Implementing an open-source tool for modelling solar PV potential in dense urban areas

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Abstract. Distributed PV has the potential for generating a significant proportion of many cities’ electricity needs. However, the number of installations in dense urban locations is still negligible. Unlike detached single-family homes in low-density neighbourhoods, where installation is relatively straight-forward and solar access is generally unobstructed, dense urban areas pose special challenges. The paper demonstrates application of a free, open-source tool to assess how building configurations affect insolation and hence PV installation potential on building envelopes (roofs and facades) in complex, irregular urban environments. A sensitivity analysis using generic building types in regular plans highlights differences in the PV potential of contrasting building typologies providing a similar number of dwellings for a prototypical 300x300m urban block with a population density equivalent to 25,000 persons/km².

1. Introduction
Photovoltaic (PV) systems are currently the only renewable energy technology which can be deployed effectively in residential environments as distributed systems in building-integrated elements. However, in most urban areas, a building’s envelope is shaded at least some of the time, primarily by adjacent buildings. Roof surfaces, which are generally the preferred location for PV panels, may face orientations that are not optimized for maximum energy production [1,2]; They may be too small to support a sufficiently large array, or the roof may be occupied by other infrastructure such as HVAC equipment or solar water heating panels [3]. Alternatively, PV panels may be installed on building facades [4], although these surfaces receive less insolation than rooftops even if the panels are not shaded by adjacent structures.

Urban typology affects access to sunlight and thus to building energy performance [5]. Various techniques have been employed to simulate building solar exposure: digital elevation models (DEM) [6]; ray tracing software in conjunction with Rhinoceros [7]; and spatial analysis software such as GRASS, ArcGIS and Autodesk [8-10]. Mohajeri et al [11] have demonstrated relationships between urban form and density. Incident solar radiation may also be estimated for individual buildings or small neighbourhoods by commercial building thermal analysis software [12].

Most of these methods were developed in a commercial or academic programming context. The present study demonstrates a free, open-source tool to assess how building configurations affect PV installation potential on building envelopes (roofs and facades) in complex, irregular urban environments. The paper presents a brief overview of the tool, a case study of a real urban neighbourhood, and a sensitivity analysis of several generic, very high density urban configurations.
2. Methodology
A method for temporal and spatial simulation of shadow patterns in the urban environment called ‘shadow’ was developed in R, an open-source language for statistical analysis [13]. The model was implemented in a case study of a neighbourhood in the city of Rishon Lezion, Israel (31.97N 34.79E), selected because it includes a wide variety of building types in a relatively small area with flat topography. This allowed direct comparison of the solar potential of different urban typologies. A parametric analysis was then performed for several generic building forms for a high-density scenario housing 25,000 persons/km².

2.1. Overview of the ‘shadow’ model
Model inputs are the azimuth and elevation of the sun, and the footprint and height of all objects, such as buildings, obtained from a GIS database. Using solar radiation data in a climate file from a weather station in the area, preferably a TMY, the model simulates the incident solar radiation at each grid point on all building surfaces at each (hourly) time step. First a test is performed to see whether the grid point is shadowed by an adjacent obstruction (to determine exposure to direct solar radiation); then the sky view factor is calculated (to determine the contribution of diffuse solar radiation). Solar radiation reflected from terrestrial surfaces is neglected. The temperature of the PV cell at each grid point is estimated using air temperature, wind speed, incident solar radiation and empirical transfer coefficients obtained by Faiman [14]. The temperature-dependent output of the PV cell at each grid point on all building surfaces can then be estimated using the rated panel efficiency. The density of the grid points may be defined by the user, considering the size of the area being simulated and available computer resources. The solar potential of different urban forms can be obtained by integrating model results over time for different building configurations. Visual representation at the desired resolution (e.g. 1m² grid) may be generated using ArcScene GIS 3D software, or any other software that can visualize a 3D point cloud.

2.2. Measures of urban density
The solar energy potential for BIPV may be compared per unit area of the envelope (facades and roof). Buildings with large roofs and/or facades, such as row houses and apartment blocks, will then have high average insolation scores. However, as energy consumption in residential buildings is typically evaluated on a per capita basis or per household, it may be useful to compare the offsetting production of electricity provided by PV systems in these terms, which allow a more useful comparison of different urban typologies. Urban density may thus be expressed in terms of population density (persons/km²), dwelling density (number of housing units per km²) or the ground space index, also referred to as the plan area density (ratio of building footprints to the total area of the site) – see Fig.1.

