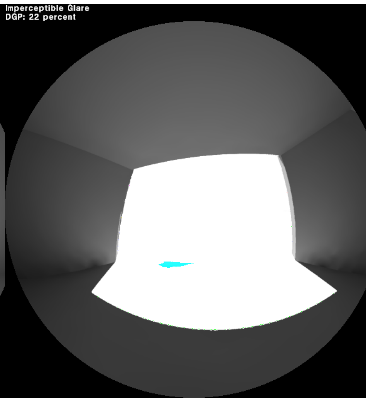


Figure 32: GLARE ANALYSIS with a 100 % of G2E

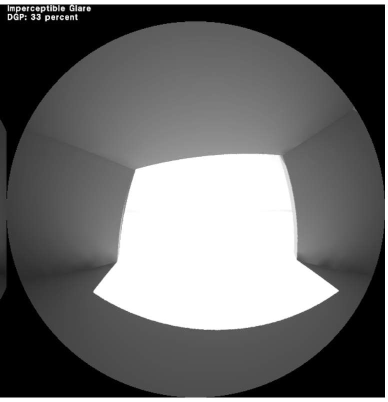


Figure 33: GLARE ANALYSIS with a 100 % of SBskin

[4] For glare, the scale for perception are: imperceptible, perceptible, disturbing and intolerable

4 Discussion

In the previous section, a thermal and daylight analysis was carried out to find or get closer to an optimal assessment of Graetzel cells of G2E and SBskin products. This section will briefly resume the results obtained previously and build some indications to communicate to the architects for an optimal Graetzel implementation in the pavilion. Finally, the limits of this research are exposed, where uncertainties have to be taken into account.

In the thermal analysis, some percentage of Graetzel ratio were selected for their lowest global energy consumption of the room. Combining these percentage with indications given by the daylight analysis, directions of Graetzel integration can be given to the Solar Decathlon architects.

In the **north**, the incoming light is very limited. Thus, the implementation of Graetzel cells has to be well thought. Regarding the thermal assessment, the optimal implementation is a 50% of G2E Graetzel cells or 0% of SBskin glass blocks. Regarding the daylight analysis, 0% of Graetzel cells is the best option to maximize the natural light and respect the Solar Decathlon rules. However, we saw on Figures 13 and 15 that the 50% of G2E Graetzel at the bottom the glazed surface had an illuminance very close to the 0%. Thus, the trade-off between energetic performance and daylight comfort will be to implement 50% preferentially at the bottom of the window. In all cases, artificial light will be necessary for the north oriented glazed surface.

In the **other orientations (east, south and west)**, the energetic optimum were 100% with a G2E module and 0% with a SBskin module. Regarding the daylight comfort, every configuration ensures a respect of the light indoor requirements. We saw in section 3.3 that the 50% of G2E at the bottom was still the best configuration in all orientations, regarding daylight performance. However, the relative change is the same order of magnitude for all configurations, thus, they can be perceived as equivalent. All implementation of Graetzel are acceptable regarding the daylight requirements. Regarding the natural daylight, if it is wished to implement them vertically, the architect shall promote the SBskin module instead, for its higher transmittance. However, the energetic performance would be of worse quality. Also, the architect may choose to use Graetzel on south surfaces for example to attenuate glare.
Yet, for those orientations, the choice of the trade-off between energy consumption or daylight performance is up to the architect.

Nevertheless, this study is based on several assumptions that must be discussed. First, even if the SBskin product incorporates a green dye of G2E manufacture, the efficiency curve used to calculate the electricity production corresponds to a red dye product as it was the only available one. Yet, the difference in efficiencies between red and green

dyes are not significant, making this hypothesis reasonable. However, as these efficiencies might be improved with a different rate, it is recommended to perform the assessment with the latest data.
Then, it is important to note that thermal simulations use a global solar transmission, but the information about what part of the electromagnetic spectrum is actually transmitted is lost. As each wavelength of the spectrum has a different energy level, if the transmission mostly occurs in the infrared but DesignBuilder set the same solar transmission factor for all wavelengths, the solar heat gains might have a non-negligible bias.
Most of all, in the thermal analysis, the embodied energy was not taken into consideration in the global energy consumption. We can expect the Graetzel cells to have a consequent embodied energy and will maybe change the thermal optimum (especially for the north orientation).
Finally, the SBskin product was modeled as a single layer and thus have different properties that the ones found on Figure 35 in the Appendix. This means that the results might have a significant bias. The best solution to this would be to implement all the layers of the glass block with a correct frame an separations.

