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The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data

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The aim of this work is to discuss the potential of facades and other vertical features for the photovoltaic potential of the cityscape. The photovoltaic potential in two representative case studies in the city of Lisbon, Portugal, is computed using a digital surface model determined from LiDAR (Light Detection And Ranging) measurements and local typical meteorological year time series. Results are compared with estimated local electricity demand derived from the population distribution.

The annual analysis shows that roof and facade PV potential exceeds the local non-baseload demand and can contribute to 50–75% of the total electricity demand. Hourly breakdown shows peak PV power can only achieve winter mid-day electricity demand if the solar potential of facades is also taken into account. Its added value for off-peak PV supply is less significant in winter since non-south facades are not particularly exposed. In summer, however, facades can satisfy non-baseload morning and afternoon demand. A conservative economic analysis shows payback times below 10 years can only be achieved with PV on roofs while a 50/50 mix would lead to payback times of 15 years.

1. Introduction

In an era of growing urbanization when most of energy demand is concentrated in cities, energy sustainability requires that a significant fraction of this energy demand can be fulfilled with local, clean and abundant sources of energy. As it has been highlighted by Hernandez [1], solar power is an unavoidable piece of the fabric of sustainable cities; solar power is plentiful in most regions of the globe, it is a renewable source of energy and CO_2 emission free.

However, solar power has relatively low energy densities, thus requiring considerably larger areas to produce relevant amount of electricity. As modern cities are characterized by high density populations, living in high rise buildings, the available roof area becomes in short supply for solar power to fulfill the local energy demand. As such, building facades offer an attractive and complementary option.

Although vertical solar panels receive less solar radiation than roofs and horizontal surfaces, in particular in the summer months, and are more affected by the compactness of the urban layout [2], facades feature high areas; in a building with 4 floors, the area of the facades is about 4 times the area of the roof[1]. If the whole available area of such building was used for solar panels and shadings from neighboring buildings neglected, the total annual electricity production would triple that of the roof. This ratio will obviously increase further for taller buildings. However, it is important to point out that in this example, the cost of the generated solar electricity (in €/kWh) would also be 4 times higher. Hence, the deployment of PV on less than optimum inclination/orientation has to be weighted by economic constraints. Nevertheless, the recent trend of fast decreasing costs of PV, which is expected to proceed in future years [3], opens a window of opportunity for this type of applications.

Additionally, vertical PV facades will produce relatively more power in winter and less in summer, and more in the early and late hours of the day, when the sun is lower in the sky. Since a building will typically have four, or at least two, exposed facades with opposite orientations, the different solar facades of a building will produce at maximum power at different times of the day. As has been recently highlighted by Hummon et al. [4], this leads to a widening of the peak of power production throughout the day and

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[1] Assuming a 10 × 10 m^2 area building with 4 storeys, each 3 m high; hence, the roof area is about 100 m^2 while the facade area is 4 facades × 4 storeys × 3 m/storey × 10 m length = 480 m^2 facade area.

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hence a closer match to the load diagram, which can then result in significant savings in electricity storage and/or fossil fuel based backup power. Also in Ref. [5] the importance of adjusting tilt and azimuth of PV installations, with higher tilts being the preferable option for south facing scenarios, is highlighted as a means to spread the electricity generation over a larger period of time. It is also worth mentioning that the lower level of solar irradiation on facades has prompted consideration of different concepts and practical solutions for increasing energy harvesting on vertical surfaces. These include reshaping of the facades themselves [6] or the development of concentration photovoltaic systems for application in buildings [7].

Furthermore, the use of facades for PV generation, and in particular Building Integrated Photovoltaics (BIPV) [8] – defined as photovoltaic cells integrated into the building envelope as part of the building structure – offers interesting opportunities as it can replace conventional building materials whilst creating a harmonious architecture by blending into the design of the building [8,9]. Since it replaces other construction materials, its net cost (per unit area) is already cost-effective in a number of applications [10]. As an added benefit, the air flow behind the solar modules reduces their temperature improving the system efficiency and longevity [11]. Another approach is the use of semitransparent BIPV which allows daylight to enter the interior spaces [12].

The purpose of this work is to analyze the cityscape PV potential, including both roofs and facades, and to understand when facades might act as added advantage to the rooftops. The methodology is described in section 2. Using Light Detection And Ranging (LiDAR) data to describe the topography of the city, including both the terrain and buildings, and reference meteorological data, the PV potential is determined for two case study areas in the city of Lisbon, Portugal, presented in section 3. The two different areas are characterized by differing building morphologies. Then, hourly PV generation potential of roofs and facades is compared with estimated local electricity demand. Results are presented in sections 4, 5 and 6, which discuss the overall PV potential of facades and the added value of better adjustment to the load diagram. In the end, conclusions are drawn regarding the contribution of PV facades to the solar potential of a city.

