# Numerical and experimental study of two PV power generation models for buildings façades

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## Abstract

The interest for Building Integrated Photovoltaic (BIPV) systems has gradually increased in the last decades. They represent a way to move buildings from passive to active in terms of energy production without substantial increase of costs.

By their conception and implantation, BIPV are able to exploit the solar potential in complex configurations. Indeed, in a dense urban context, multiple phenomena that have impact on power generation potential occur (shading, inter-building reflections, wind channeling, etc.). In addition, they could be installed on vertical walls, where the intrinsic potential is lower but surges with urban densification as façade areas are bigger than roofs. In such configuration the urban environment has a huge effect on operating conditions due to interaction with the ground and with the surroundings buildings.

This study is a confrontation between numerical and experimental results aiming to evaluate the accuracy of two models of production (one power model and one single-diode model) and the necessity of taking into consideration local meteorological conditions instead of weather of typical day.

*Keywords: transient energy production, photovoltaic (PV) solar collectors, power generation models, multifunctional building envelopes, urban environment, microclimate simulation*

## 1. Introduction

Most of studies dedicated to the evaluation of solar potential in urban areas only focus on horizontal façades because their potential are generally higher (Horváth et al. (2016), Sarralde et al. (2014), Zhang et al. (2019)). Nevertheless, in a context of urban densification the façade/roof ratio increases. Thus, as shown by Díez-Mediavilla et al. (2019), the potential of the accumulated vertical façades can surpass the one of roofs (twice higher in summer and even three times greater in winter). Yet the production models for the latter are much more developed than the one for vertical walls.

During the last decades, increasing focus has been put on the solar potential of buildings on urban areas. The methods for solar potential assessment range from very simple ones, like on-field measurements, to more sophisticated ones, like GIS[1]/LiDAR[2]. The latter are more accurate and applicable at the largest scale. Petrichenko et al. (2019) used LiDAR method to assess the solar energy potential of rooftops of New-York City. Brito et al. (2017) have extended this kind of study to vertical façades. Aggregated both horizontal and vertical façades can contribute to 50 % to 75 % of the annual electricity demand. As shown by Lobaccaro et al. (2018), vertical façades, and more specifically their upper parts, which are less frequently shaded, can significantly contribute to this energy production.

Even if solar potential can be used to produce thermal energy, most of the studies (as well as this one) only

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[1] GIS: Geographical Information System
[2] Light Detection And Ranging

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consider the PV production. In this context, BIPV (Building Integrated Photovoltaics) systems offer a good way to take advantage of the solar potential to turn buildings from passive to active in terms of energy production without having a negative influence on indoor or outdoor comfort (Jelle et al. (2012)) and negative aesthetic rendering.

In this paper, two models of power generation, which take the close environment of the studied building into account, are considered. They may be a useful tool for urban planners or energy producer as the cities are becoming greener with buildings moving from passive to active in terms of energy production. Tools aimed at the general public, such as solar cadaster, are currently under development. They are meant to help increase the use of solar technology in cities and therefore to move the energy mix towards sustainable and clean energy. This is the main aim of the G2 Solaire project, focusing on the solar potential of buildings' façades of the greater Geneva, Switzerland.

This study relies on a confrontation between numerical and experimental results. The electrical power produced on façades is measured and compared to the one predicted by the two production models. The latter are calculated with the output data from a simulation carried out with ENVI-met, an urban microclimate simulation software. Thus, this article is broken into two main parts. The first part is dedicated to the presentation of the two developed models. In a second part, the models are applied successively to measurements and simulated data in order to evaluate their accuracy. Finally, the results are discussed and the outlooks are presented.

## 2. Developed models

Two PV production models, the first one based on the power generation and the second one on equivalent diode circuit, have been developed for the evaluation of the power generation potential of buildings' façades. They are presented in detail in the two following sections.

### 2. 1. Power model

The first implemented model is a power model. It means that the output power of the PV panel is proportional to the solar irradiation and inversely related to the surface temperature of the PV panel (see eq.1). This model is a simplified version of the model proposed by Myers, 2009 and used by Govehovitch et al. (2018).

$$P_{out} = \min\left(P_{max_{STC}} \times \frac{G}{G_{STC}} \times \left(1 + \gamma(T - T_{STC})\right), P_{max_{STC}}\right) \qquad \text{(eq. 1)}$$

where $P_{out}$ (W) is the output power of the PV panel, $P_{max}$ (W) is the maximal power that the PV panel can generate, G (W/m$^2$) is the solar irradiation, $\gamma$ (%/°C) is the temperature coefficient of $P_{max}$ and T (K) is the surface temperature of the PV panel. The subscript STC stands for Standard Test Conditions ($T = 25\,°C\,; G = 1\,000\,W/m^2; AM = 1.5$). The minimum function is used to ensure that the calculated output power does not get higher than the maximum power of the PV panel (it can occur numerically, but would have no physical meaning).

The main strength of this model is its ease of implementation. However, for this model, the PV panel is assumed to operate at the maximum power point (MPP), regardless of what the weather conditions are. In addition, the temperature coefficient of maximum power is a set parameter although it depends on the nature of the PV material and its degree of aging.

