Study of the Influence of the Vertical/Horizontal Series Connections on the Photovoltaic Power Generation Potential on Building's Facades

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Abstract

In a context of urban densification, the exploitation of the solar potential of the facades of buildings is a promising way in order to meet the growing demand for energy whilst fighting against global warming – notably through BIPV (Building Integrated Photovoltaic technologies).The study presented in this paper focuses on the impact of the orientation of the series connection of photovoltaic (PV) panels installed on building facades. The solar potential of buildings is assessed considering the surrounding environment, using the ENVI-met urban micro-climate simulation software.

Keywords: BIPV, energy production, active facades, photovoltaic, ENVI-met

1. Introduction

Interest in building-integrated photovoltaic (BIPV) power generation technologies has been growing over the past two decades (Hagemann, 1996; Shukla et al., 2017; Saretta et al., 2020). These technologies are a promising way to make buildings producing energy from a renewable source.

Nevertheless, the predicted potential of energy production is often far away from the reported one. This is particularly true for the facades. This gap tends to be filled with new algorithms such as the one developed by (Redweik et al., 2013). But, despite the improvement brought by this algorithm, some phenomena that occur in urban environment are still not taken into consideration, notably the inter-building reflections and aeraulic phenomena.

The solar production potential of roofs has been the subject of studies for several decades (Sarralde et al., 2015). However, the interest in facades, although more recent (Díez-Mediavilla et al., 2019), highlights the fact that the level of irradiation of facades can be higher than that of roofs, depending on the latitude (especially in winter). Evaluating the solar potential in facades requires considering the environment close to the building. Indeed, different phenomena must be taken into account in relation to the case of an isolated building, including masking and shading of buildings on each other or inter-reflections between buildings. These phenomena are considered through the use of the urban micro-climate simulation software ENVI-met. The results of the simulations (facade irradiation level and surface temperature) are then used as input data for the photovoltaic production model.

The main goal of this study is to evaluate the influence of the direction of the series connections on the potential of the photovoltaic power generation of modules installed on facades of buildings. This paper falls into two main parts. First, the context of the study is put, as well as the developed model of PV production. Next, the results are presented and discussed.

2. Context of Study

The study reported here is carried out as part of the Interreg France-Swiss G2 Solaire, which aims to implement a solar cadaster on the scale of Greater Geneva. It involves the evaluation of the potential of production regarding the morphology of the neighborhoods. The final goal of this project is to achieve the energy transition in a context of urban densification by intensifying the use of solar energy in accordance with the technical and economical

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imperatives. In order to precisely assess the influence of all the phenomena that occur in urban environment, it is important to start from simplified cases, for which the evaluation of each phenomenon is easier.

2.1. Fictional Neighborhood

The modeled district shown in figure 1 is a fictional district, positioned at a location corresponding to the city of Geneva, Switzerland. The climate of Geneva is temperate, with mild and humid winters, and cooler summers than in subtropical climates and with variable weather.

The fictional district is inspired by the study of (Natanian et al., 2019). Unlike the study presented in this paper, the main goal of the one carried out by (Natanian et al., 2019) was to evaluate the energy load and daylight autonomy of buildings. Nonetheless, the morphologies of the neighborhoods used in this paper have demonstrated their impact. Thus, the interest focuses on the building number 5, which is particularly impacted by the surrounding buildings. In this neighborhood, all the buildings are 30 meters high, 20 meters wide and separated from each other by 20 meters. The spatial resolution is equal to 1 meter in each direction. Although expensive from the point of view of the computational time, this resolution allows to obtain a greater precision concerning the spatial heterogeneity in terms of solar irradiance on the facades and thus in terms of PV power generation.

The results presented in section 3 concern the south facade. Buildings 1, 2 and 3 can create shadows or reflections on building 5. Studies on the assessment of the photovoltaic potential of buildings consider surrounding buildings only as masks (therefore having a negative impact on solar potential). However, these buildings can also reflect part of the solar radiation, allowing a surface which is not facing the Sun to receive part of this radiation (which therefore contributes to an increase in terms of solar potential). In order to take these reflections into account, all the facades of the buildings in this district have a coefficient of reflection equal to 0.2, corresponding to that of conventional cement.

