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2017



*Citation for published version (APA):*
Kanters, J., & Davidsson, H. (2017). *Assessing combined object and mutual shading on the performance of a solar field*. Paper presented at 15th International Conference of the International Building Performance Simulation Association, Building Simulation 2017., San Francisco, California, United States.

*Total number of authors:*
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# Assessing combined object and mutual shading on the performance of a solar field

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## Abstract

To make well-informed decisions on the implementation of solar energy on roofs within the urban environment, a new method was developed and described that could support such decision-making. This method takes both the mutual shading and shading from external objects into account. The method consists of the following six steps: 1) construction of the scene, 2) performance of annual solar irradiation analyses, 3) performance of statistical analyses, 4) calculation of the energy output, 5) calculation of the parameters payback time and profit, 6) displaying the results. Analysing the data by setting own preferences will make more informed decision-making possible. The outputs from the method are maps indicating which locations surrounded by objects that are profitable for PV installations. Alternatively, the maps can be used to show payback times for the PV installation.

## Introduction

Producing on-site renewable energy within cities has become a common strategy when planning for new buildings. Especially rooftops, which normally receive the highest amount of irradiation of the building envelope, are often used to produce electricity by means of photovoltaic panels (PV). Rooftops in the city context could however be shaded by surrounding buildings and objects, which might reduce the output of a PV system significantly (Ahmed & Salam 2015; Bai et al. 2015; d'Alessandro et al. 2015; Kanters & Davidsson 2014). Previous studies, especially those that resulted in the creation of so-called solar maps (Chow et al. 2016; Lukač et al. 2013; Jakubiec & Reinhart 2013), have mainly focused on the actual irradiation of flat and inclined roofs, but normally not on the performance of a real PV field with rows of panels where also mutual shading occurs. One example that makes it is possible to analyse the output of a PV system with rack mounting to tilt the panels can be seen in the Solar Potential Map of some Australian cities (Australian Photovoltaic Institute 2016), making the exploitation of flat roofs more realistic.

While some solar maps only show irradiation levels, other solar maps are more advanced (Kanters et al. 2014). Such solar maps could provide e.g. a more detailed analysis of the produced energy and saved amount of greenhouse gasses. Other features seen in some solar maps are heritage restrictions (city of Basel 2016) or proximity to the urban district heating network (city of Vienna 2016). Some also provide more information about financial parameters such as payback time or investment costs. Those financial parameters are important when discussing solar energy with potential stakeholders like real estate developers.

The aim of this study is to provide and discuss a method to analyse the full solar potential of a roof within the urban context. In this study, both mutual shading and external shading are taken into account, because it will provide a more realistic picture of the solar potential of roofs. Also, there is a focus on the financial parameters rather than on irradiation levels. The method was applied on a case study to function as an applied example of the developed method.

## Method

Every roof within the urban environment has its own unique setting, due to the difference in surrounding objects causing shading on that roof. Proximity, height, orientation and form of these surrounding buildings will shape their own shading pattern on the roof that is to be analysed. An example can be seen in Figure 1.

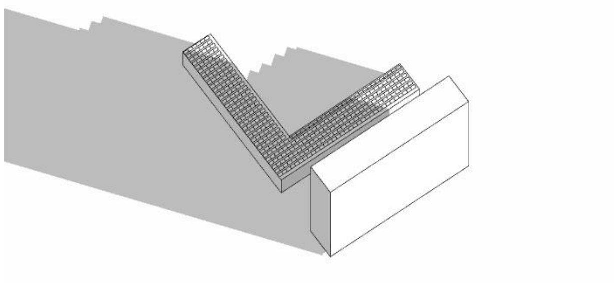

Figure 1: A possible scene in the urban context

As a case study, a simple scene was developed and modelled. This case study consists of a scene which could reflect the reality, having one building located South of a field of solar cells (Figure 2), representing a large flat roof of a building. It should however be kept in mind that the reality probably looks differently, but the scene was thought to provide a good example of how the method could be applied.

