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Impact of Urban Street Network on BIPV Generation Capacity of Buildings

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Abstract. Climate change necessitates a critical reconsideration of the built environment since buildings are among the top fossil fuel consumers. Solar energy generation through building integrated photovoltaic (BIPV) systems is one of the most common onsite energy generation methods. However, many factors regarding urban morphology can negatively affect BIPV generation. Urban block typologies and spatial patterns are commonly studied descriptive metrics of an urban morphology that affect the solar energy potential. Similarly, the street network pattern is a measure of the spatial quality of an urban environment. Although various urban morphology indicators have been extensively studied in relation to solar energy potential, a comparative analysis of urban fabric focusing on street network patterns is also needed. In this study, four representative urban areas with different morphological characteristics are studied. The selected morphologies are parametrically modelled and compared with different building height configurations. A comparative analysis of BIPV generation capacity per square meter façade or roof area is presented. Urban areas without a dominating street network pattern have resulted in greater PV generation on facades, whereas the impact of urban morphology was found negligible for roof PV potential. The findings of this research have the potential to aid in urban planning and architectural design decisions, as well as the efficient use of BIPV systems in diverse urban morphologies.

1. Introduction

Cities consume close to 70% of the energy worldwide, where buildings alone account for about 36% of the energy used [1] and 40% of global carbon emissions [2]. In addition, the world population might reach 11 billion by 2050, with the majority of the additional population residing in cities, bringing the total urban population to 6.5 billion [3]. An increase in the urban population implies a growing energy demand due to varying needs brought by modernization and change in comfort conditions where most energy is of fossil fuel origin. These statistics imply the necessity of energy-efficient buildings in cities to lower the environmental impact of buildings.

The onsite energy generated from renewable energy resources in the building sector has been vital to eliminating the dependency on fossil fuels to meet building energy demand. Solar, wind, geothermal, and biomass energies are commonly considered for building applications. Among the many other options, solar energy has become a key renewable resource for electricity generation worldwide since it is readily available and abundant [4]. From being the major shareholder of global energy use, buildings have the potential to generate the energy they demand due to the high potential for harvesting solar energy from their envelopes.

Passive solar design strategies and active solar energy technologies have been developed and involved in design development to benefit from the sun. Initially, buildings were designed to attain the direct use of solar energy by adjusting their location, geometry, building components, and materials. Deliberate decisions on site selection, placement, form, and orientation with a thoughtful arrangement of windows and choice of building materials lead to absorption and storage of solar heat and improvement in the daylighting benefit [5]. In recent decades, not only the passive design strategies but also the involvement of technology has encouraged the performance-based architectural design strategies for efficient utilization of solar energy. From small residential units to large commercial buildings, PV systems have started being considered during the early design processes [6]. Since the integration of solar technologies through PV into buildings represent an essential branch of approaches for reducing dependency on fossil fuels, solar systems are recommended to be applied or even become an obligation in some cases where new buildings are designed in European Union countries [7]. Due to climate change, onsite energy generation from BIPV gains more importance due to the shift in building energy loads [8].

Increasing urbanization and growing energy demands in cities make buildings in urban contexts the primary target for integrating PV systems. On the other hand, urban contexts can alter the energy yield of BIPV systems through overshading, hence requiring consideration of urban design parameters for solar building design. Numerous earlier research has been conducted to establish a link between urban morphology and solar potential. In this respect, a recent review aimed to outline key metrics and their formulation principles for solar performance metrics for urban planning [9]. In the past decades, researchers focused on the relationship between urban block typology [10,11], street canyons [12], and urban density [13]. Additionally, new metrics are proposed in addition to existing urban morphology indicators [14]. With the involvement of machine intelligence in urban form-solar potential studies, researchers have pointed out the importance of street network patterns as a metric of assessment for urban morphology [15]. Although many aspects of urban morphology have been thoroughly examined for solar energy potential assessment, the impact of street network patterns on solar energy potential remains unaddressed and should be explored in detail.

This study aims to make a contribution to the knowledge of the impact of urban morphology on solar energy generation capacity by tackling the research opportunities and shortcomings described so far. After an introduction to recent studies focusing on the relationship between urban morphology and solar energy, the impact of the street network pattern will be explored with a parametric modelling approach.