This assumption may have an important impact on the power generation estimation by overestimating the actual performances of the PV panel. Indeed, the evolution of a PV panel is not linear and depends on multiple parameters, including solar irradiance, surface temperature and wind speed. Thus, the further from the MPP the PV panel operates, the less accurate the power model.

### 2. 2. Single-diode model

The diagram below (from the work of Tian et al. (2012)) represents the equivalent circuit for a solar cell, which is a semiconductor device that is able to convert sunlight into electricity. This equivalent circuit can be extended to a module (cells connected in series) and to a PV array (cells connected in series and in parallel).

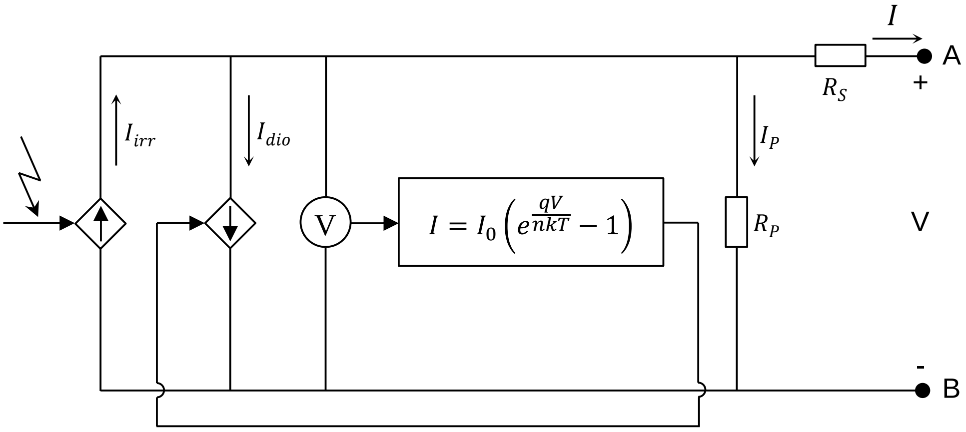

**Figure 1: Equivalent circuit for a solar cell**

This single-diode model is a simplification of the double-diode model proposed by Chan and Phang, 1987. As shown by Ahmad et al. (2016) the double-diode model provides better efficiency than the single-diode model. Nevertheless, it requires the evaluation of seven parameters, making its implementation more difficult for reasons related to computational costs. The single-diode model reduces the number of parameters to five:

- the photocurrent $I_{irr}$ (A),
- the diode saturation current $I_0$ (A),
- the ideality factor n (∅),
- the shunt resistance $R_p$ (Ω),
- the series resistance $R_s$ (Ω).

As previously said and unlike the power model, the single-diode model is able to take into consideration the variation of the PV panel I-V curves, which are depending on both the temperature and solar irradiation. This improves the accuracy of the single-diode model, compared to the power model. Nevertheless, it assumes that the recombination loss in the depletion region is negligible, which may be a strong assumption, especially at low voltages.

Taking into consideration the variations of the output current and voltage is important to improve the accuracy of the prediction of power generation. Thus, the single-diode model is expected to be more accurate than the power model, while not dramatically increasing computational cost. The greater accuracy of the single-diode model is due to the presence of the diode. Thus, this model takes better account of the actual behavior of the PV technology, while the power model relies on linear relation between output power and solar radiation and PV panel temperature, from a reference point.

## 3. Study performed

### 3.1. Studied building

The studied building is a test building located in the R&D Laboratory of EDF[1] in southeast of Paris. On the left-hand side of the figure 2 is represented the actual building and the modelled one is shown on the right-hand side. The grey building is about 25 m south of the ETNA building. It may represent a mask for it and then have an influence on the solar potential of the façades.

As a test building, it has plenty of different sensors. In this way, twenty thermocouples are installed on the vertical and slanted walls, as well as pyranometers. In addition, a weather station is installed on the roof to get local climatic conditions (air temperature, wind velocity and direction, solar irradiance (total and direct, what enables to deduce the diffuse irradiance)).

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[1] EDF is the main electricity producer in France.

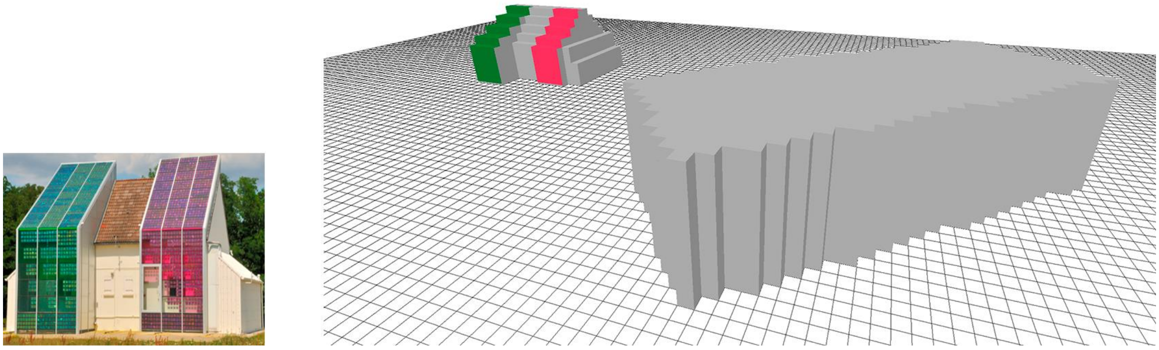

**Figure 2: Test building ETNA – EDF R&D Lab. (Real building on the left-hand side – Modeled domain on the right-hand side)**

The use of local meteorological measurements is important to improve the accuracy of the results. Indeed, as demonstrated (Kyriakodis and Santamouris, 2018), the Urban Heat Island (UHI) effect may exceed 6 °C to 7 °C. The weather stations being usually installed in rural areas (typically airports) the provided temperatures may induce by themselves a bias in the energy production assessment of several percent.