2. Methodology

The estimation of the cityscape PV potential is based on a 3D PV potential tool which uses LiDAR data and reference meteorological data to determine the expected insolation of all points on the ground, roof and facades of buildings in the study areas. The discussion entails the comparison of the PV generation potential with the local electricity demand, which is determined from the population distribution and the per capita average load.

2.1. 3D photovoltaic potential

The estimation of solar potential in the urban environment typically requires combining radiation models, accounting for the apparent movement of the sun in the sky, as well as the beam and diffuse fractions of the global solar irradiation, and Geographical Information Systems (GIS) to describe the opaque obstacles met by beam irradiation (i.e. shadow casting) and sky view factors (SVF) that determine the amount of diffuse irradiation. For an overview of solar potential models in the urban environment see Freitas et al. [13].

In this study, the solar power potential of roofs and facades is determined using the SOL algorithm, a software tool described in Redweik et al. [14] and Catita et al. [15]. The algorithm starts from a geo-referenced LiDAR data cloud, re-sampled for a $1 \times 1\text{m}^2$ raster. As vertical surfaces are not directly detected by the aerial LiDAR sensor, which only measures the surface height, they are decomposed into hyperpoints, i.e. each XY point is used to produce a set of 3D points sharing the same XY coordinates (cartographic coordinates) but with different Z (elevation) located in space along a vertical column on a facade.

The local typical meteorological year (TMY) data set associated to the SOLTERM database is used. This includes hourly mean values for horizontal direct and diffuse irradiation calculated over 30 years of local observations. The hourly global irradiance, G, on any point of the tilted surfaces is determined by its two main components: direct and diffuse irradiance (eq. (1), adapted from Ref. [16]).

$$G = G_{bh}\frac{\cos\theta}{\cos\theta_z}SC + G_{dh}F_dSVF \tag{1}$$

where G_{bh} and G_{dh} are respectively the hourly direct and the diffuse horizontal irradiance components, SC denotes a Shadow Caster attribute (0 or 1), $F_d = \frac{1+\cos\beta}{2}$ is the transposition factor for isotropic diffuse radiation, SVF denotes the Sky View Factor (i.e. the fraction of sky visible from a point), θ_z is the sun's zenith angle and θ is the angle of incidence of the sun rays on the tilted plane calculated according to the following equation [16]:

$$\begin{aligned}\cos\theta = {} & \cos\delta\sin\beta\sin\gamma\sin\omega + (\cos\phi\cos\beta \\ & + \sin\phi\sin\beta\cos\gamma)\cos\delta\cos\omega + (\sin\phi\cos\beta \\ & - \cos\phi\sin\beta\cos\gamma)\sin\delta\end{aligned} \tag{2}$$

where δ is the declination angle, ϕ is the latitude of the location, β is the surface tilt, ω is the hour angle and γ is the surface azimuth. The model does not consider reflected light.

At any given time, a shadow algorithm takes each point of the Digital Surface Model (DSM), including trees, as a shadow caster along the line opposite to the direction of the sun. As long as this line is not interrupted, i.e. whenever a DSM cell along that profile features a Z value lower than the shadow line height at that XY position, the pixel is in shadow and receives the Shadow Caster attribute 0, creating then a binary map. For facades the process is further refined by taking into account shadow height and behavior of the neighbourhood. The result is that at any given time, points belonging to the same facade hyperpoint may have different Shadow Caster attributes, i.e. such a hyperpoint may be totally shaded, partially shaded or totally unshaded.

The diffuse irradiation on a given point is constrained by its SVF, a measure of the amount of sky seen from the location. For the same facade, ground floors normally have a lower SVF than top floors because of an increase in view obstructions to the sky. Therefore, even when a point is in shadow, diffuse irradiance is still available according to its SVF. This is taken into consideration in the SOL algorithm whereby the SVF is calculated for each hyperpoint element (as well as for the roofs and ground).

The SOL algorithm delivers hourly irradiation data on every point of roof and facade for every day of a year in form of maps and tables, which can be used to obtain solar irradiation estimates for different periods and timescales.

The PV potential mapping is determined by multiplying the solar irradiation by an efficiency of 15% for a typical module. Because the effect of module temperature on the efficiency of silicon based modules is not negligible, this is also taken into consideration [17]:

$$\eta_{mod} = \eta_{ref}\left[1 - \Delta\eta\left(T_a + \frac{T_{NOCT} - 20}{800}G - 25\right)\right] \tag{3}$$

where η_{mod} is the module operating efficiency, $\Delta\eta$ is the