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Sky view factor as predictor of solar availability on building façades

Christina Chatzipoulka[a,b,*], Raphaël Compagnon[b], Jérôme Kaempf[b], Marialena Nikolopoulou[a]

[a] Kent School of Architecture, University of Kent, Marlowe Building, CT2 7NR Canterbury, United Kingdom
[b] Haute Ecole d'Ingénierie et d'Architecture de Fribourg, Bd Pérolles 80, 1700 Fribourg, Switzerland

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ABSTRACT

Solar availability on urban façades varies significantly, affected by obstructions by nearby buildings as well as orientation. A convenient way to evaluate their solar energy potential is deemed to facilitate the task of architects in increasing the use of photovoltaic systems and, thus solar energy generation in the urban environment. This study explores to what extent the sky view factor (SVF), a measure of the openness of a point to the sky, can be employed for evaluating solar irradiation of façades in complex urban scenes. For this purpose, extensive statistical analysis was performed testing the correlation of SVF with solar irradiances for 30 orientations, considering three European climates (i.e. Athens, London and Helsinki), and three periods (i.e. year, January and July). Special emphasis is put on global irradiance, which expresses the sum of three solar components, i.e. direct, diffuse and reflected. The study uses 24 urban forms - of 500 × 500 m area - in London for which SVF and solar irradiance simulations were performed for nine sky models (three locations by three periods). The results reveal a strong linear relationship ($R^2 > 0.8$) between SVF and annual global irradiance in all orientations, at all three locations. In fact, as SVF was found to correlate well with both major solar components, direct and diffuse, it can be presumably used for predicting façades' annual solar irradiation at any location within the tested range of latitudes. With respect to monthly global irradiance, the relationship appears less consistent, affected by the increased sensitivity of the relationship of SVF with monthly direct irradiance to façade orientation and location's latitude, associated with the variations of solar altitude.

1. Introduction

Solar radiation is one of the renewable energy resources with the greatest potential as it is estimated that, upon certain conditions, it could contribute up to 27% of the global electricity production by 2050 (International Energy Agency, 2014). Unlike other renewable energy technologies, photovoltaic (PV) systems can be relatively easily implemented in the urban environment, integrated into new or existing buildings replacing conventional materials in roofs, walls and windows, or applied externally onto the building fabric (Peng et al., 2011).

Using building-integrated photovoltaics (BIPV) is an elegant way of generating electricity in a distributed manner (Pearce, 2002), exploiting otherwise unutilized surfaces instead of specifically devoting land (Mulcué-Nieto and Mora-López, 2015; Norton et al., 2011). In addition, BIPV produce electricity at the point of use limiting losses and other implications associated with transmission and distribution (Paatero and Lund, 2006). On-site energy generation is essential for achieving the "Zero Energy Buildings" target (Kanters and Horvat, 2012) and will be a requirement for all new buildings in the European Union after 2020 (EPBD, 2010). Furthermore, PVs located in urban areas are commonly grid-connected feeding all, or surplus electricity produced directly to an electricity network offsetting total urban demands (Mulcué-Nieto and Mora-López, 2014).

A major factor determining the solar electricity yield and economic feasibility of a PV system is the availability of solar radiation as determined by latitude and climate, as well as the placement and position of the PV module in the urban setting. Aiming to maximize solar access, roofs are preferable for the implementation of PVs compared to façades, as they allow more optimal placement (i.e. orientation and tilt, especially on flat roofs) and are usually less shaded. Correspondingly, an important number of studies on solar energy potential in urban environments focuses exclusively on roofs (e.g. Assouline et al., 2017; Bergamasco and Asinari, 2011; Mavromatidis et al., 2015; Hachem et al., 2012; Wiginton et al., 2010; Wittmann et al., 1997).

Nonetheless, with façades comprising the greatest part of urban buildings' surface, their solar irradiation represents a considerable percentage of cities' solar potential (Esclapés et al., 2014; Redweik et al., 2013) and their exploitation becomes critical for the attainment of energy efficiency targets at building and urban scales. According to a study for Lisbon, Portugal, the PV potential on façades and roofs can

* Corresponding author at: Kent School of Architecture, University of Kent, Marlowe Building, CT2 7NR Canterbury, United Kingdom.
E-mail address: C.Chatzipoulka@kent.ac.uk (C. Chatzipoulka).

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reach 50–70% of the areas' total electricity demand, with the contribution of façades being significant in the winter, as well as in the morning and afternoon hours during the summer (Brito et al., 2017). In countries at higher geographical latitudes, such as in Scandinavia, the role of façades in generating adequate amounts of electricity may be even more significant, provided that the urban design is optimized for preventing their overshadowing (Lobaccaro et al., 2017). At building scale, a study in Montreal, Canada, showed that PVs integrated in roofs and façades of residential buildings can produce up to 90% of the electricity demand of a four-story building, decreasing with increasing building height to 50% for twelve stories high (Hachem et al., 2014). Besides a large contribution to the annual solar energy potential, PVs integrated in the façades of a building in Spain resulted in a more stable production throughout the year compared to those on the flat rooftop (Sánchez and Izard, 2015). This is in line with another study examining monthly average yields of PV modules at various European locations, mounted at different angles, which ascertains that vertical ones present a more balanced seasonal profile (Šúri et al., 2007). As a result, it can be argued that adopting a wider range of recommended façade orientations for the installation of PVs ensures a more even distribution of electricity production in the day, especially at middle latitudes.

