MAXIMIZING THE SOLAR PHOTOVOLTAIC YIELD IN DIFFERENT BUILDING FACADE LAYOUTS

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ABSTRACT: The Building Integrated Photovoltaics (BIPV) market constitutes a great opportunity for electricity production in urban areas. As new solar cell technologies with improved performance and morphological properties emerge in the PV market, BIPV becomes cost-competitive and eye-catching. In this paper, we address unconventional facade designs and estimate their PV potential. Five different layouts were optimized for the maximization of annual solar irradiation, showing that tilted louvers may increase the electricity yield in more than 20%, when compared to a flat vertical layout. For a more refined assessment, an analysis accounting for losses due to high incidence angle of solar rays, mutual shadowing and PV windows on vertical walls, the optimized louvers will feature stronger tilts and produce around 40% more than the vertical layout. As far as building orientation is concerned, it is shown that the electricity yield for an East/South/West arrangement is about 25% higher than a Southeast/Southwest building, with relative independency from building location.
Keywords: Solar radiation, PV facades, optimization, Grasshopper, DIVA-for-Rhino

1 INTRODUCTION

In the last decades we have witnessed a significant migration of population from rural areas to built environments and, with it, an increase in electricity demand in urban areas. According to the 2020 Horizon goals, this demand ought to be tackled with local, CO_2 emission free and abundant energy sources and technology. Solar photovoltaics (PV) is among all renewables the one that better suits cityscapes' electricity load profile. Furthermore, it is in mid-latitude overpopulated cities that solar irradiance reaches higher levels. However, commissioning PV power plants in the urban environment presents challenges: as available ground area becomes scarce the urban fabric has to grow more vertically, and thus the easy and straightforward integration of photovoltaics in rooftops alone represents only a small fraction of a high-rise city's solar potential [1]. In this sense, building integrated photovoltaics (BIPV) has progressively become an interesting investment, with building facades gaining special attention. In spite of the relatively lower performance of BIPV, with thoughtful planning PV facades are able to play a relevant role in the electricity supply chain due to the amount of available area and peak production at different times of the day according to their orientations [2].

But building facades can go further. Due to concerns with thermal and visual comfort for the occupants in indoor spaces, facades are not just vertical and flat surfaces. They embed structures such as balconies and louvers in most sunlit locations. Moreover, aesthetic concerns also incite architects to create non-flat facades, sometimes with complex shapes, which are becoming more common in contemporary construction. In a BIPV perspective, these non-vertical structures could also be used in favour of electricity production since solar radiation would reach each surface at different times of the day. On an annual basis, vertically mounted solar cells receive less solar radiation than with other inclinations, thus it becomes interesting to study how this drawback can be overcome if we optimally dispose facade features.

A huge amount of facade area that otherwise would remain unused may gain a new complementary functionality if proper BIPV elements are selected. The study conducted in [3] emphasizes the complementary relationship that other building construction technologies should have with BIPV facade systems in order to make them appealing to architects and engineers, who prefer more standardized products. And so does the construction industry, but the development of market for BIPV solutions for facades with unconventional layouts requires a trade-off between bulk production and design flexibility [4]. Also, it is clear that the opportunity for the BIPV market growth is enormous. The existing BIPV systems surveyed in [5] helped understanding that BIPV facade applications are a cost-effective substitute for conventional facade solutions, especially in earlier stages of building design and construction.

2 METHODOLOGY

Different building facade layouts were created and optimized for maximum annual solar irradiation (sub-section 2.1). The best performing scenario underwent complementary analysis (sub-section 2.2).

2.1 Annual solar irradiation optimization

The computation of solar irradiance in complex structures and environments is not trivial. Three components are mandatory for a detailed study: the solar radiation model, the digital representation of the surfaces and context, and results visualization and processing [6].

In the first part of this study, we aimed at a detailed assessment of a rather simple case-study that consisted on a parallelepiped representing a typical $10x10x3m^3$ building storey with no surroundings. The selected location is Lisbon, Portugal, and only the East + South + West set of facades were studied (see example Fig.3). A base scenario consisting on flat vertical PV facades was computed as a base for comparison with more complex layouts.