2. Background and related work

Urban morphology indicators have been identified as significant drivers of BIPV potential in recent literature (Figure 1). 10 most recent articles (published between 2019-2022), which focus on solar energy potential and urban form, are investigated [10,11,13,16–22]. Overall, the examined parameters are grouped into building, context, and sky categories. Parameters relating to building geometry, such as building typology, block area, block orientation, window to wall ratio (WWR), shape factor, and compacity, have been investigated most frequently based on the examined studies. On the other hand, parameters that expose the urban settings' interaction with the sky, namely, sky view factor (SVF) and sky exposure factor (SEF), received the least research interest according to the selected studies.

Urban form, revealing the impact of context and neighboring buildings, has been a critical parameter for solar potential. From dispersed to compact neighborhoods, researchers have found that energy production capacity decreases from 94% to 79% for roofs and 20% to 3% for facades [23]. A recent study examined ten urban morphology parameters by conducting a correlation analysis with roof and facade irradiance [18]. Researchers have found that SVF, a measurement of "the fraction of the overlying hemisphere occupied by sky" [24], correlates significantly with solar irradiation. Researchers have also identified the urban morphology indicators that lower solar energy potential. A recent study has shown that a simple parameter, building height, decreases the solar energy potential of the surrounding buildings by 15% [21]. Similarly, Natanian et al. reported that a higher floor area ratio and lower distance between buildings negatively affect PV production [19].

Street geometry has also attracted research interest in urban morphology and solar energy potential studies. Mohajeri et al. [12] studied 1600 street canyons in terms of orientation, width, length, SVF, and asymmetric aspect ratio. The received yearly solar radiation by street surfaces and facades is strongly influenced by street orientation. Researchers have found that for surfaces, the most radiation is received from roadways aligned with WNE-ESE, whereas the highest radiation is obtained from facades facing SSW. Another study has conducted sensitivity analysis between nine parameters; shape factor, floor area ratio, plot ratio (the ratio of floor area to plot area), aspect ratio (the ratio of building height to the width of the distance between buildings), verticality, the distance between buildings, and building width, height, depth [25]. Implying the importance of street networks, the results revealed that the aspect ratio and distance between buildings substantially affect solar energy potential. In addition, street networks have also been indirectly involved in studies for the solar potential assessment. Researchers have considered street network density when selecting the size of the studied urban area [14].

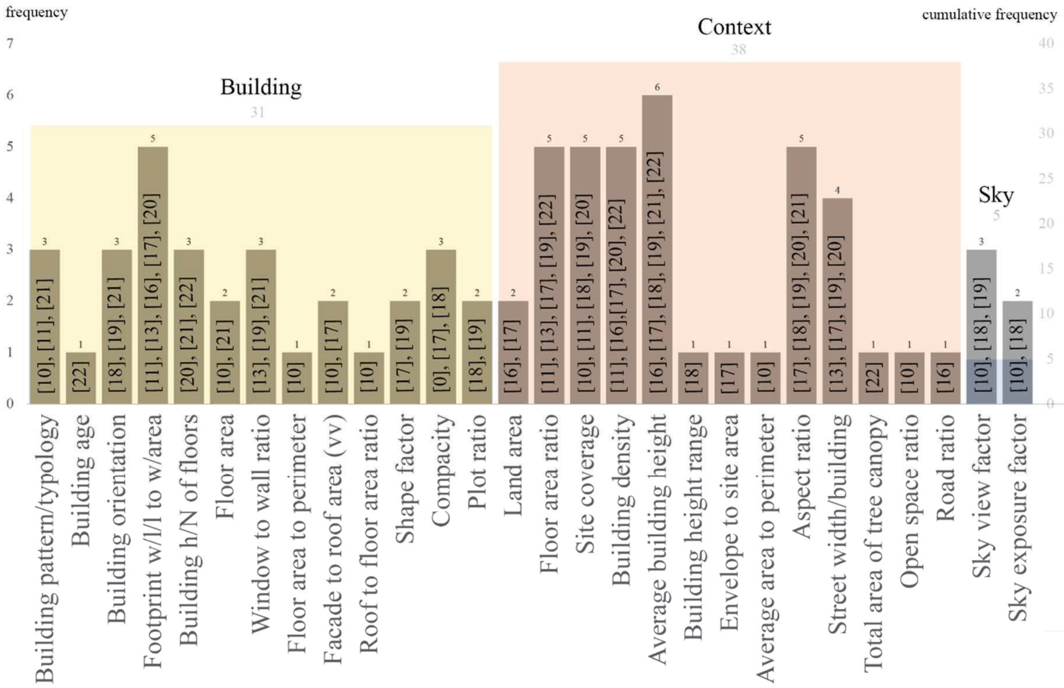


Figure 1. Frequency of studied urban morphology parameters in 10 publications (between 2019 and 2022).