Figure 1. Measures of density in the Rishon Lezion case study neighbourhood, Israel.
2.3. Urban typologies
A parametric analysis of the solar potential of different (regular) urban typologies was performed for population densities of about 25,000 persons/km², assuming 3.5 occupants per 120 m² apartment. The scenarios included high-rise towers (16 and 24 floors), medium-rise blocks (8 floors), courtyard blocks (5 floors, large and small), linear blocks (4 floors) and compact 4-story ‘H-buildings’. The analysis was carried out for a 300x300m tile representing an urban block, surrounded by 8 identical tiles on all sides.

3. Results
3.1. Demonstration case study
The method was demonstrated on a dataset representing a large residential neighbourhood in Rishon-LeZion, Israel, which includes several contrasting building types. The images (Fig. 2), referring to four specific buildings from that neighbourhood, show fairly uniform insolation levels on roofs, but substantially lower and more varied insolation levels on building facades, due to self-shading, shading by adjacent buildings and the effect of orientation.

Figure 2. Annual insolation on complex building form, showing direct and diffuse components and their sum.

Figure 3. Distribution of the solar potential of façade integrated PV in the case study neighbourhood in Rishon Lezion.

In the case study neighbourhood, low-rise high-density typologies, such as row houses, apartment blocks and terraces, have the greatest overall solar potential (Fig. 4). The ‘realistic’ scenario accounts for windows, balconies etc., comprising some 20% of the façade, which are not unavailable for installation of PV panels. Row houses, which have the largest roof area per dwelling, also offer the largest solar potential considering the electricity generated per unit area of the site (Fig. 5).
Figure 4. Total insolation on different building types in Rishon Lezion neighbourhood. Left: façades only; right: facades and roof.

Figure 5. Total solar potential of hypothetical 1km² urban site with different building types with the same exposure as actual Rishon Lezion neighbourhood. Left: façades only; right: facades and roof.

3.2. Parametric study of urban typologies
The parametric study of the contrasting urban typologies was performed at hourly resolution for an entire year.

3.2.1. Total annual potential. For a population density of 25,000 inhabitants per km², the typology with the highest potential for generating electricity by building integrated photovoltaics was ‘small courtyard buildings’, about 18.8 million kWh/yr, of which 60.2% were generated on the roof. A neighbourhood consisting entirely of ‘tower blocks’ with the same overall number of apartments had the lowest potential, about 7.0 million kWh/yr, of which only 24.2% were generated on the roof.

3.2.2. Seasonal and diurnal variations. Simulation results highlight not only differences among typologies in the total output of BIPV arrays on roofs and facades, but also diurnal and hourly profiles for a winter month (January) and summer month (August) – see Figs. 6 and 7. In Israel’s Mediterranean climate, the variance in BIPV output during winter months is much larger than during summer. Some building types, such as tower blocks, also exhibit a characteristic double-hump output curve with two diurnal maxima (late morning and early afternoon).
4. Discussion
Comparing the solar PV electricity potential of different urban forms is of particular relevance in countries undergoing rapid urban expansion, such as much of the developing world, where the proportion of the population living in cities is still only 40-60%. Among developed countries, where some 90% of the population may already live in cities, Israel is somewhat of an outlier: due to rapid population growth, construction of urban neighbourhoods continues apace.

A second consideration shaping urban development in Israel is the relative scarcity of land. To preserve open space, whether for agriculture or as natural green space, Israel’s National Guideline Plan 35 specifies minimum building densities in new neighbourhoods, in terms of dwelling units per dunam of site area (1 dunam = 1,000m²). The required density makes it very hard to achieve guaranteed solar access for all buildings, despite the country’s relatively low latitude (29-32°N) and high solar elevation. Dense construction is not, however, unique to Israel. High density is not only a feature of city-states
such as Hong Kong and Singapore, but is also regarded as a means of promoting walkability and efficient public transportation all over the world.

The holy grail of modern energy-efficient construction is ‘zero-energy buildings’, which produce all of the energy required for their operation and habitation. Clearly, there is a limit to the dwelling density that can be supported, which is determined by the annual insolation, the conversion efficiency of the PV systems and the energy requirements of each family. The role of urban planners and architects is not just to maximize the utilization of solar energy for electricity generation, but also to optimize the allocation of sunlight for daylighting, passive space heating and provision of hot water. This requires comprehensive studies analysing all of these end uses in an integrated manner.

5. Conclusion
Where land prices are high and new urban construction is geared towards high density, the solar potential of each building type may be a key indicator of sustainability. Our results can be used to estimate solar potential given different construction densities in the different parts of the neighbourhood.

The detailed output available by this method may be applied by power utilities to model the effects of large-scale distributed electricity production by BIPV in future urban development scenarios, for any given urban density.

Acknowledgement
The study was funded by the Israel Ministry of National Infrastructures, Energy and Water Resources of Israel under research grant no. 021-11-215.

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