Five facade layouts (Fig.1) were modelled in the 3D modelling software Rhinoceros [7] using an integrated graphical algorithm editor called Grasshopper [8] that allows parametrization of the variables. Employing the plug-in Diva-for-Rhino [9], a Radiance-based tool able to include the effects of a wide variety of material types, sky and lighting conditions, and physical phenomena related to light propagation of a specific scene, we computed the yearly solar irradiation on the surfaces of interest with a 0.1m^2 point grid. The solar radiation model is that of Perez [10] with Tregenza sky patch model [11] and a cumulative sky approach [12] to reduce computation time.

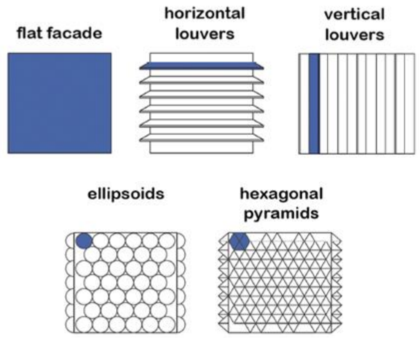

Figure 1: Studied facade layouts: flat walls, horizontal and vertical louvers/sunscreens, ellipsoids and pyramids on the walls. PV surfaces are coloured in blue.

Each scenario underwent a single-objective optimization process using Galapagos [13], an optimization module inside Grasshopper. The evolutionary solver was selected, with default options, for the maximization of overall annual solar radiation incident on the facade features: louvers' length was kept constant while tilts and orientation changed with every new iteration (1 variable), while ellipsoids and hexagonal pyramids changed their length, base radius and shed angles (4 variables). It took around 10 seconds to compute each individual inside a population of a maximum of 50 individuals, and the whole process took less than 4 hours in the case of louvers layouts, and double that time for the other layouts.

Average electricity production was estimated considering 15% solar cell efficiency and an 80% performance ratio to account for building integration.

Then, the best performing scenario underwent another optimization process introducing the Southeast + Southwest set of facades (see next section's Fig.4) and a second location with dissimilar climatic conditions: Geneva, Switzerland.

2.2 Partially shaded PV optimization

In order to take into account the nonlinear response of solar modules to partial shading and the effect of incidence angle dependence, a new MatLab routine was written to read meteorological data series of both locations, to calculate solar irradiance on arbitrary orientation and tilt and to estimate electricity production on base flat facade scenario and the tilted sunscreens. We also introduced a 6% efficiency [14] to account for semi-transparent PV on windows on the base scenario. The glazing fraction of each facade according to the orientation was as defined for typical buildings in Portugal: south 35%, east and west 25%, southeast and southwest 30% [15]. For simplicity, a conservative formulation was employed: the PV output is zero when there is mutual shadow (i.e. solar zenith is higher than the angle between sunscreen edge and the wall); radiation losses due to high incidence angle are considered [16]; diffuse radiation is now isotropic; and the upper louver does not have PV cells, as it might be part of the roof.

3 RESULTS

An overview of results from the use of Rhinoceros and Diva-for-Rhino can be found in Fig. 3. All optimized layouts perform better than the base scenario (upper plot). Horizontal louvers achieve 25% higher yields, followed by ellipsoids, pyramids and vertical louvers. However, the amount of solar cell area required to fill all the features clearly highlights the low outcome of complex and vertical surfaces (lower plot).

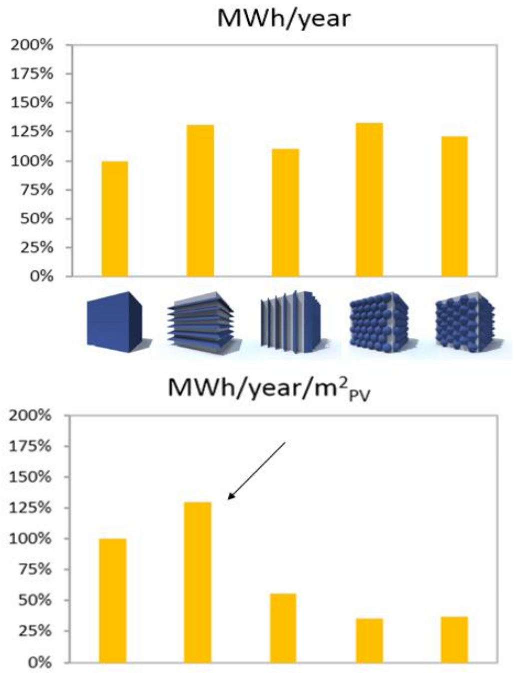

Figure 2: Comparison between the five layouts. The best performing is the horizontal tilted sunscreens.