Street width, building density, plot ratio, and building interval parameters are also related to the street network pattern of an urban area. Street network pattern distinguishes itself from other urban morphology parameters focusing on various details of roads, such as width, aspect ratio, intersection density, or orientation, since it involves the visual and intuitive perspective of humans [15]. Four street network patterns have been frequently observed in cities and described in the literature as gridiron, organic, radial, and no pattern [26]. The gridiron pattern can be characterized by the streets crossing each other perpendicularly, while in the radial pattern, roads direct movement to a central point. Urban areas with organic patterns can be identified with streets in the form of curved polylines, designating the natural growth of the paths and roadways in the city. On the other hand, no pattern regions are urban areas that cannot be represented using the previously established patterns. Biljecki et al. proposed a method based on deep learning for visually classifying road networks into these four distinct categories [14]. Researchers have studied nine cities worldwide to uncover underlying patterns in their road networks through clustering with a classification accuracy of 87.5% and aimed to explore its relation with urban viability. In solar energy potential studies, most of the recent research focusing on urban morphology considered urban areas with simplified gridiron plans [13,18–20]. However, this might result in biased results preventing generalizable conclusions about the impact of urban contexts.

Although street networks have been partially considered in solar energy potential studies, to the authors' knowledge, street network patterns and their impact on solar potential have not been studied thoroughly yet. Therefore, this study aims to explore energy generation capacity from PV through roof and façade surfaces for four street network patterns. For this purpose, four urban areas representing different network patterns are parametrically modelled with three building height options. BIPV generation potential of the urban areas is compared based on power generated by the façade or roof area based on the PV application area.

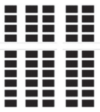
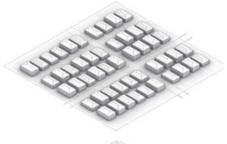
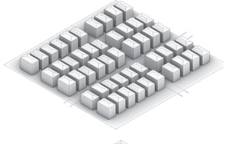
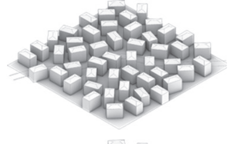
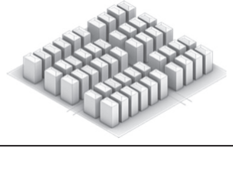
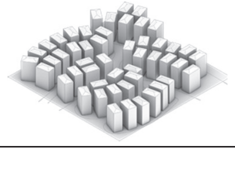
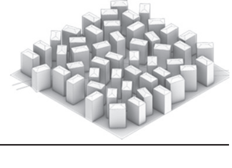
3. Methodology

This chapter presents the methodology proposed to estimate rooftop and façade (exterior wall) BIPV potential for four different urban areas with different morphologic characteristics. Initially, selected urban morphologies are parametrically modelled using Rhino Grasshopper parametric modelling interface [27]. BIPV generation from roof and façade surfaces for the modelled urban areas is calculated with the PVWatts software [28], implemented inside the Ladybug Tools [29] add-on for Grasshopper.

3.1. 3D Modelling of Representative Urban Areas

Four representative street network categories are modelled as synthetic urban areas (Table 1) in reference to a recent study investigating the classification of road network patterns [15]. Each urban area was sampled with a 250 × 250 m^2 land area. Forty-five identical buildings with a footprint area of 15 × 40 m^2 are located in each sample. WWR of 0.25 is set to the building facades. Only wall surfaces of facades are considered for solar energy generation. Pitched roof geometry is generated over the building volumes. Inclined roof surfaces are considered for roof BIPV generation.

Table 1. Studied street network patterns and building height options.