The studied days are the representative average days of each month of the year. The representative average day of the month is defined, according to the equation 1, as the day for which the meteorological conditions (including: irradiation level, temperature, wind speed and direction) for each hour are equal to the average of these conditions over all the days of the month. Carrying out the study over the whole year makes it possible to assess the evolution of the impact of the surrounding environment on the PV power generation potential.

$$X_{RAD}(t) = < X_i(t) >_{N_{day}} \quad \text{(eq. 1)}$$

where X is the averaged variable, t is the time of the day, N_{day} is the number of days in the month, the subscripts i and RAD represent the i-th day of the month and the representative averaged day, respectively.

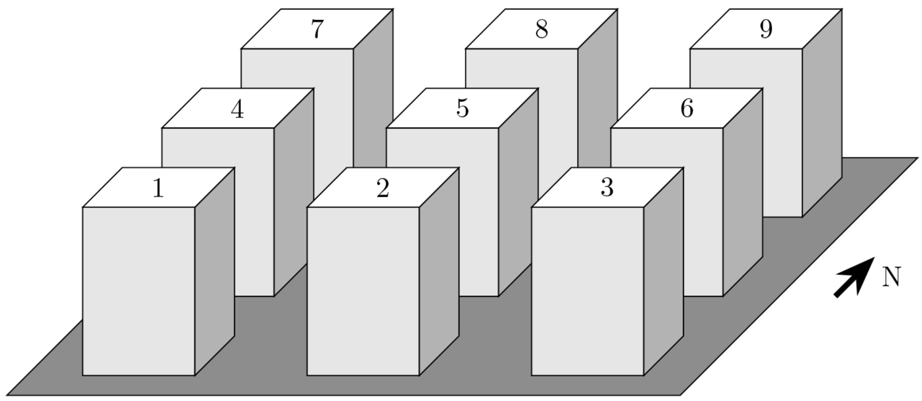


Figure 1: Fictional Studied Neighborhood – Geneva

2.2. Double-diode Model

The PV production model used is based on the double diode model developed by (Et-torabi et al., 2017). It is represented in figure 2. Owing to the similarity in their construction, the constituents of a photovoltaic (PV) panel can be approximated by one or more diodes to produce the desired electrical response. An example of a such a current-voltage characteristic curve is shown in figure 3.

