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Edward Ng, Square Fong, Chao Ren

Assessing the Photovoltaic Potential of Flat Roofs:
Insights from the analysis of optimised array arrangements

G. PERONATO[1], S. AGUACIL[1], A. LEGRAIN[1], S. VITALI[1], E. REY[1], M. ANDERSEN[1]

[1]Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland

ABSTRACT: PV installations on flat roofs offer a wide range of design options, which are usually neglected in urban-scale assessments as these typically assume horizontal or other fixed arrangements. In this study, we analyse the influence of common design parameters (tilt and inter-row distance) in evaluating the potential of PV arrays installed on flat roofs, using three different performance indicators. By comparing optimised arrangements to horizontal ones, we show that the latter could be misleading, unless building- and indicator-specific correction coefficients are applied.
KEYWORDS: urban PV potential, building-applied photovoltaics

1. INTRODUCTION

Building-installed photovoltaic systems are a valuable on-site renewable source of energy offsetting the building carbon footprint. Although building-integrated photovoltaic (BIPV) solutions encounter an increasing interest (higher user acceptability, use as replacement of existing envelope cladding), building-applied photovoltaic (BAPV) systems installed as tilted arrays on flat roofs are still a very common solution. In fact, these are generally cheaper than BIPV and provide optimal installation conditions, due to flexible orientation and tilt angle, and good ventilation.

When assessing the photovoltaic potential of a city, a large variety of installation conditions of roof BAPV arrays exists, such as size, azimuth and simple/double orientation (e.g. S or E-W), and tilt angle. However, in solar cadastres the assessment is commonly done assuming that PV panels are installed horizontally [1], [2] or by adjusting the results considering a fixed tilt and spacing [3]. Yet even if a horizontal array would maximise the number of installed panels, such an installation is not technically feasible, because of lack of water drainage and dust self-cleaning. On the other hand, optimal tilt angle and spacing will depend on the specific building and surrounding conditions (in terms of size, shading, inter-reflections), regulatory framework (e.g. self-consumption, incentives) and optimisation objectives (e.g. financial or environmental).

In this study, we compare different tilted installation strategies, maximizing either the financial or the environmental benefits, to simplified horizontal assessments on three flat roofs in a dense urban area. We show that the results are dependent on the roof size and optimisation objective. We finally discuss the relevance of these findings for applications in urban-scale PV potential assessments, such as solar cadastres.

2. METHODOLOGY

We assessed the possible installation of PV arrays on three buildings in the city of Neuchâtel in Switzerland, whose characteristics are included in Table 1. Results from tilted array maximising different indicators are compared to those obtained with a simplified calculation model assuming horizontal panels, arranged according to a Cartesian division of the roof surface where the y-axis is North-oriented.

Table 1: Characteristics of the analysed buildings.

Building	A	B	C
Roof area [m^2]	459	591	207
Floor area [m^2]	1353	3014	880
Orientation	South-East	South-East	South-East
Type of obstructions	Vegetation	Stairwell, chimneys	Stairwell, chimneys

2.1 Installation strategies

We selected three possible installation strategies corresponding to three different approaches installers may take in current practice. The first indicator (“energy cost”) exemplifies the approach of an energy utility company that wants to minimise the Levelised Cost of Energy (LCOE). The second approach (“profit”) is aimed at maximising the profit of an investor, considering the cost of both self-consumed and grid-injected electricity, calculated as the Net Present Value (NPV) on a 25-year period. The third indicator (“CO_2 avoidance”) considers the environmental impact of the installation by maximising the avoided carbon intensity with respect to an alternative energy source.

Financial parameters refer to current Swiss local and federal legal framework, with one-time power-based subsidies for <100kWp installations, and a feed-in rate varying depending on the size of the installation, but always lower than the electricity-buying price, which makes self-consumption particularly interesting. Estimated income-tax deductions and interest rate (5%) are also included in the financial model.

For the environmental model, we assumed a substitution of the imports from the German grid (conservative value of 300 gCO_2/kWh [4]) and estimated the carbon footprint of solar panels as 70 gCO_2/kWh, which is consistent with LCA studies [5].