In addition, on-site measurements can be used as inputs for simulations. Thus, the more accurate the measurements, the more accurate the experimental/numeric comparison.

### 3.2. Input data for the PV models

In this study, the simulations were done with the version 4.4 of the software ENVI-met. ENVI-met is a prognostic, three-dimensional, high-resolution microclimate model, which is specifically designed to simulate phenomena that occur in urban environment (Bruse and Fleer, 1998).

In ENVI-met, the aerodynamics equations are solved using a RANS (Reynolds Averaged Navier-Stokes) method. Buoyancy effect is also taken into account with the Boussinesq's approximation. Regarding radiation, both direct and diffuse parts are taken into consideration and treated as two ranges of wavelengths wavelengths. The radiation reflections are playing a greater role as the urban environment gets more and more dense. They are all addressed via the albedo and the inter-building reflections (the latter being evaluated for shortwave radiations only).

The computational domain (shown in the right-hand side of figure 2) has a spatial resolution of 1 m in all directions. It allows getting precise results in terms of spatial heterogeneity regarding values such as surface temperature and solar irradiance.

The input data for air temperature and humidity, wind speed and direction and solar irradiation for the day of the 15th October 2012 are presented in the figures 3 to 5. The solar radiation is broken into two parts:

1. The shortwave radiation, with wavelengths ranging between 290 and 400 nm,
2. The longwave radiation, with wavelengths ranging between 400 and 2500nm.