Careful inspection on the scenario with tilted louvers (Fig.3) reveals that in Lisbon (38.44 N, 9.9 W) the optimum tilt of south facing louvers is similar to the latitude even with mutual shadowing. Early morning and late afternoon are not symmetric, with higher solar irradiance in the morning.

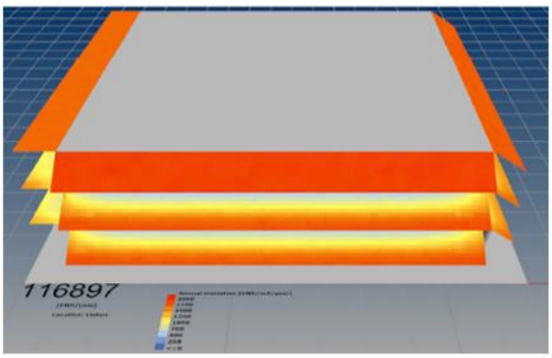

Figure 3: Optimized tilts on the best performing layout: East=33°, South=37° and 0°. The value in the lower left corner of each image corresponds to the total solar irradiation [kWh/year].

Optimization for SE + SW shows an increase of around 9% in total solar income from horizontal tilt to optimum tilt (Fig.4). Once again, morning features higher irradiation levels.

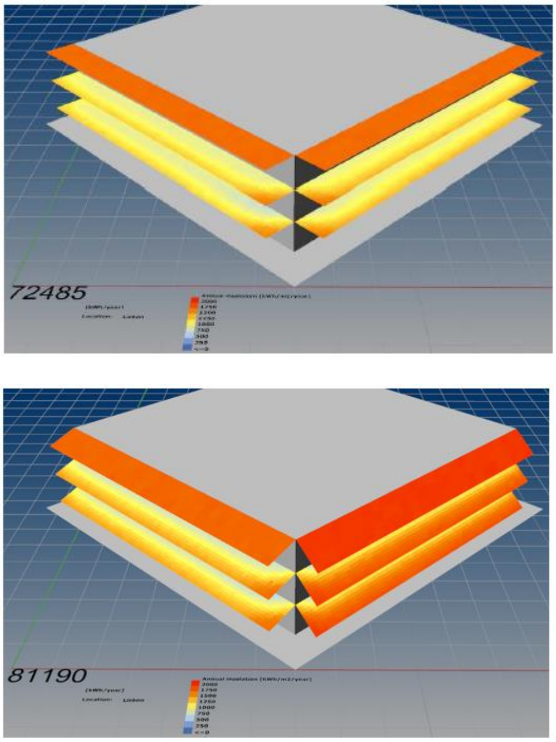

Figure 4: Lisbon horizontally and optimally tilted louvers: Southeast=42° and Southwest=22°. The value in the lower left corner of each image corresponds to the total solar irradiation [kWh/year].

Solar irradiation in Geneva (46.20N, 6.14E) is clearly lower than in Lisbon, but the optimized tilt of louvers presents an increase in solar irradiation of the same order of magnitude that in Lisbon. The morning-afternoon symmetry seems more evident in this case (Fig.5), maybe because diffuse radiation represents a greater share on the global solar radiation.

The methodology described in sub-section 2.1 gave significantly different results. In Fig.6, the best tilts for all facade orientations are located within a 10° interval: from 50° to 60° in Lisbon and 40° to 50° in Geneva. Of course, the simplistic assumption that PV output is zero when there is mutual shading is too conservative, but these result highlight the importance of considering the solar cell/module behaviour in detailed potential estimates.

The relative results are independent from location. In both cases there is a 40% inscrease in potential from PV walls and windows to PV tilted sunscreens. The south facing facade has the largest share, however the SE + SW arrangement is very appealing since it produced only 25% less than E+S+W while using 33% less solar cell area (Fig. 7).