We studied two typical orientations: South-facing to maximise per-panel production and East-West double-oriented to maximise the size of the installation while matching the building load-curve.

2.2 Modelling and simulation workflow

We implemented a parametric study to test the effect of different tilt angles (5-26°, with a 1° step) and distance of arrays (0-195 cm, with a 15-cm step) on the chosen indicators for the two considered orientations. Unlike typical approaches defining the inter-array distance based on a maximum number of shaded hour in the winter solstice [6], our method avoids the arbitrary choice of such a parameter and allows the inclusion of indirect radiation to find the optima for each indicator.

The parametric study was conducted in Grasshopper coupled with Daysim, through the Honeybee interface, to simulate hourly solar irradiances on tilted panels, using a detailed 3D model. The PV yield was calculated using a fixed efficiency of 19.7% and an annual degradation rate of 0.55%, corresponding to a high-tier polycrystalline module available on the market at real installation conditions.

3. RESULTS AND DISCUSSION

If we consider the "profit" indicator (Table 2), S-oriented arrays provide the best results for buildings A and B, while an EW orientation gives the best results for building C, as it maximises the number of panels on its smaller roof surface (hence benefiting from peak-power subsidies).

Table 2: Arrangements maximizing the "profit" indicator for the analysed buildings and orientations.

Building	A		B		C	
Array orientation	S	EW	S	EW	S	EW
NPV [kCHF]	15.5	1.2	26.7	19.1	9.8	10.5
Tilt angle [°]	26	5	26	5	5	7
Spacing [cm]	165	195	165	80	15	0
Power [kWp]	29.0	36.9	27.6	51.1	18.6	21.7
N. of panels [-]	84	107	80	148	54	63
Yield [MWh/y]	24.1	27.6	25.2	41.9	15.6	17.8

Table 3 shows that the electricity yield with optimised tilted arrays is always lower or equal to the one calculated assuming flat panels (simplified method). Similar values are reached when using the "CO_2 avoidance" approach as well as when considering building C, as in both cases the number of installed panels is maximised by using an EW orientation.

Table 3: Yield ratios of tilted arrays to horizontal arrays for the analysed buildings and indicators.

Building	A	B	C
"Energy cost"	0.74	0.73	0.93
"Profit"	0.44	0.38	0.93
"CO_2 avoidance"	0.99	1.03	0.96

Despite the peak-power subsidies and self-consumption benefits, financial-based strategies ("energy cost" and "profit") favour smaller size, higher-yield South-facing installations for buildings A and B. However, for building C, due to the smaller available roof surface, the array size should be maximised for economy-of-scale reasons, and hence installed facing East-West. Horizontal installations can approximate only the "CO_2 avoidance" indicator. Differently, for the financial indicators, there is no generalizable tilted-to-horizontal ratios, as the roof size, coupled with the incentive/feed-in framework, plays also an important role. Therefore, we can argue that simplified assessments from horizontal estimations (as used in solar cadastres) should consider these factors to determine the optimised arrangement and hence the effective PV potential of flat roofs, whereas this is usually neglected.

4. CONCLUSION

Based on the results from simulations on three roofs with similar urban context and under the same climate, we have shown that there is no unique best arrangement for PV arrays on flat roofs. Regulatory and incentive framework, installer goals and roof size are among the factors influencing the results. In the tested buildings, tilted arrays provide 38 to 103% of the energy yield on a hypothetical horizontal installation. In this sense, results from horizontal arrays, often used for urban-scale analyses, should be corrected using building- and indicator-specific ratios, while this is often neglected.

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Conference Chair:

Edward Ng,

Yao Ling Sun Professor of Architecture,

School of Architecture,

The Chinese University of Hong Kong

Conference Proceedings Edited by:

Edward Ng, Squre Fong, Chao Ren

School of Architecture

The Chinese University of Hong Kong

AIT Building

Shatin, New Territories

Hong Kong SAR, China

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