Regarding the daylight analysis, considering and defining Graetzel as a glass could be a high source of uncertainties. At first, this hypothesis moves apart the color consideration which can be the first reason of indoor discomfort. Then, the only input given to the software to model the surface is the visible transmittance and the refractive index which is a very restrictive hypothesis for a photovoltaic of third generation. To improve the accuracy of the illuminance results, the assessed Graetzel products should be modelled as materials that consider the angular dependency of the optical properties. Indeed, a factor to represent diffuse and direct light would be more realistic for a daylight analysis.
Furthermore, the glare analysis has been made in an empty room which will change while filling the room with furniture. Indeed, the level and the kind of occupation influences consequently the glare occurrence in a room.

Additional simulations were run on DesignBuilder by using external blinds with high reflective slats and with the standard window. The blinds are set to automatically lower when the indoor temperature is above 21°C. Table 4 compares the reduction in energy consumption when using the blinds and the best Graetzel ratio of the G2E w2 product (see Figure 34). The external blinds appear to always have a better energy performance. Even if 50% of Greatzel w2 has a comparable value for a north orientation of the room (6.51 and 6.65 kWh/m2 respectively), the embodied energy has not been accounted for, and the one from the Greatzel w2 is expected to be higher than the sum of the blinds and the standard window.

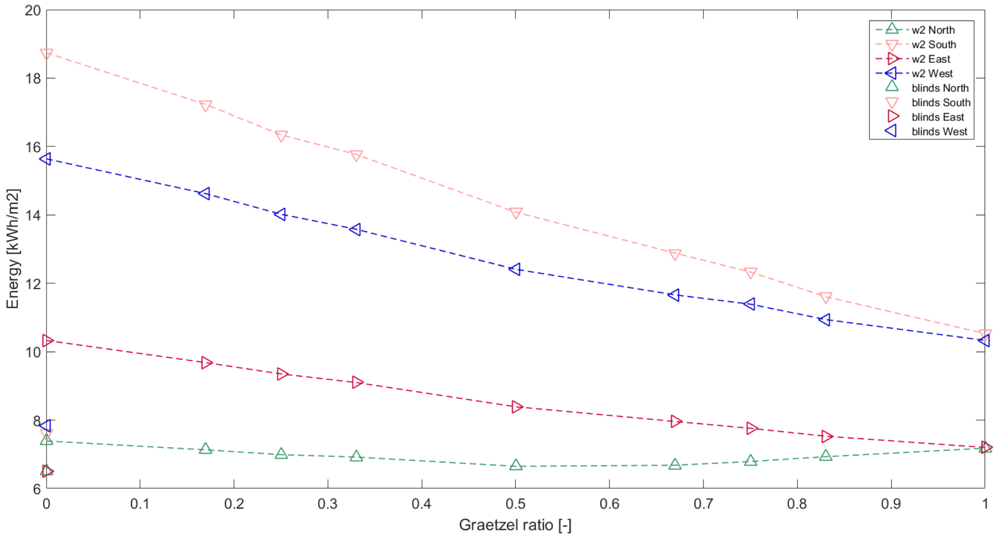


Figure 34: ROOM ENERGY CONSUMPTION: with the product G2E w2 and external blinds

Table 4: Energy consumption reduction by using external blinds or the best Graetzel ratio for each orientation

	N	S	E	W
G2E w2	0.10	0.44	0.30	0.34
Ext. blinds	0.12	0.59	0.37	0.50

5 Conclusion

In the context of the Solar Decathlon construction, transparent BIPV using the Graetzel technology potentially plays an important part. Indeed, this native product can be a positive point in a few categories. At first, the architecture aspect could consequently be highlighted with Graetzel cells for its color and its building component function. Then, it definitely puts forward the engineering part for its electricity production that could help in the pavilion autonomy. To conclude, the innovation category can be highly valued with the assessment of this new technology that includes energy production as a fully integrated building component. As this technology has been created in Switzerland by a professor from the Ecole Polytechnique Fédérale de Lausanne, its assessment could be the representation of the Swiss brand.