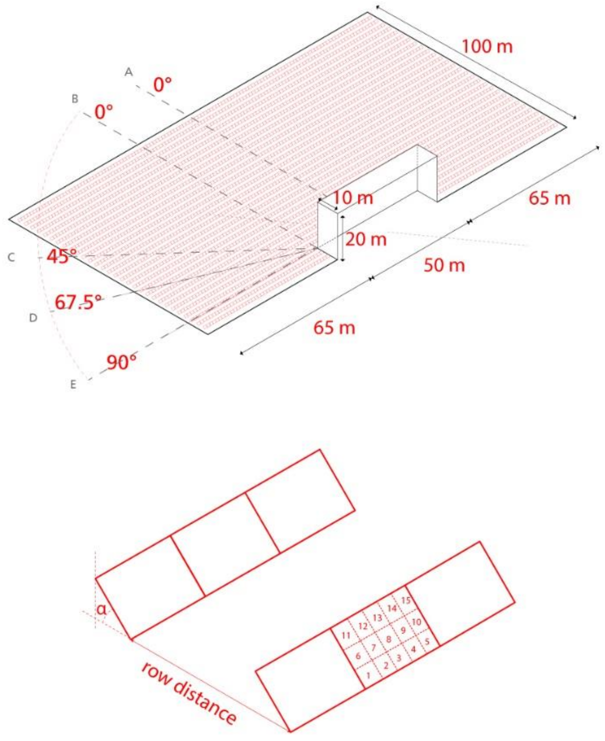


*Figure 2: setup of the geometry (top), inclination and row distance (bottom)*

The method presented in this study consists of the following steps:

1) A 3D model was set up using Rhinoceros (McNeel & Associates 2015) and Grasshopper (McNeel & Associates 2016) with the shading building as fixed geometry. With help of Grasshopper, a solar field was coded of which its design depends on the set inclination of the PV panels and the row distance between the modules. The amount of rows and panels are set accordingly. Different configurations of the solar system were analysed: inclinations of the panels were varied between 5º, 15º, 25º, 35º, 45º as well as different row distances (1 m, 1.5 m, 2 m and 3 m); in total 20 configurations. An angle $\beta$ was defined as the obstruction angle between the bottom of the panel and the highest point of the shading object direct in front of the panel (Figure 3).

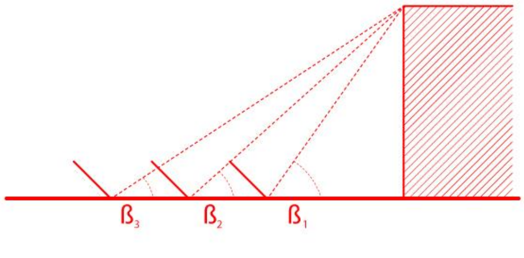


*Figure 3:definition of the obstruction angle*

2) Analysis lines were specified (line A, B, C, D, E) where the panels that intersected those lines were selected for further analysis. Every configuration of the system (inclination and row distance) led to specific obstruction angles $\beta$.

3) To be able to compare different configurations at the same obstruction angle, irradiation levels were simulated with Radiance through the DIVA4RHINO plugin (Solemma LLC 2016) with weather data from Copenhagen (Denmark) for those panels on the lines A, B, C, D, E and with *high* quality settings. For every panel, 15 points where analysed to include the effect of mutual shading combined with shading from external objects (Figure 1). Other panels not on the analysis line and the shading building were imported so they cause shading on the selected panels. Simulated results of the annual irradiation analyses were exported to Microsoft Excel. In Excel, a trendline was fitted for the irradiation levels as a function of the obstruction angle for every configuration. The fitted trendline was of high degree in order to achieve a good agreement with the simulated data.

   Newer PV cells sold on the market normally consists of three strings with bypass-diodes. That means that when the shading is only caused by other modules in the system (i.e. mutual shading), the cell will still produce electricity when parts of it is shaded. However, shading from external objects could cause a vertical shading pattern, which could cause the cell to not produce anything due to its string layout. By subdividing the panels into 15 cells, both effects would be approached more accurately.

4) With the output of the simulated annual irradiation levels, the energy output was simply calculated by multiplying the irradiation level with the efficiency of a solar cell (15%), omitting, amongst others, the actual effect of temperature on the performance of the solar cells. The authors are aware of the fact that by doing so, the production of a solar cells will be overestimated, since in reality, shading move from left to right or vice versa will drop the production of a PV cell that has its string layout horizontally. This however is mainly the case when the solar cells is partly lit by the sun which normally happens only a very limited of time per day.

5) Two financial parameters were calculated for each of the analysed modules: the payback time and the profit after *n* year. The parameter *n* can be changed in the analysis, but in the case of our case study, a 25 years period was chosen for the profit. The payback time was calculated as the investment cost divided by the product of the irradiation, the efficiency of the cells and the electricity price. The calculation is based on fixed prices over the lifetime.

$$pb = \frac{inv}{irr \cdot \eta \cdot el} \quad (1)$$

Where pb is payback time (years), *inv* is investment costs (euro), *irr* is annual irradiation (kWh), $\eta$ is the efficiency of the PV panels and *el* is the electricity price (Euro/kWh).