	 Gridiron	 Organic	 Radial	 No pattern
Low-rise (2-3 floors)				
Middle-rise (6-7 floors)				
High-rise (12-13 floors)				

While building density (building footprint /land area) is kept constant for each street network pattern, building configurations vary considerably on the designed land area. In addition to different street network patterns, three building height classifications, low-rise, middle-rise, and high-rise, are examined. The floor height for each building in different scenarios was set to 3 m. Synthetic urban areas are assumed to be located in Ankara, Turkey. According to the Köppen climate classification scheme, Ankara has a hot-summer Mediterranean climate (Csa), with hot and dry summers and rainy and chilly winters.

3.2. Annual PV Generation

PVWatts is a software offering an online calculation tool developed by the National Renewable Energy Laboratory (NREL) of the US Department of Energy [28]. It takes two types of inputs; field and advanced. Field inputs include system size (DC output in kW), module type (PV technology), system losses (PV efficiency in %), array type (e.g., fixed roof mount, fixed open track, etc.), tilt angle (degrees), and azimuth angle (degrees). Advanced inputs are DC/AC ratio, inverter efficiency, and ground coverage ratio as user-defined inputs [28]. For the empirical BIPV performance estimation, first, weather files specific to a location are utilized. The parameters obtained from the weather files for PV generation calculations are beam and diffuse irradiance, ambient temperature, and wind speed at 10 m height. PVWatts is also implemented in Ladybug Tools, an environmental design software connecting computer-aided-design interfaces, and is available for use during the design development phase [29]. Therefore, it is a suitable BIPV performance estimation model for an urban form study and was implemented in the further stages of this study.

Shading from neighbor buildings is taken into account in simulations for BIPV potential. A shading factor is calculated for each hour of the year with neighbor buildings in close proximity. Hourly derating factors are obtained with the "Sunpath Shading" component of Ladybug tools. Although BIPV potential can be quickly estimated without shading analysis, computational cost increases with the inclusion of shading geometries. Computational cost is highly correlated with the number of surfaces that shade the analyzed surface. Therefore, the limitation of the analysis region is critical for each building. For low-rise configuration, buildings inside a circle centering the analyzed PV surface and having a 48 m diameter are included in shading factor calculations as context geometries (Figure 2). The same method is used for mid-rise and high-rise buildings with diameters of 64 and 96 meters, respectively.

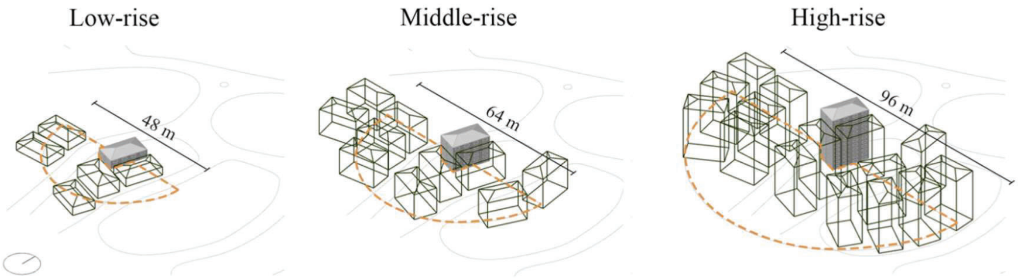

Low-rise
Middle-rise
High-rise

Figure 2. Definition of shading region based on building height.

The computational cost of modeling each BIPV module precisely while considering the shading factor is high in district-scale assessments. Therefore, the whole façade and roof surfaces are assumed to be covered with BIPV modules. These surfaces are the smallest units for estimation. 70% of the roof surfaces and %90 of opaque façade surfaces are assumed to be available for BIPV deployment. In order to increase the accuracy of results, a number of points on the BIPV surfaces are included in shading and efficiency estimations. The average shading factor of each point is used for BIPV generation estimation for the analyzed roof or façade surface. BIPV generation is calculated for building envelopes installed with open-rack rooftop PV panels. For façade surfaces, the tilt angle is assumed to be the same as the vertical wall surfaces. Similarly, roof surfaces are covered with BIPV panels aligned with the tilt angle of each roof surface. Module parameters are set based on a commercial monocrystalline solar module provider (Table 2) [30].

Table 2. Solar module parameters [30].