However, the implementation of these products has to be controlled as it has an impact on the building envelope optical and thermal properties. This research put forward that for different orientations and different products using the Graetzel technology, some indications should be acknowledged by the architects. It was seen that optimal solutions are 100% Graetzel coverage for the east, south and west orientations of the glazed facade and 50% with a bottom configuration for the north-oriented variant, with a certain degree of liberty. As they only are directions, the architect can adapt this research to his proper building and design.
It should be noted that if the Graetzel technology was to increase its efficiency of electricity production, the north best performance of the G2E w2 product could give better results than external blinds (for energetic consumption at least). Also, this study was done by using an already selected window type (argon-filled triple glazed with low-emissivity panes) on which the G2E module was inserted. It might be that the use of a completely different window would lead to significantly better results from the Greatzel products compared with external blinds.

Despite the better energetic performance of external blinds and their more practical implementation, other usage of the Gratzel technology should be assessed for a profitable performance. For example they can be used as a rotating shading device, which then won't reduce the thermal properties of the window as it would be physically separated from it. For indoor daylight it won't have negative points as it could be adapted to the current indoor daylight. This solution would have the advantage of a better practical maintenance as the breaking of a cell would not imply the change of the whole window.

References

[1] BOUVARD Olivia, VANZO Sara, SCHÜLER Andreas (2015) *Experimental determination of optical and thermal properties of semi-transparent photovoltaic modules based on dye-sensitized solar cells*, Ecole Polytechnique Fédérale de Lausanne (EPFL), Solar Energy and Building Physics Laboratory (LESO-PB)

[2] WIENOLD Jan (2009) *Dynamic daylight glare evaluation*, Fraunhofer Institute for Solar Energy Systems

[3] GRONDZIK Walter T., KWOK Alison, STEIN Benjamin, REYNOLDS John S. (2010) *Mechanical and Electrical Equipment for Buildings (XIth edition)*, Hoboken, New Jersey : John Wiley & Sons

6 Appendix

6.1 Materials properties

APPENDIX TO CHAPTER 5

New thermally-optimized and PV-integrated Configurations (Green g2e 75%)

			COMSOL U-value		WINDOW CENTER OF GLASS DATA				WINDOW OPTICAL DATA									
Configuration			2D	3D	U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3	Abs4
Configuration 1 - G2E GREEN 75%	1.01	V	0,9	1,4	0,2	0,288	25,10%	184	29,44%	9,92%	17,91%	19,43%	14,43%	26,37%	61,02%	3,53%	1,59%	-
		A	1,2	1,6	1,4	0,321	27,90%	211	29,44%	9,92%	17,91%	19,43%	14,43%	26,37%	61,02%	3,53%	1,59%	-
	1.02	V	1,7	1,8	1,3	0,391	34,00%	259	30,14%	10,48%	20,28%	24,96%	11,98%	17,82%	57,91%	2,62%	2,53%	-
		A	1,9	2,0	1,9	0,406	35,50%	271	30,14%	10,48%	20,28%	24,96%	11,98%	17,82%	57,91%	2,62%	2,53%	-
	1.03	V	1,1	1,5	0,2	0,274	23,80%	174	26,94%	10,65%	22,76%	17,15%	14,84%	26,82%	61,58%	3,69%	1,38%	1,36%
		A	1,4	1,7	1,1	0,290	25,20%	190	26,94%	10,65%	22,76%	17,15%	14,84%	26,82%	61,58%	3,69%	1,38%	1,36%
	1.04	V	1,5	1,7	0,9	0,346	30,10%	227	27,62%	11,25%	24,75%	21,68%	12,58%	20,90%	58,70%	2,74%	2,18%	2,12%
		A	1,7	1,8	1,4	0,358	31,20%	237	27,62%	11,25%	24,75%	21,68%	12,58%	20,90%	58,70%	2,74%	2,18%	2,12%
Configuration 3 - G2E GREEN 75%	3.01	V	0,9	1,4	0,2	0,288	25,00%	183	29,35%	7,00%	16,03%	19,36%	11,14%	25,58%	64,41%	3,51%	1,59%	-
		A	1,2	1,6	1,4	0,323	28,10%	212	29,35%	7,00%	16,03%	19,36%	11,14%	25,58%	64,41%	3,51%	1,59%	-
	3.02	V	1,7	1,8	1,3	0,394	34,30%	261	30,01%	7,56%	18,31%	24,88%	8,72%	16,01%	61,25%	2,62%	2,53%	-
		A	1,9	2,0	1,9	0,411	35,70%	274	30,01%	7,56%	18,31%	24,88%	8,72%	16,01%	61,25%	2,62%	2,53%	-
	3.03	V	1,1	1,5	0,2	0,273	23,80%	174	26,81%	7,72%	21,19%	17,07%	11,55%	26,18%	64,99%	3,66%	1,38%	1,35%
		A	1,4	1,7	1,1	0,302	25,30%	198	26,81%	7,72%	21,19%	17,07%	11,55%	26,18%	64,99%	3,66%	1,38%	1,35%
	3.04	V	1,5	1,7	0,9	0,348	30,30%	228	27,46%	8,31%	23,10%	21,59%	9,31%	19,50%	62,08%	2,73%	2,18%	2,11%
		A	1,7	1,8	1,4	0,361	31,40%	239	27,46%	8,31%	23,10%	21,59%	9,31%	19,50%	62,08%	2,73%	2,18%	2,11%