Façades are visible and fully functional parts of building envelopes providing daylight, natural ventilation and views through windows, which imposes restrictions on the application of BIPV systems. With PV technology advancing rapidly, a variety of quality products available nowadays achieve an increased architectural integration, aesthetically (e.g. variety of colours, levels of transparency) as well as functionally (e.g. rain-screen cladding, providing solar and glare protection). Further research and development of BIPV products are anticipated to play a key role in the establishment of façades as energy generators, particularly for of existing buildings (Jelle, 2015). For instance, the retrofitting of typical residential buildings in Italy by applying coloured PV panels on the façades as cladding material improved both their energy performance and appearance (Evola and Margani, 2016), while the PV potential in building façades replacing conventional shading devices with BIPV awnings or louvres was investigated for Greece (Karteris et al., 2014).

Forecasting solar irradiation of façades remains critical for ensuring the economic feasibility of PV applications and can be very challenging in urban areas, where façades' solar irradiation varies significantly due to the combined effect of orientation and degree of obstruction by nearby buildings (Yun and Steemers, 2009). In this context, information about annual solar irradiation or solar losses as a function of surface orientation and inclination (e.g. in Cronemberger et al. (2012) for Brazilian cities) is indicative but omits potentially significant shading losses. For the latter to be considered, annual solar simulations are required based on the actual 3D urban geometry.

Although the use and scope of solar modelling has increased, this is still mostly performed by researchers and specialist consultants. A study on the architectural barriers to spreading solar energy systems into the general building practice showed that only 2% of the architects were satisfied with the existing tools (Wall et al., 2012). Among the major challenges identified by the survey was the architects' poor skills of energy and solar simulation tools, as well as that the available tools being commonly perceived as complex, time-consuming or simply not suitable for the early design phase. Acknowledging the significance of considering BIPV early in the design process, a method which would address architects' need for a simpler and quicker evaluation of annual solar irradiation of building surfaces could strongly promote the solar energy production within cities.

This study examines to what extent solar irradiance on vertical façades can be predicted using solely two parameters, openness to the sky, as expressed by the sky view factor, and orientation. Past studies, employing statistical analysis, have shown a strong negative relationship between degree of sky obstruction, associated with built density and compactness, and façades' solar irradiation (Chatzipoulka et al., 2016; Mohajeri et al., 2016); however, their findings refer to average values over entire urban areas, neglecting the orientation parameter.

2. Background and objectives

Initially introduced by urban climatologists, the sky view factor (SVF) is a geometric measure that expresses openness of a point to the sky and thus, capability to emit and receive longwave radiation to and from the sky. It is calculated as a ratio with its value ranging from 0 to 1, denoting a totally obstructed and unobstructed point respectively. For vertical façades, the maximum value is 0.5 as an unobstructed façade can be seen only by half of the sky vault. In the literature, the SVF is equally considered as an urban geometry variable, for instance, investigating its relationship with spatial variations of urban air and surface temperatures (Eliasson, 1996; Giridharan et al., 2007), and as performance indicator evaluating environmentally built forms (Project PREcis, 2000; Ratti et al., 2003). With respect to façades, SVF values are strongly associated with illuminance levels and daylight availability (Cheng et al., 2006; Zhang et al., 2012), whereas, the relation between SVF and solar availability is less established (Robinson, 2006).

In the past, SVF measurements were feasible only in situ and at one point each time, using special equipment such as fish-eye cameras (Steyn, 1980). Nowadays, an increasing number of solar and thermal analysis models perform accurate SVF calculations as part of their simulations, over entire urban surfaces and at different spatial resolutions. Compared to solar irradiance simulations, the calculation of SVF is much faster and requires one input, the 3D urban geometry information.

This paper investigates extensively the relationship of SVF with solar irradiance by façade orientation, addressing different research objectives. First, it examines whether the SVF can be employed for estimating solar energy potential on building façades at different locations, i.e. combinations of latitude and climate. For this reason, solar irradiance simulations are performed for three locations in Europe, Athens, London and Helsinki, with special emphasis on the annual global irradiance results. Second, it provides graphical tools to architects working in the three cities for calculating annual global irradiation of a façade, or a section of it, based on its average SVF value and azimuth degree. Third, it broadens our understanding about the relationship between SVF and façade solar availability by examining separately the three solar components, i.e. direct, diffuse from the sky and reflected by buildings irradiances. Finally, the repetition of the analysis for a winter and summer month, January and July, aims to investigate the effect of varying solar altitude on the relationship of SVF with façades' solar irradiation, especially its direct component.

3. Methodology

3.1. Cases studies

The study is based on the analysis of 24 urban forms, of 500 × 500 m area each, which were selected from three areas of London: central, west and north areas (Fig. 1). These represent urban environments of different built density with the studied forms covering values from 3 to 22 m^3/m^2 (total built volume within the site over the site area). The criteria for their selection and the results from their geometric analysis are presented in Chatzipoulka et al. (2016). For the naming of the urban forms (as presented in Fig. 2) the letter denotes the area to which an urban form belongs (C, W, N for central, west, north areas, respectively), and the number derives from its position in the area's map (starting from top left corner and counting from top to bottom).

3.2. SVF and solar irradiance simulations

Solar simulations were performed in the PPF software, a powerful