Parameters (m)	Value
Module efficiency, η_{PV}	20.08%
Temperature coefficient	-0.40%/°C
DC to AC derate factor	0.85

4. Results

Four street network patterns, gridiron, organic, radial, and no pattern are modelled with three uniform building height configurations. The energy generation capacity of modelled urban areas is calculated in the city of Ankara with a Warm-summer Mediterranean climate. Unit area BIPV generation (kWh/m^2) for each network pattern was selected as the comparison metric. Total BIPV generation from façade surfaces was divided by the total façade area, including all four orientations of building geometry. Total generation from the surfaces of a pitched roof is divided by the total area of roof surfaces. Overall, facade BIPV generation capacity per roof area (Mean=143.698, Std Dev=0.743) is greater than the roof BIPV generation capacity per façade area (Mean=43.650, Std Dev=9.606).

4.1. Facade PV Generation

An increase in the building height for densely built homogenous urban environments resulted in a decline in unit area BIPV generation (Figure 3). This result can be related to the impact of shading, which increases with building height. The highest unit area generation capacity is observed in the low-rise urban areas for all four street network patterns where shading from neighbor buildings is minimal. In addition, urban areas with no pattern street network category outperform all evaluated building height options. Irregular building intervals and a wide range of facade orientations observed in no pattern areas might result in an extended insolation period.

4.2. Rooftop PV Generation

Contrary to the façade generation, BIPV generation per roof area was largely unaffected by the change in building heights (Figure 4). The BIPV generation capacities are observed to be very similar in evaluated building height options. The surfaces with no shading define the upper threshold of the roof BIPV generation. Therefore, the maximum generation is determined by the same upper limit in all tested floor height options and street network patterns. Since the tested urban areas have homogenous building heights, the shading effect is very limited. Due to the negligible shading effect, a narrow range of BIPV generation is observed for roof surfaces.

5. Discussion and Conclusion

This study aims to compare the BIPV generation capacity of four street network patterns with three building height configurations in a city with a warm-summer Mediterranean climate. Total energy generation from the façade and pitched roof surfaces were calculated and normalized with the gross application area for the comparisons. BIPV generation from roof surfaces was almost three times greater than the facades, which is a common finding in the literature since most rooftops receive greater solar irradiation than facades. Street networks with no pattern have offered higher BIPV generation capacity per PV deployment area for facades. However, the impact of street network patterns and building heights has been negligible for BIPV generation from roof surfaces. Since this study examined uniform urban areas with similar building heights, the influence of shading on roofs was minimal.

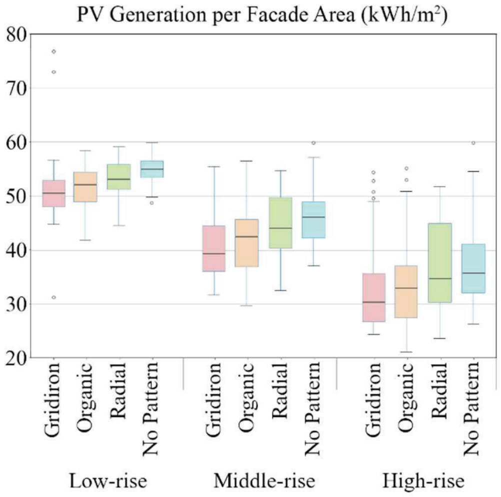


Figure 3. Facade PV generation (kWh/m^2).

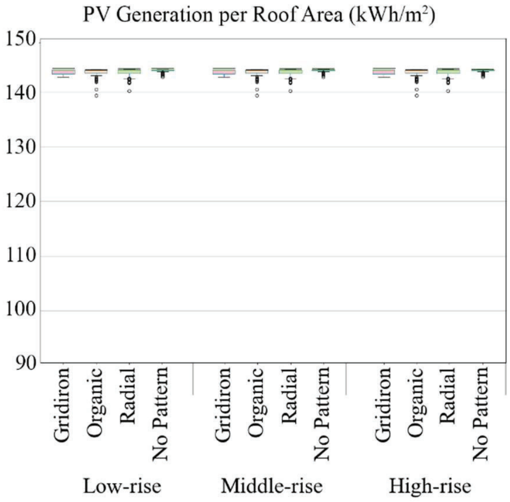


Figure 4. Roof PV generation (kWh/m^2).

The results of this study can be validated further by testing the described street network patterns in different orientations within the city fabric. The observed high energy generation potential of the no pattern street networks for facades could be challenged with a study design considering multiple orientations of streets. The impact of urban morphology on rooftop BIPV potential might also be observed with mixed building height options. The impact of street network patterns on solar energy potential in existing built environments can be explored in future work.

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