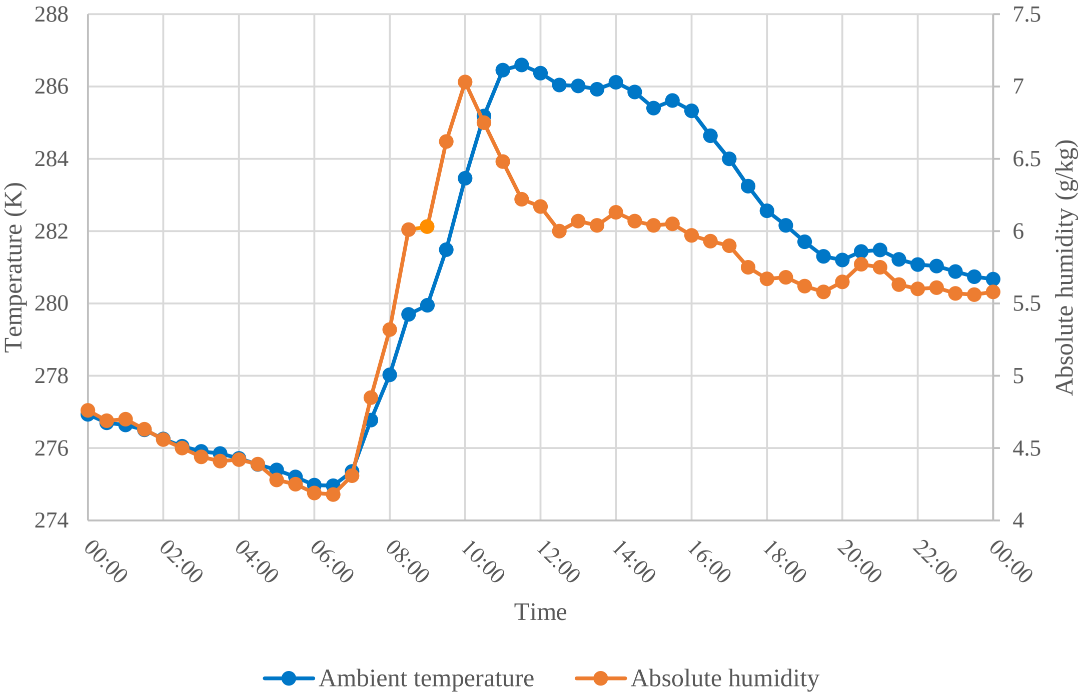

**Figure 3: Evolution of ambient temperature and absolute humidity during the day**

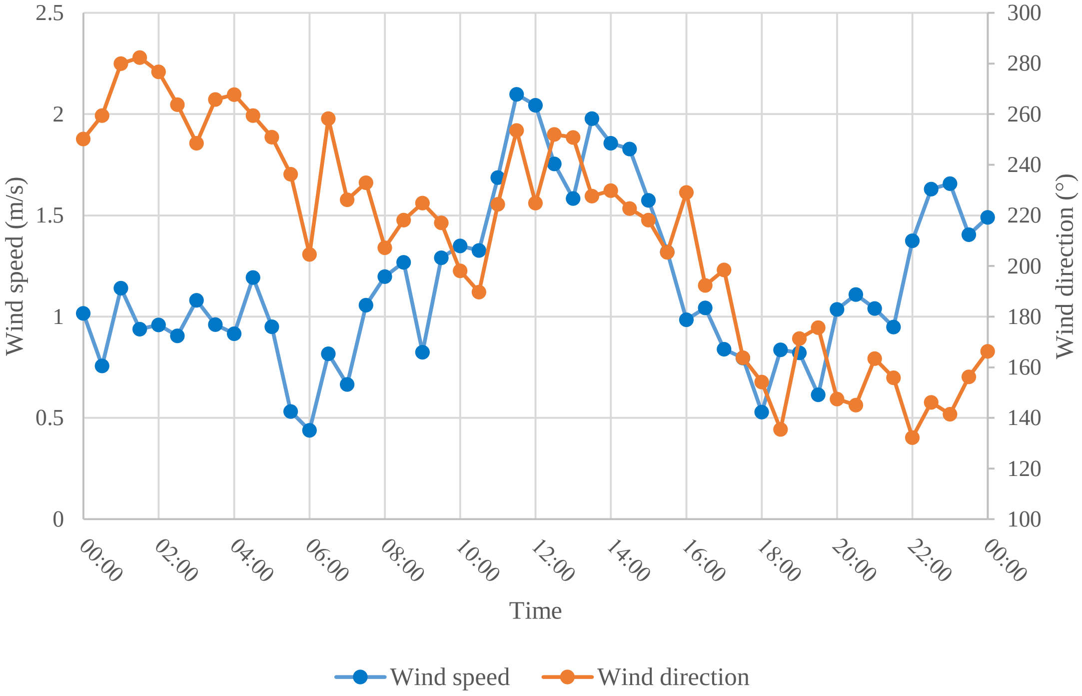

**Figure 4: Evolution of wind speed and direction during the day**

In ENVI-met, the reference angle (0°) corresponds to a wind from the north. A wind from the east corresponds to an angle of 90°. The other angles are set clockwise.

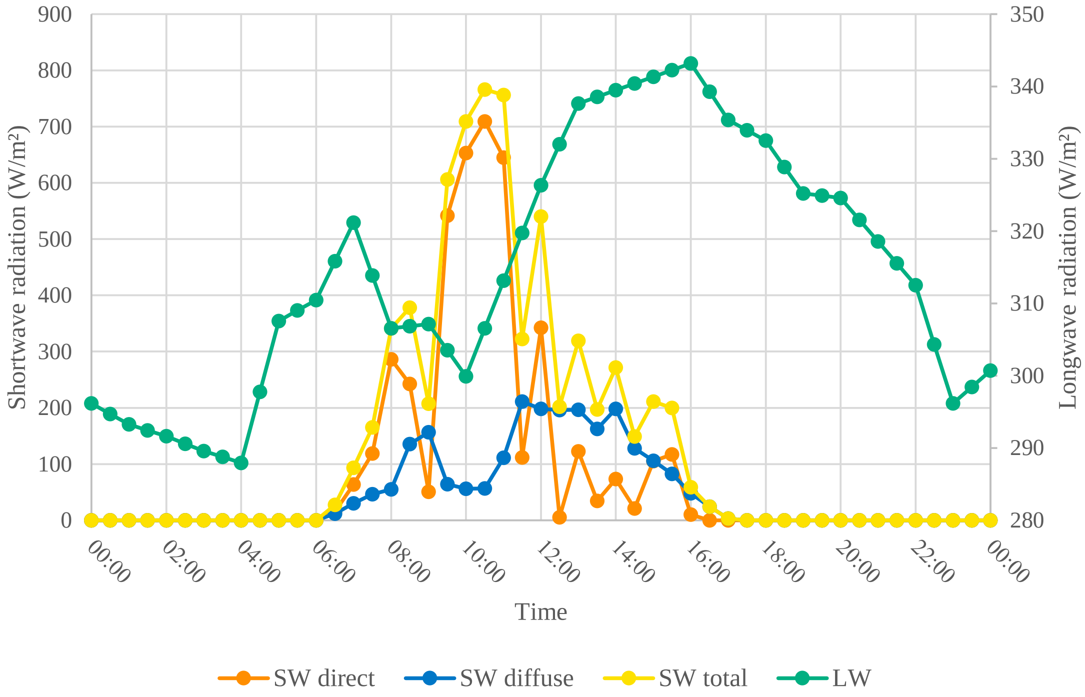

**Figure 5: Evolution of shortwave and longwave radiation during the day**

The day of Monday 15th October 2012 is then a sunny day and not windy day, given the season of the year, with a peak of shortwave solar radiation measured on the vertical façade above 750 W/m² and a wind speed between 1.5 km/h and 7.2 km/h. Yet the temperature level stays low, ranging between 1.4 °C and 13.4 °C, while the relative humidity stays relatively high (between 60 % and 100 %).

As recommended (Bruse, 2015), the last 12 hours of 14th October have been simulated only in order to spin up the model and to get rid of the influence of the initial conditions on the results. Thus, 36 hours are simulated but only the 24 last hours are used for analysis.

## 4. Results and discussion

The experimental/numeric comparison is based on the results of the day of October 15th, 2012. They are used to evaluate the accuracy of the two models presented in section 2.