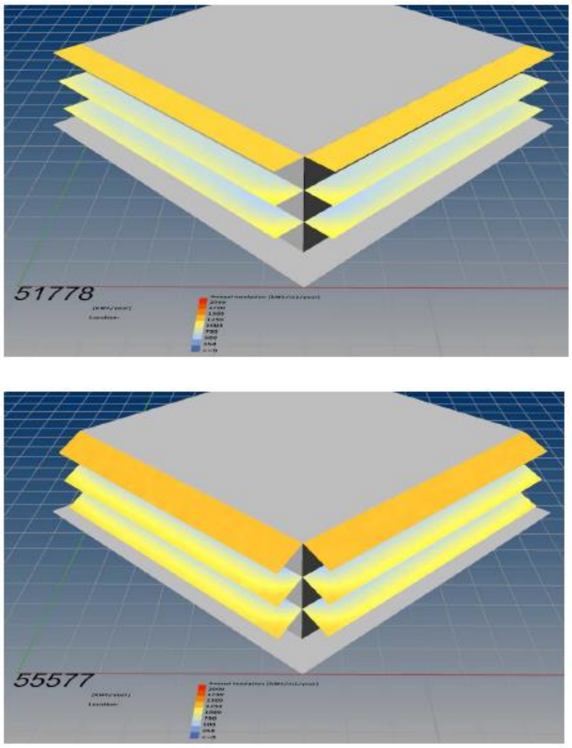

Figure 5: Geneva horizontally and optimally tilted louvers: Southeast=24° and Southwest=31°. The value in the lower left corner of each image corresponds to the total solar irradiation [kWh/year].

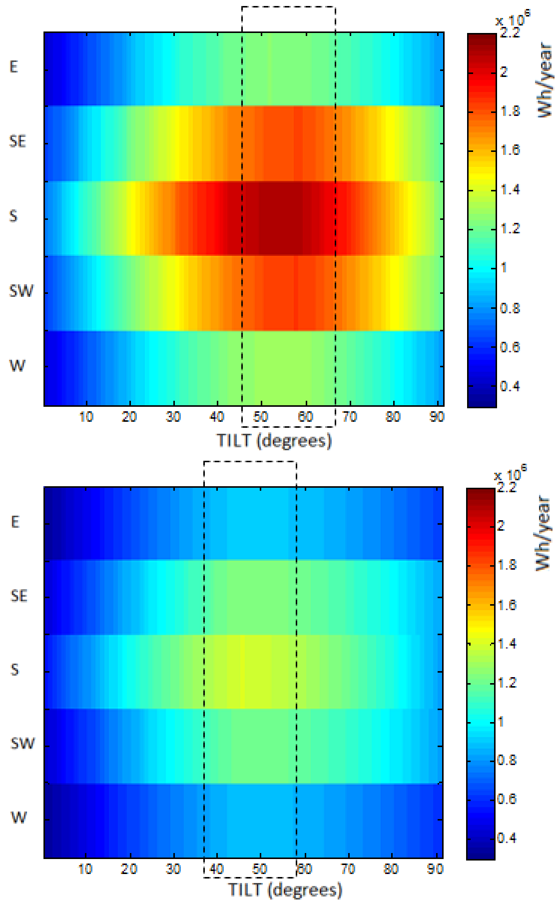

Figure 6: Sunscreen yield in Lisbon (upper plot) and Geneva (lower plot) according to tilt angles.

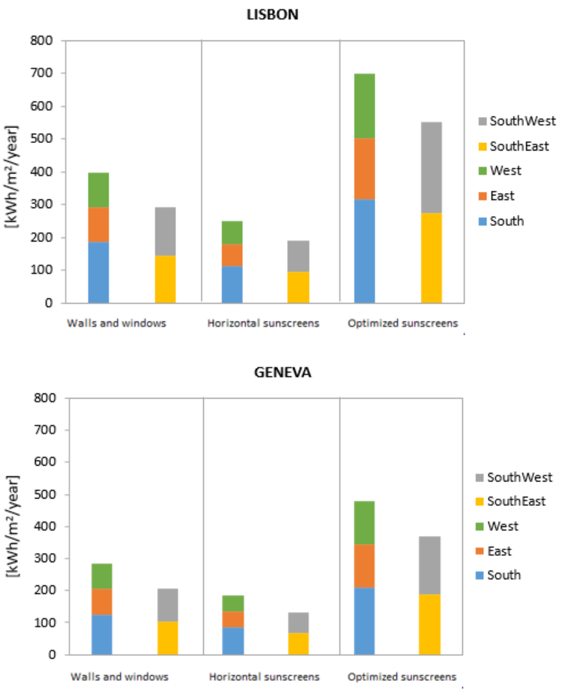

Figure 7: Comparison between base vertical scenario and horizontally and optimally tilted sunscreens.