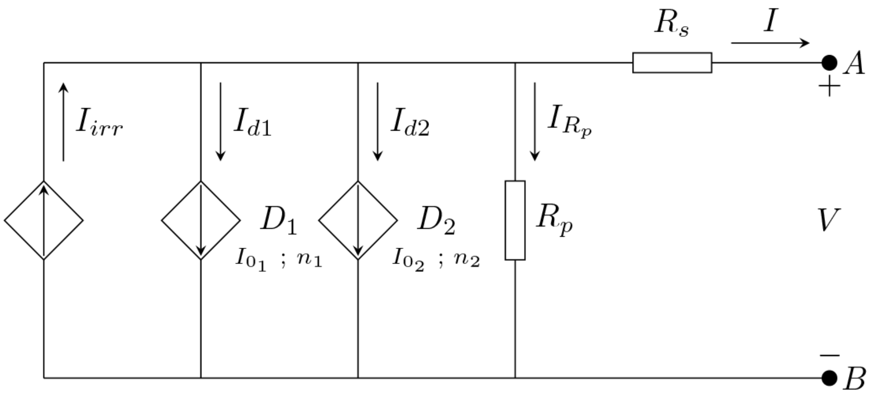


Figure 2: Double-diode Model Equivalent-Circuit

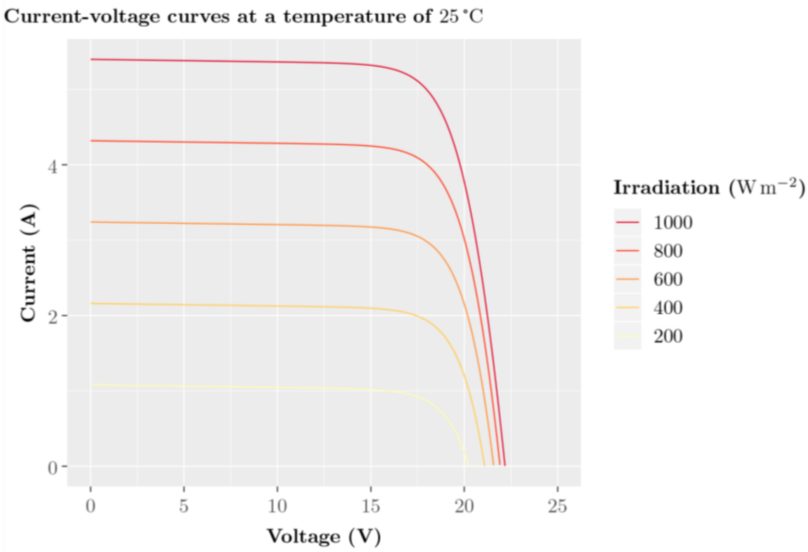


Figure 3: Current-voltage curves of the multicrystalline photovoltaic module TEX854

The purpose of the double diode model is to bring greater precision to the production model for low irradiation, compared to the single diode model (Humada et al., 2016). Indeed, an increasing number of diodes, although making the resolution of the model more complex, also makes it possible to take into account the evolution of the ideality factor of the diodes, which depends on the voltage to which the panel is subjected. For strong irradiations, the ideality factor is close to 1, while for lower irradiation levels, it approaches 2. This variation of the ideality factor is obtained by adding a second diode in parallel with the first (Gao et al., 2016). The electrical characteristics of the TEX854 multicrystalline PV panel used in this study are presented in Table 1.

Table 1: Electrical characteristics of the TEX854 photovoltaic module

Photovoltaic Module TEX854	
Rated voltage	18.0 V
Rated current	5.0 A
Open-circuit voltage	22.2 V
Short-circuit current	5.4 A
Temperature coefficient: short-circuit current	1.53 mA/C

Temperature coefficient: open-circuit voltage	-76.32 mV/C
Solar cells	36 (4 × 9)

3. Results and discussion

3.1. Irradiation on facade

An example of the irradiation profile on the south facade of building 5 at different time of October 16th, 2018 is shown in figure 4. The figure presents the total direct and diffuse solar radiation incident on the facade, including sky diffuse and ground reflected components The lower levels of irradiation on the facade are due to the shadow of buildings on the southern row. The mask that they create have an influence on the production profile, as discussed in section 3.2.