### 4. 1. Application of the models to the local measurements

The figure 6 compares the measured PV power generation on the façades to the modelled ones. The models are applied to the local measurements of surface temperature and solar irradiation recorded on the prototype. Measurements are carried out every minute. It makes possible to assess the accuracy of the models regarding the evolution of actual operating conditions (i.e.: intermittency).

Figure 6 shows that both models react to high frequency changes in surface temperature and solar irradiation. It highlights the ability of these models to give full account of the variations in operating conditions. However, it can be noticed a global overestimation of the power generation by the power model (in orange in the figure 6) and, albeit to a lesser extent, by the single-diode model (in blue in the figure 6). This is particularly marked before 9:00 am. Nevertheless, this overestimation is not due to the production models themselves but to the operating and regulating modes of the PV façade. Indeed, the estimated power is consistent with the solar radiation curve (see figure 5). The shortwave solar radiation starts rising at 6:00 am with a first peak at 380 W/m² at 8:30 am, corresponding to the first peak of predicted production of about 200 W.

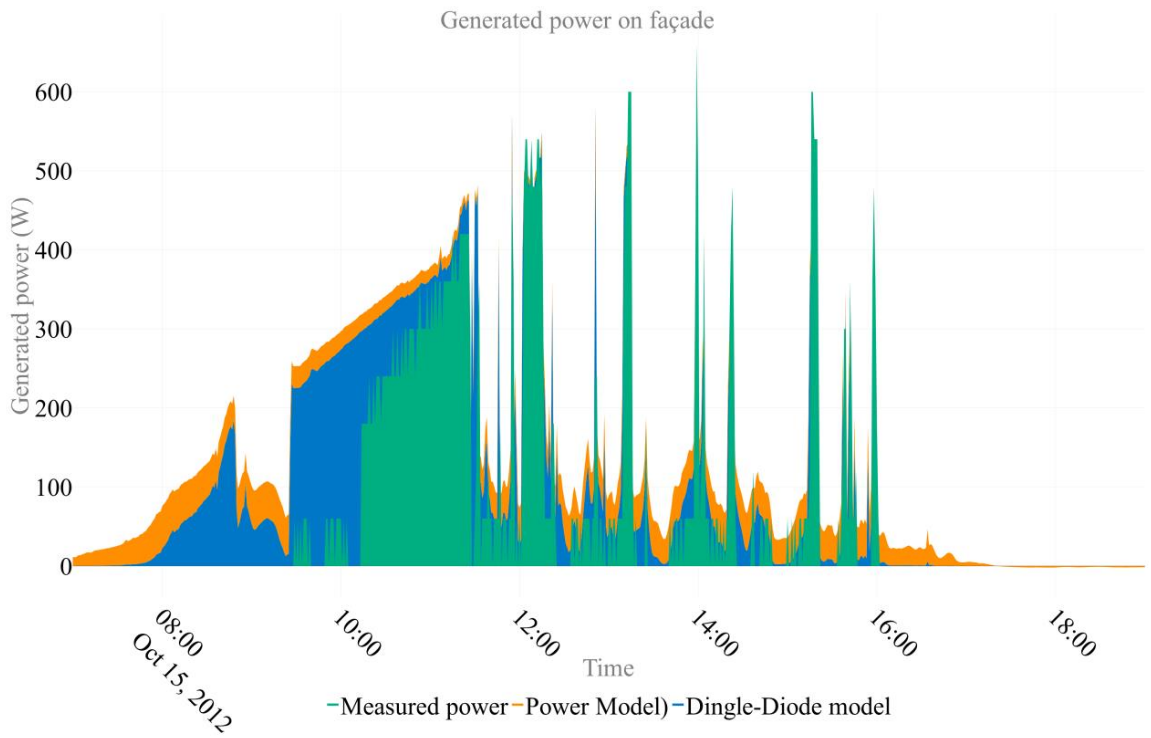

**Figure 6: Comparison between the on-site measured power and the modelling results**

Regarding the comparison of the two models, according to the table 1, the single-diode model is more accurate than the power model. Indeed, the lower the RMSD (Root Mean Square Deviation), the more accurate the model. RMSD and NRMSD (Normalized Root Mean Square Deviation) are defined as follows (eq. 2 and 3):

$$RMSD = \sqrt{\frac{\sum_{n=1}^{N}(P_n - O_n)^2}{N}} \quad \text{(eq. 2)}$$

$$NRMSD = \frac{RMSD}{O_{max} - O_{min}} \quad \text{(eq. 3)}$$

where N is the number of observations, P is the predicted value and O the observed value. The subscripts max and min refer to the maximum and the minimum of the observed values, respectively.

**Table 1: RMSD and NRMSD of the two production models applied to measurements**

| Production model | RMSD | NRMSD |
|---|---|---|
| Power model | 75.3 W | 11.4 % |
| Single-diode model | 64.2 W | 9.7 % |

### 4. 2. Application of the models to the simulated meteorological data

As solar irradiance is measured in a single spot, the results of simulation carried out with the meteorological tool ENVI-met are aggregated over the whole green façade (see the left-hand side of figure 2). On the other hand, measured data are averaged in bouts of five minutes. This corresponds to the shortest time period allowed by ENVI-met for the values outputs.

The comparison between the predicted power generation from the simulated data and the measured one is presented in figure 7.