Table 5A.7 *(continues in the next page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

Figure 35: Datas for SBSKIN module

G2E 32 cell 13 Wp module

Data given here are preliminary and subjected to changes and improvements

Features: Semi-transparent DSC glass module

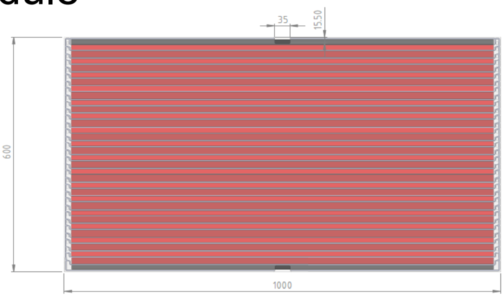
Color: Red - transparent

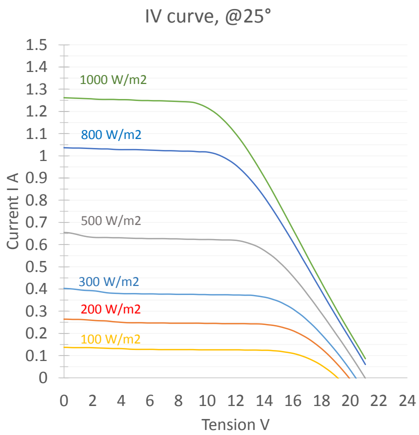
Dimension: 600 mm x 1000mm x 6.5mm

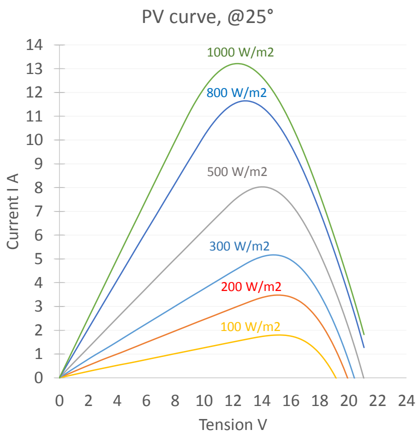
Dye sensitized solar cells are the third generation of solar PV technologies

•The cell is embedded between two 3.2mm thickness glass plates (front and back glass).