The profit $pr_n$ (Euro/m$^2$) after *n* years was calculated to be:

$$pr_n = inv - (irr \cdot \eta \cdot el \cdot n) \qquad (2)$$

In our case study, an investment costs of 232 Euro / m$^2$ was chosen, corresponding to a costs of 1550 Euro / $kW_p$. An electricity price of 0.10 Euro / kWh was chosen, which resembles the buying price for electricity in Sweden. The idea was that by using different metrics, the most favourable configuration of the system for that specific metrics could be found.

6) Finally, the results were displayed, based on the chosen financial parameter. The figures show the chosen financial parameters in relation to the obstruction angle *(β)* from the shading object.

## Results

Step number 3 of the method provided results of the annual irradiation levels on the specific panels and served as input for the creation of the trendlines.

As expected, annual irradiation levels were low close to the shading object. Figure 4 shows the results of the adapted irradiation levels on the panels located on line A (lines are shown in Figure 2). In the Figure, a selection of the configurations are stated as (x;y) where x is the inclination and y is the row distance. E.g. (5;1) means panels with an inclination of 5° and a row distance of 1 metre). The highest irradiation levels close to the shading object were reached with a low inclination on the panels, since they have, seen over the whole panel, a less obstructed view and therefore receive more irradiation. Figure 4 also shows that the difference between the different configurations at high obstruction angles, i.e. close to the shading object, were smaller than at lower obstruction angles (far away from the shading object).

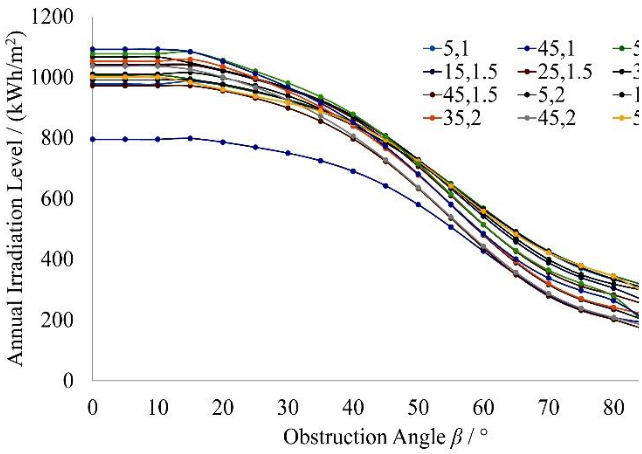


*Figure 4: Annual Irradiation Levels on Panels on Line A (after trendline)*

The results of the other lines (B, C, D and E) showed that there was less difference in irradiation levels since the shading object affected those panels less than on line A.

For the results of step 4, a similar pattern could be seen since the energy output is linearly connected to the irradiation level on the panels.

For step 5, different results were obtained, depending on the chosen financial parameter (payback time or profit after *n* years). With the obtained results at all lines (A-E), a preferred payback time and profit can be set. As an example, Figure 5 shows the results of those configurations where the profit was higher than 0 and the payback time under 15 years. Choosing a different payback time or another amount of years in the profit calculation will lead to a difference in results. The numbers in the white circles show the shortest payback time for a PV panel placed at that specific spot. The different colours show the configuration at that specific place that will lead to this shortest possible payback time.