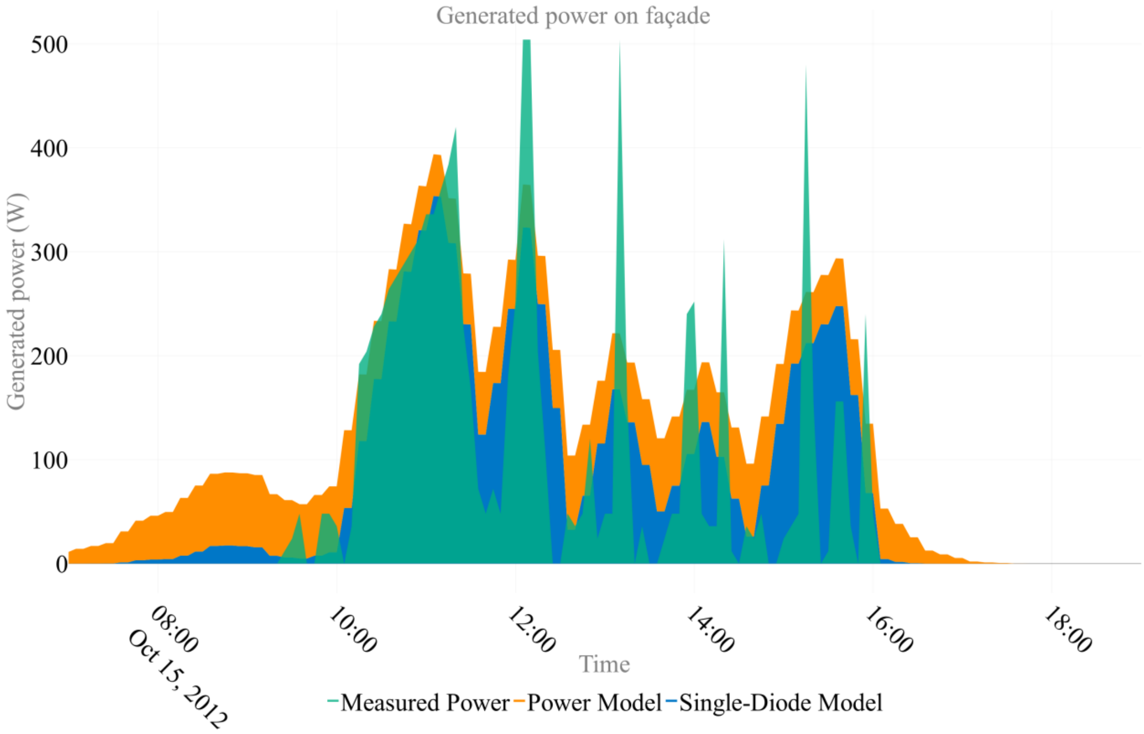

**Figure 7: Comparison between the on-site measured power and the one from simulated data**

The overall behavior noticed in figure 6 is also present in figure 7. Indeed, both models respond to solar radiation changes. The estimated production before 9:00 am is also present but does not reflect any bias in the model since it is consistent with the solar radiation on the façade (see figure 5).

The higher accuracy of the single-diode model is also confirmed, as shown in table 2. However, the power generation results from the simulated data seem less accurate than the one from measurements, as evidenced by the increase in RMSD (respectively +30 % for the power model and +20 % for the single-diode model). This is due to the time interval of the data (five minutes for simulated data against one minute for measurements). This underlines the need to take the intermittency of solar radiation into account in order to improve the accuracy of the power generation prediction.

**Table 2: RMSD and NRMSD of the two production models applied to simulation results**

| Production model | RMSD | NRMSD |
|---|---|---|
| Power model | 98.0 W | 19.5 % |
| Single-diode model | 77.3 W | 15.3 % |

### 4.3. Comparison of results between a typical day and on-site measurements

Typical day values[1] are often used in simulation whereas they can be widely separated from the on-site measurements. Thus, it is important to compare them and to evaluate the impact of using typical values instead of actual values.

As shown in figure 8, the shortwave radiation on the site of ETNA building is very different from the one of a typical day at the same location and the same day of the year. However, the total energy from the shortwave radiation over the day (the integral of the total shortwave radiation) is only 1.5 % higher for the on-site measurements than the one of the typical day.

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[1] Typical days are defined as International Weather for Energy Calculations (IWEC), which are the results of ASHRAE Research Project 1015 (ASHRAE, 2001).