Comparing Fig. 7 with Fig.4 and 5, horizontal sunscreens are underperforming, which is due to the assumption that the upper sunscreen would not be PV – as seen before the upper louvers evidently receive solar radiation without the influence of obstructions.

4 DISCUSSION

The E+S+W horizontal rotating louvers achieve higher energy yields per m^2, while more complex shapes require more solar cell area (Fig.2). This solution allows for more than 25% increase in solar radiation incidence than purely vertical integration.
It can be observed that the irradiation optimized shapes tend to adjust in order to gather more of the diffuse component of solar radiation in detriment of smaller shapes, which is misleading when dealing with partially shaded PV systems – solar cells are connected in series and modules in strings, thus the optimization for total annual irradiation is not enough, there must be a technical optimization [17].
After employing a conservative estimate to account for losses due to high incidence angle of solar rays, mutual shadowing and PV windows on vertical walls, the optimized louvers feature stronger tilts and production estimates were around 40% higher than the vertical layout. The SE+SW production is only around 25% lower than E+S+W facade set, regardless of building location (Fig.7).
This study also highlights the importance of choosing the right approach when execution time and/or level of detail matter, but further investigation has to be conducted to understand the error associated with both methodologies.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] A. Scognamiglio and H.N. Røstvik, 2012, Photovoltaics and zero energy buildings: a new opportunity and challenge for design, 27th EUPVSEC, Frankfurt

[2] Brito, M.C., Redweik, P., Catita, C., 2013. Photovoltaics and zero energy buildings: the role of building facades, 28th EU PVSEC,

[3] Polo Lopez C., Frontini F., Bonomo P., Scognamiglio A., 2014, PV and Facade Systems for the Building Skin. Analysis of Design Effectiveness and Technological Features. 29th EUPVSE, Amsterdam

[4] Hagemann, Ingo B., 2011, Perspectives and Challenge of BIPV Product Design, 26th EUPVSEC, Hamburg

[5] G. Verberne, P. Bonomo, F. Frontini, M.N. van den Donker, A. Chatzipanagi, K. Sinapis, W. Folkerts, 2014, Proceedings of the 29th EUPVSEC, Amsterdam

[6] Freitas, S., Catita, C., Redweik, P., Brito, M.C., 2015. Modelling solar potential in the urban environment: State-of-the-art review. Renewable and Sustainable Energy Reviews 41, 915–931

[7] Rhinoceros 3D (2015), https://www.rhino3d.com/

[8] Grasshopper (2015), http://www.grasshopper3d.com/

[9] Diva For Rhino (2015), http://diva4rhino.com/

[10] Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R., 1990, 'Modeling Daylight Availability and Irradiance Components From Direct and Global Irradiance', Solar Energy, vol. 44, issue 5, pp. 271-289

[11] Tregenza, P.R., 1987, Subdivision of the sky hemisphere for luminance measurements. Lighting Research and Technology, 19:13–4

[12] Robinson, D., and Stone, A., 2004, "Irradiation modeling made simple: the cumulative sky approach and its applications", PLEA2004 - The 21st Conference on Passive and Low Energy Architecture. Eindhoven, The Netherlands, 19 - 22 September 2004

[13] Galapagos (2015), http://www.grasshopper3d.com/group/galapagos

[14] CC Chen, L Dou, J Gao, WH Chang, G Li, Y Yang, 2013, High-performance semi-transparent polymer solar cells possessing tandem structures. Energy and Environmental Science, 6 (9), 2714-2720

[15] Instituto Nacional de Estatística, Direção-Geral de Energia e Geologia, 2010, Inquérito ao Consumo de Energia no Sector Doméstico

[16] Martin, N., Ruiz, J.M., 2001. Calculation of the PV modules angular losses under field conditions by means of an analytical model. Solar Energy Materials and Solar Cells 70, 25–38

[17] Freitas, S., Serra, F., Brito, M.C. (2015). "PV layout optimization: string tiling using a multi-objective genetic algorithm". Solar Energy, Volume 118, Aug 2015, 562–574, 10.1016/j.solener.2015.06.018