•The module can be integrated in different window and façade products, curtain walls, sound barriers and a large variety of



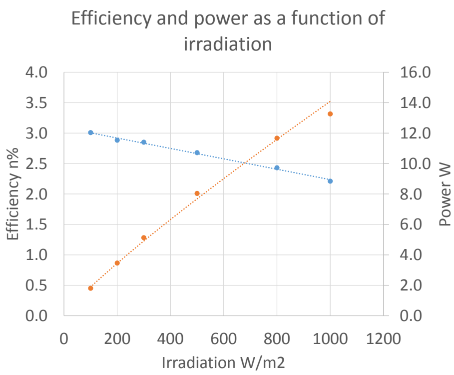




Electrical data @	1000W/m²	800 W/m² (NOCT)	
Maximum Power Pmax:	13.3	12.1	W
Open Circuit Voltage Voc:	22.0	21	V
Short circuit current Isc:	1.26	1.25	A
Voltage @ Pmax Vmpp:	12	13	V
Current @ Pmax Impp:	1.08	0.9	A
Module efficiency:	2.2	2.5	%

Maximum System Voltage:	60V
Over current protection:	Anti-return Diode
Operaton Temperature Range :	0°C to + 70°C
TNOCT :	45°C
Weight:	9.6 kg

Temperature coefficients
Voc: - 0.3 % / °C
Isc: + 0.1 % / °C
Pmpp: + 0.05 % / °C



Higher performance at lower irradation levels

In vertical façade operation situations predominantely moderate solar irradiation conditions of 300-500 W/m² are dominant.

Therefore it is very advantageous to have higher performance at lower irraditions.

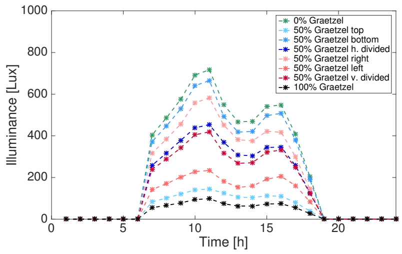
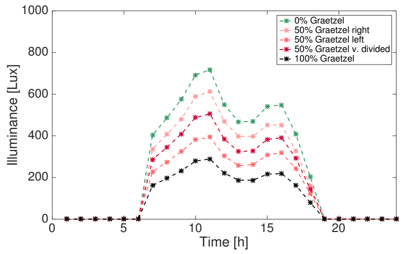
Manufactured by:
g2e glass2energy sa
Z.I. Le Vivier
CH-1690 Villaz-St-Pierre
Switzerland
Tel: +41 24 441 99 52
Fax: +41 24 441 99 54
info@g2e.ch

glass 2 energy

Figure 36: DATAS for G2E module

6.2 Daylight analysis

Table 5: Indoor Illuminance for the points : Wall, Window, Down Left and Down Right in September for the north

<table>
<tr><td rowspan="2"></td><td colspan="2">September</td></tr>
<tr><td>G2E</td><td>SBskin</td></tr>
<tr><td>Wall</td><td>
</td><td>
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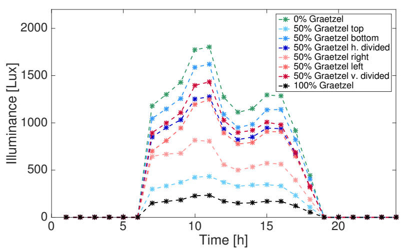
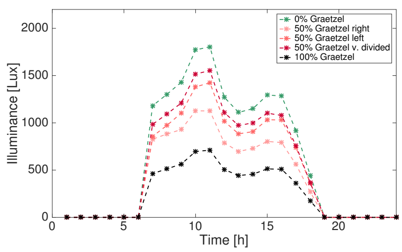
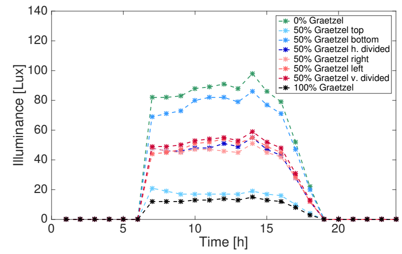
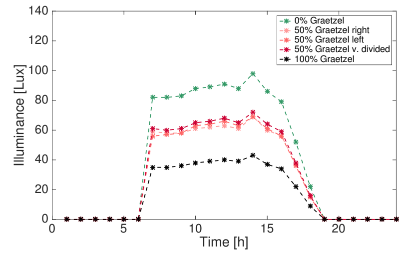
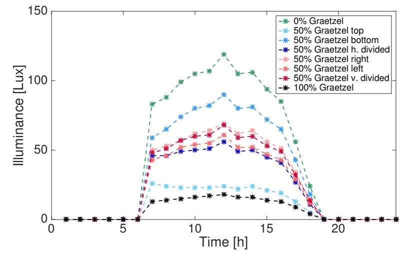
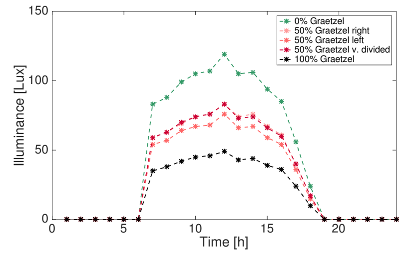
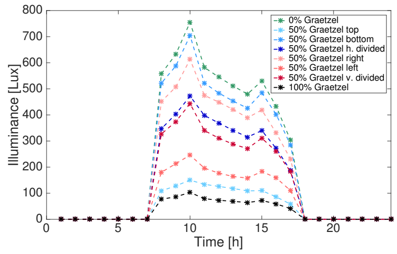
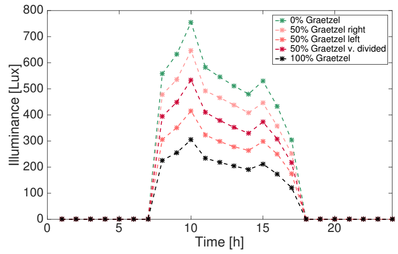
<tr><td>Window</td><td>
</td><td>
</td></tr>
<tr><td>Down Left</td><td>
</td><td>
</td></tr>
<tr><td>Down Right</td><td>
</td><td>
</td></tr>
</table>