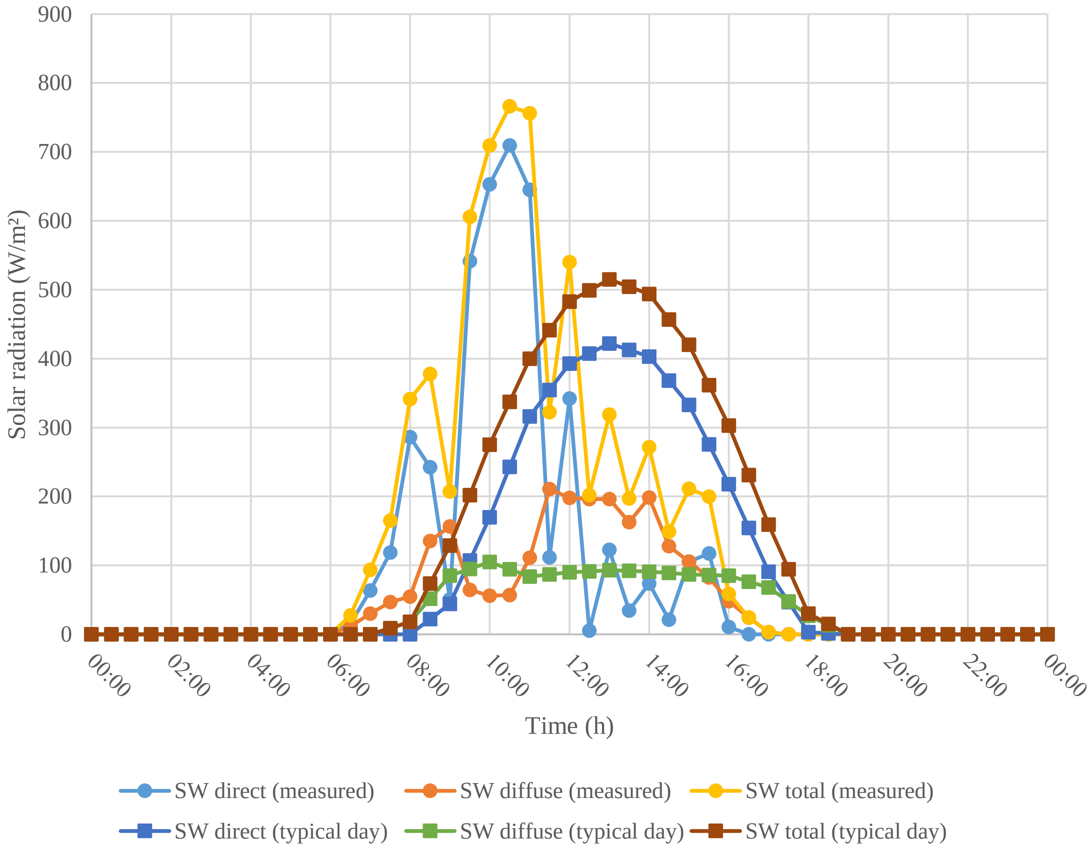

**Figure 8: Comparison of shortwave radiation on ETNA building and for a typical day (October 15th, 2012)**

As expected and shown in figure 9, the predicted power generation does not match with the measured power generation. Indeed, both measured and predicted power generation follow their respective radiation curves. Thus, the power generation in the morning is underestimated whereas the one in the afternoon is greatly overestimated.

This leads to a global overestimation of power generation for both models. Nonetheless, the single-diode model comes out better than the power model with an overstatement of 53 % compared to the measured power against 63 % for the power model.

In terms of instantaneous values, the difference is even more staggering. Indeed, the NRMSD exceeds 20 % for both the models, which is higher than the result obtained in the previous section. It highlights the importance of taking into account the local climatic conditions in order to get results as accurate as possible.

**Table 3: RMSD and NRMSD of the two production models applied under conditions of a typical day**

| Production model | RMSD | NRMSD |
|---|---|---|
| Power model | 88.4 W | 21.0 % |
| Single-diode model | 88.8 W | 21.1 % |