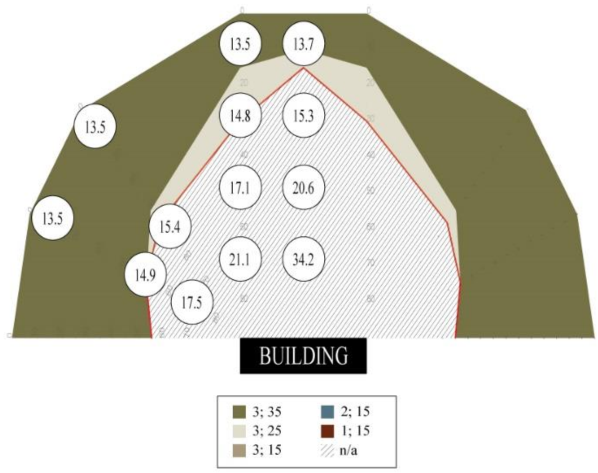


*Figure 5. Payback time <15 years*

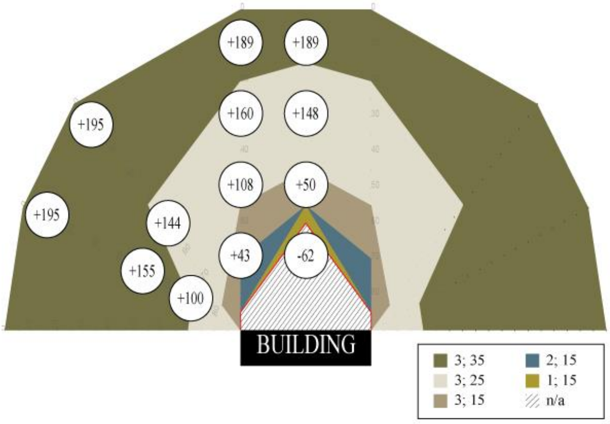


*Figure 6. Profit after 25 years*

Figure 6 shows that when it comes to a positive profit after 25 years, none of the configurations will provide this for an obstruction angle higher than 60 degrees on Line A and 70 degree on Line B. For the other lines, a positive profit will already be reached at all obstruction angles as the shading from the shading object is less at these locations. At line A, different configurations will provide a positive profit based on different obstruction angles. First, a configuration with a row distance of 1 m and an inclination of 15° (1;15) is providing the highest profit, followed by 2 m (row distance) and 15° (inclination) (2;15), and then configurations with a 3 metres row distance.

When it comes to the payback time under 15 years, a different results can be seen. Table 1 shows the results of the payback time of panels on Line B.

*Table 1. Payback times for all configurations at Line B. Green indicate a payback time lower than 15 years*

| obs. angle | 1;5 | 1;25 | 1;45 | 1.5;5 | 1.5;25 | 1.5;45 | 2;5 | 2;25 | 2;45 | 3;5 | 3;25 | 3;45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80° | 24.7 | 28.5 | 33.3 | 24.5 | 25.4 | 28.6 | 24.4 | 25.1 | 28.0 | 24.6 | 24.6 | 26.5 |
| 70° | 21.6 | 24.6 | 28.1 | 21.4 | 21.7 | 24.2 | 21.3 | 21.5 | 23.5 | 21.4 | 21.2 | 22.6 |
| 60° | 19.4 | 22.0 | 24.7 | 19.2 | 19.3 | 21.2 | 19.2 | 19.0 | 20.5 | 19.3 | 18.8 | 19.9 |
| 50° | 17.9 | 20.1 | 22.4 | 17.7 | 17.5 | 19.1 | 17.7 | 17.3 | 18.4 | 17.7 | 17.1 | 17.9 |
| 40° | 16.7 | 18.8 | 20.8 | 16.6 | 16.2 | 17.6 | 16.6 | 16.0 | 16.8 | 16.6 | 15.8 | 16.4 |
| 30° | 15.9 | 17.9 | 19.7 | 15.8 | 15.3 | 16.5 | 15.8 | 15.0 | 15.7 | 15.8 | 14.8 | 15.3 |
| 20° | 15.3 | 17.3 | 19.0 | 15.3 | 14.6 | 15.7 | 15.2 | 14.3 | 14.8 | 15.2 | 14.1 | 14.4 |
| 10° | 14.9 | 16.9 | 18.5 | 14.9 | 14.1 | 15.0 | 14.9 | 13.7 | 14.2 | 14.9 | 13.6 | 13.7 |
| 0° | 14.7 | 16.7 | 18.3 | 14.7 | 13.8 | 14.6 | 14.7 | 13.4 | 13.7 | 14.7 | 13.2 | 13.1 |

The green cells highlight those configurations that provide a lower payback time than 15 years. For Line A, a payback time lower than 15 years is only reached with an obstruction angle under 25° and with a configuration of 3 m, 25° and 3 m, 35°, as indicated with the several colours in Figure 5. It should be kept in mind that even on Line E, payback times lower than 15 years will only be reached with an obstruction angle under 55°. It can also be seen in Figure 3 that, at low obstruction angles, the impact of the shading object gets negligible.

The method discussed here is flexible in the sense that another filter can be applied and that by choosing other boundaries (like choosing a lower/higher payback time and profit), another result will be displayed.

## Conclusion

When planning for implementing solar energy on roofs in urban environments, it is important to have the right facts at hand to make any decision.

Finding the best performing system configuration of a PV system, which is subject of mutual shading as well as shading from external objects is not that straightforward and depends on the chosen metrics –energy, payback period, profit after *n* years or profit percentage.

Since investors in solar energy often are more interested in financial parameters rather than knowing how much radiation is received by the solar cells, this method makes it possible to know for instance where the placement of solar cells is *not* profitable.

By visualising the results of the different analyses, a more informed decision can be taken by different stakeholders such as engineers, architects and real estate developers.

The method can be fully automated. This will make it possible to analyse complex shading in a fast and straightforward way.

## Acknowledgement

The authors would like to thank the Swedish Research School in Architecture and the Swedish Energy Agency for the financial support.

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