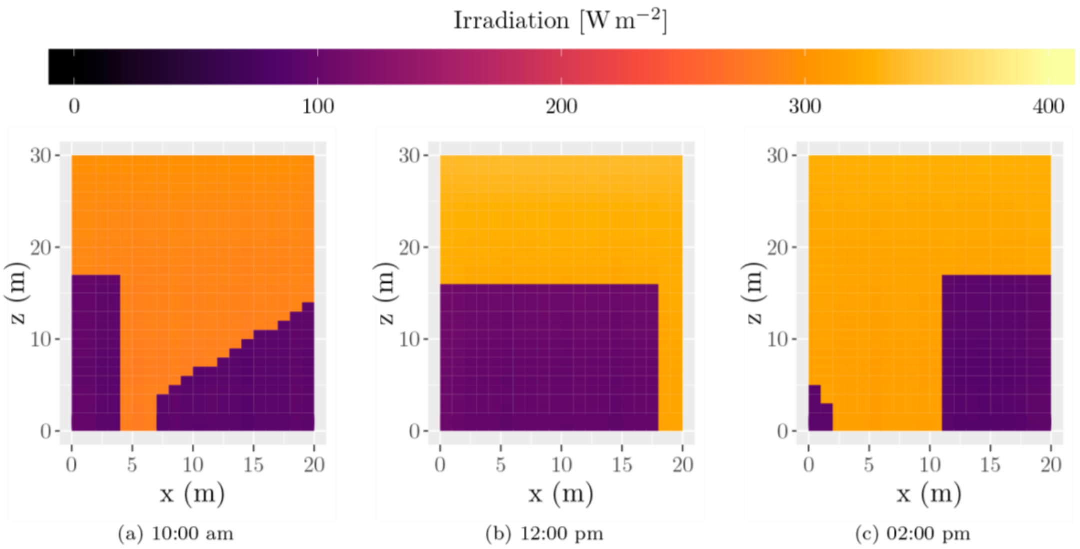


Figure 4: Irradiation on south façade of the building 5 on October 16th, 2018

3.2. Influence of the type of series connections on the production profile

Connecting the panels in series affects the current flowing through them. In the case of micro-inverters, each panel is electrically independent. Thus, the current-voltage couple of the PV panel is only dependent on its level of irradiation and its temperature. However, in the case of a series connection of several PV panels, the current flowing through them is equal to the lowest current flowing through all these panels. Different connection configurations are considered:

- one micro-inverter per PV panel,
- one inverter for all PV panels,
- one inverter for each vertical row,
- one inverter for each horizontal row.

The results of these different configurations obtained from the irradiation profiles (figure 4) are shown in figure 5 and 6. They correspond to a situation where the entire facade would be covered with PV panels. The case of micro-inverters (figures 5a and 6a) are the most favorable from the point of view of energy production. Indeed, only the area of the facade that is effectively hidden is affected. Thus, this case is taken as a reference for the calculation of the power generation drop. The case where all the panels are connected in series (figure 5b and 6b) are the least favorable cases. This is because the area of the facade, which is shaded also impacts the non-shaded area. The instantaneous production profile is like the case where the entire wall was shaded. Finally, the cases of vertical and horizontal connections (respectively figures 5c and 6c, and 5d and 6d) have an intermediate impact on the level of production potential. Indeed, the panels impacted by the shading are those effectively hidden, as well as those connected in accordance with the direction of the series connection.

The drop of power generation due to shadowing is depending on the time of the day. Indeed, on October 16th, 2018, this drop is higher in the case of a vertical series connection. The potential of instantaneous PV power generation for the case of the micro-inverters reaches 13.39 kW. This is reduced by 20.8 % with horizontal series connection (10.60 kW) and up to 40.0 % with vertical series connection (8.04 kW). Nonetheless, the drop of power generation due to the horizontal series connection is more important than that of vertical series connection the same day at 2:00 pm. Indeed, the drop of power generation reaches 27,3 % for the horizontal series connection against 20,5 % for the vertical series connection.