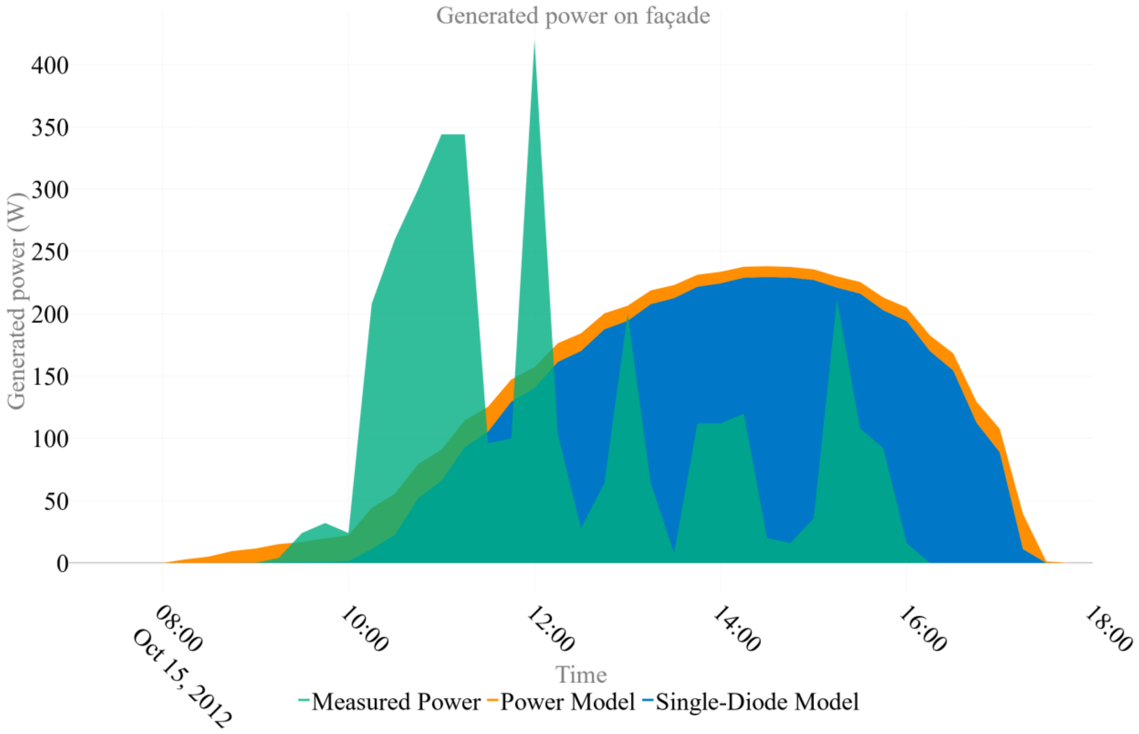

**Figure 9: Comparison of the modeled PV generation with typical day radiation and measured power generation**

As shown in figure 9, the instantaneous relative errors of the models can reach high levels (more than 2 500 %) in the afternoon. This is due to the fluctuations in the on-site solar radiation that cannot be reproduced by the curve of a typical day.

The same amount of incoming energy between a typical day and on-site measurements leading to a very different instantaneous power generation highlights the need to reason in terms of power and not only in terms of energy to accurately predict power generation. Indeed, electricity is a type of energy that can hardly be stored at district scale. Thus, electrical power shall be consumed when it is produced. Reliable and accurate prediction of power generation is then necessary to exploit the full solar potential of vertical façades at district scale.

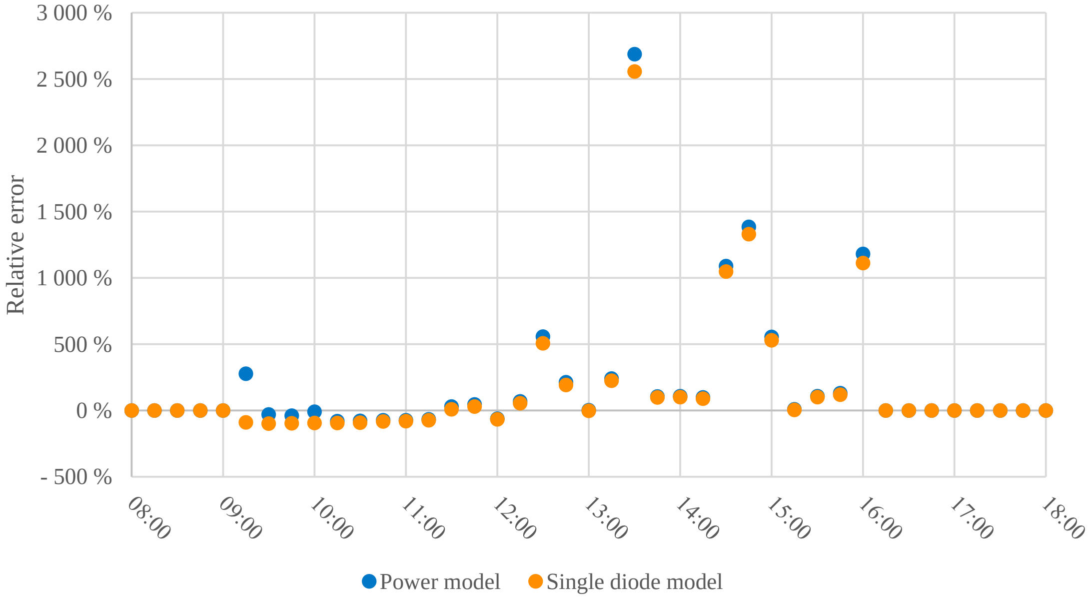

**Figure 10: Time evolution of the relative errors**

It should be noted that, in this case, the values are aggregated in bouts of 15 minutes. As mentioned in the previous section, it may have an impact on the accuracy of the results. In addition, the intermittency cannot be evaluated in these conditions.

## 5. Conclusion and outlooks

This study demonstrates the possibility to use ENVI-met to evaluate the PV power generation potential of vertical façades. Among the proposed models, the single-diode model appears to be more accurate. Despite a higher computational cost, it turns out to be a good compromise between ease of implementation and accuracy. Then it can certainly be used to evaluate the PV potential at district scale.

In addition, the use of local measurements in ENVI-met instead of generic results from IWEC shows a significant improvement in the prediction of power generation. This highlights the need for using the most accurate input data for the microclimate simulation. Nonetheless, it positions ENVI-met as a useful tool for urban planners and energy producers in the perspective of making the cities greener.

Some issues still need a deeper investigation. Indeed, this study emphasizes the importance of taking the intermittency of solar radiation into account. However, because of a lack of information (only one point of measurements for the solar radiation), the influence of the spatial heterogeneity was not assessed. In a context of dense urban environment, phenomena such as shading occur frequently and have a negative impact on the solar energy potential. On the contrary, inter-building reflections have a positive and non-negligible impact (Govehovitch et al. (2018)) that also need to be considered.

As previously demonstrated (Kawamura et al. (2003), Salam et al. (2010)), the accuracy of the single-diode model decreases when the PV panel is shaded. In the context of urban installation of PV panels, shadings occur very often. Then, despite the higher computational cost of this model, a comparison between single- and double-diode models may be interesting to evaluate the possibility of implementing this model for the evaluation of PV power generation at district scale.

## 6. Acknowledgments

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