Table 6: Indoor Illuminance for the points : Wall, Window, Down Left and Down Right in October for the north

<table>
<tr><td rowspan="2"></td><td colspan="2">October</td></tr>
<tr><td>G2E</td><td>SBskin</td></tr>
<tr><td>Wall</td><td>
</td><td>
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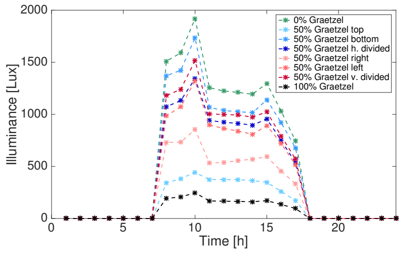
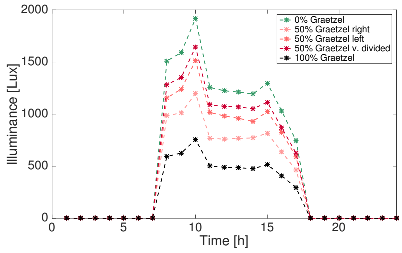
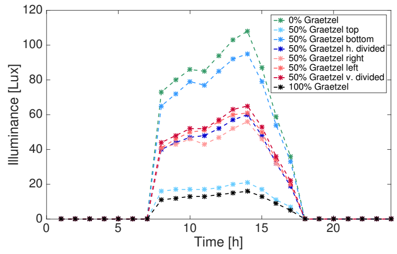
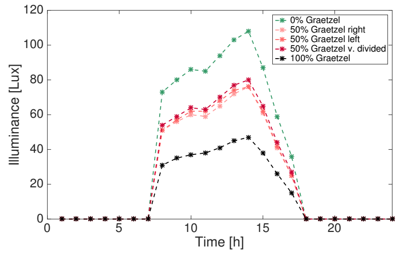
<tr><td>Window</td><td>
</td><td>
</td></tr>
<tr><td>Down Left</td><td>
</td><td>
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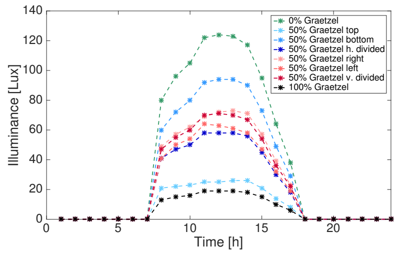
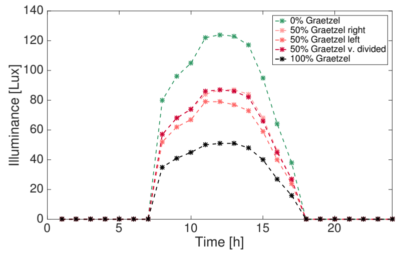
<tr><td>Down Right</td><td>
</td><td>
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