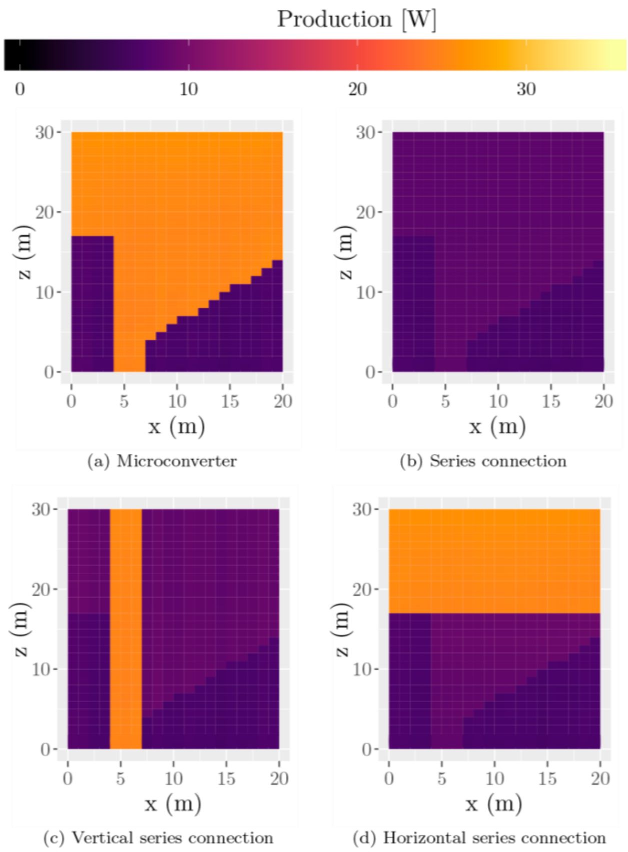
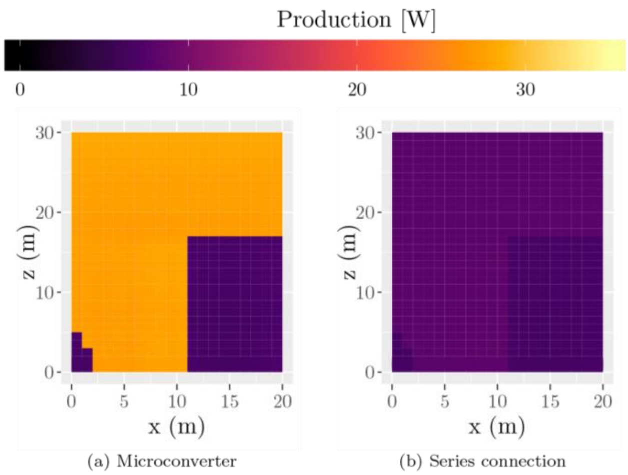
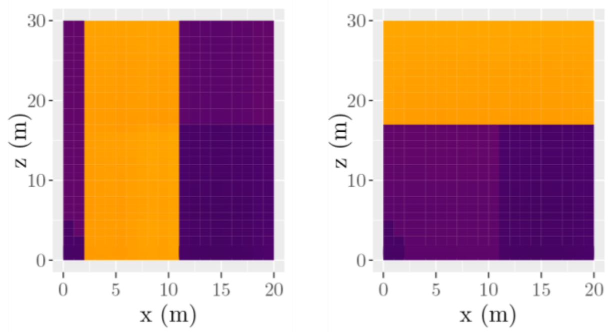


Figure 5: Power Generation Map on October 16th at 10:00 am, for different connection types





(c) Vertical series connection (d) Horizontal series connection

Figure 6: Power Generation Map on October 16th at 2:00 pm, for different connection types

3.3. Impact on the daily power generation

The different instantaneous production profiles presented in figure 5 and 6 have an impact on the daily production potential of the facade. The daily power generation, depending on the type of connection, is shown in figure 9.

As seen in the previous section, the case of a connection by micro-inverters is the least impacted by shading on the facade. Thus, the level of production is the highest regardless of the time of day. Conversely, the series connection impacts the production potential of all the panels. In this case, the level of production is the lowest throughout the day.

As seen in figure 5 and 6, the impact of the series connection on the energy production can alternatively be more important for the horizontal or the vertical series connection, depending on the time of the day. This alternance in terms of potential of power generation has an impact on the daily power generation profile.

Table 2 groups the differences in terms of power generation for representative average days of each month of the year, according to the type of connection of the PV panels. The production by micro-inverters is taken as a reference for the calculation of the drop of PV power generation.

Table 2: Drop of PV Power Generation[1] According to the Connection Type

Table Headers	Connection Type		
	Vertical Series Connection	**Horizontal Series Connection**	**Series Connection**
01 – January	-35.27 %	-36.83 %	-80.97 %
02 – February	-35.56 %	-24.49 %	-62.71 %
03 – March	-38.06 %	-15.00 %	-62.79 %
04 – April	-18.87 %	-4.46 %	-42.99 %
05 – May	-1.68 %	-0.44 %	-2.94 %
06 – June	-1.92 %	-0.51 %	-3.36 %
07 – July	-1.92 %	-0.58 %	-3.41 %
08 – August	-1.15 %	-0.38 %	-2.02 %
09 – September	-29.48 %	-9.67 %	-53.13 %
10 – October	-36.56 %	-17.90 %	-58.47 %
11 – November	-28.47 %	-27.40 %	-61.65 %
12 - December	-24.57 %	-35.20 %	-66.05 %

[1] Power generation by micro-inverters is taken as a reference

It appears that the case of the serial connection is the most impactful, with a loss of generation that can reach 80.97 % in January compared to the case of production by micro-inverters. This sharp decrease in production potential is since the smallest hidden square meter of the facade impacts the whole of it. Thus, this type of connection amounts to amplifying the phenomenon of shading of the facade. Regarding the influence of the orientation of the series connections, at the same time of the year, the horizontal and vertical series connections have a similar impact on the power generation with a drop of 36.83 % and 35.27 %, respectively.

This way, the table 2 offers a dual reading. The first reading is horizontal. Indeed, as can be seen in figure 7 as well, between the months of May and August, the impact of the series connection is very low (less than 5 % in the worst case). This can be explained by the sun's path. Indeed, between these two times of the year, the sun passes over the buildings (see figure 8). Thus, the shading effect is much less significant.

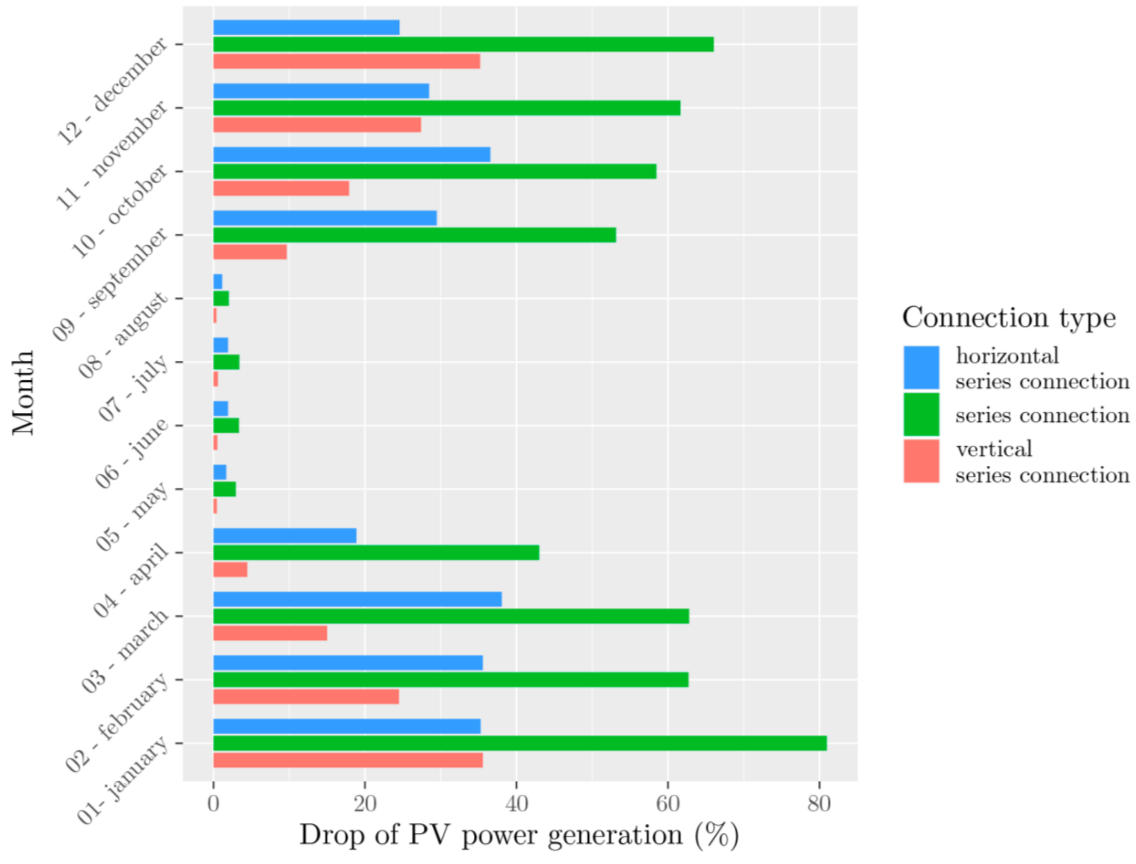


Figure 7: Comparison of the drops of PV power generation

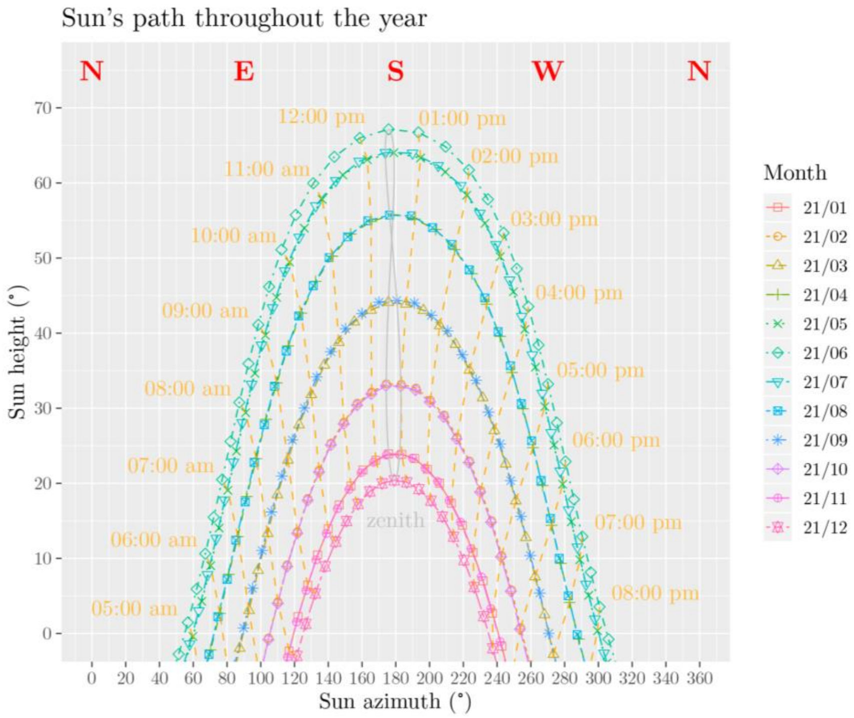
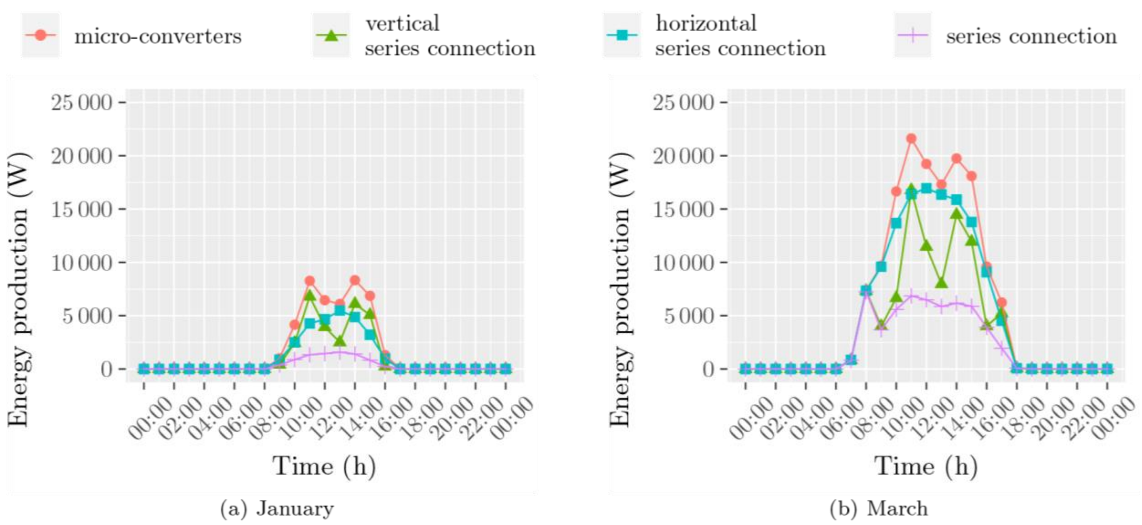
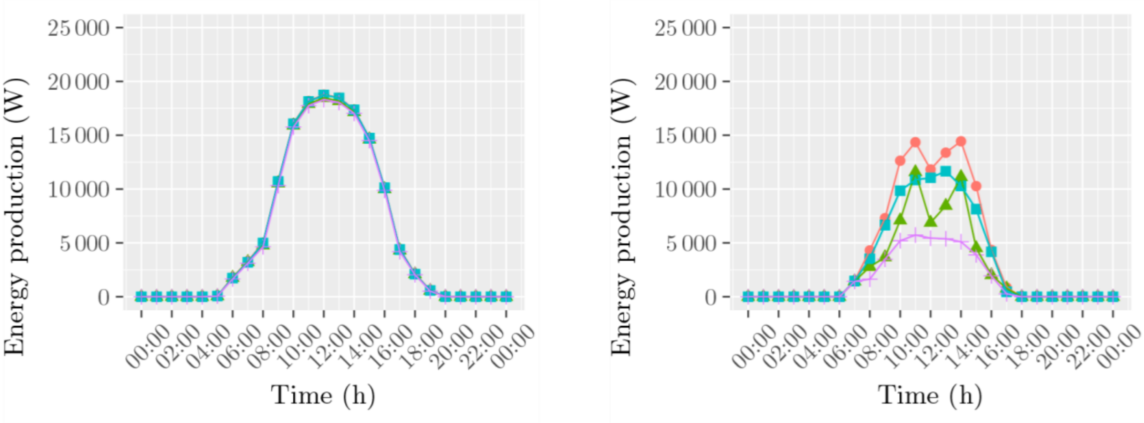


Figure 8: Annual sun's path over Geneva

The second reading is vertical. As aforementioned, the least positive case considering the power generation is the series connection. Regarding the direction of the series connection, except the months of December and January, the horizontal series connection appears as the solution to be preferred. In terms of energy production over the year, the horizontal series connection presents a drop of 14.4 %, compared with 21.1 % for the vertical one.

The energy production over a long period of time is not the only result arising from the study. Indeed, the evolution of the hourly power generation is clearly relevant. As can be seen in figure 9, the influence of the series connections depends on the time of the year as well as the time of the day. On the one hand, it appears that the energy production is barely impacted in May. On the other hand, for some time of the day, it can be more interesting to use vertical series connections than horizontal. For example, in figure 9a, the PV power generation with vertical series connection is higher than that of horizontal one at 11:00 am, 2:00 pm and 3:00 pm. The opposite is true for the rest of the day.





(c) May (d) October

Figure 9: Daily Power Photovoltaic Power Generation on South Facade

4. Conclusion and outlooks

Although generally less irradiated than roofs, facades have a significant solar potential in terms of PV power generation. Indeed, even if the production potential per square meter of a facade turns out to be lower than that of a roof, in a context of urban densification where buildings are always more vertical, the solar potential of the latter can become superior (Díez-Mediavilla et al., 2019).

The study presented here shows the importance of taking into account the surrounding environment when evaluating the solar potential of facades. Indeed, the shading created by neighboring buildings has a significant impact on the level of irradiation received on the surrounding facades. From the point of view of PV power generation potential, the series connection of the panels has a big impact. It appears, in this study, that a horizontal connection of the panels is to be preferred, most of the time. Nonetheless, adaptative solutions (real-time switching of the direction of the series connection) could be an efficient way to exploit the solar potential of the facades to the full, whilst complying with technical and economical constraints.

Moreover, the results presented in this paper relate to a fictitious neighborhood. To confirm these results, it is therefore important to extend this study to different morphologies of neighborhoods, including actual ones. In addition, the conclusions are drawn only from numerical results. In order to validate this model a confrontation between numerical results and measurements data should be carried out.

5. Acknowledgments

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