A feasibility study for Bremen's PV self-sufficiency on heating consumption – a demo in an old Bremen district

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Introduction

In November 2022, The Bremen state has adopted a climate adaptation goal for achieving climate neutral in 2038. Such target would require a substantial transformation of its energy systems towards renewable sources such as solar energy. The installation of rooftop photovoltaic (PV) panels for individual households established a promising decentralized solution for domestic energy generation, on top of saving energy costs for individual households (Joint Research Centre, 2024; Wirth, 2025). However, the feasibility of achieving household electricity self-sufficiency through PV installations remain an open question for the Bremen city. This study proposed a district-scale analysis to evaluate the technical potential of rooftop PV installations in Bremen for compensating the heating consumptions in household units. Using Old Bremen Houses as a signature for the residential buildings in the Bremen City, this study focused on a number of districts with high density of typical Bremen Houses. By combining the building geometry in FreeCAD with solar irradiance calculation via PVGIS (PVGIS, 2025), this study estimates the electricity generation by PV panels and compares it against the current consumption patterns. The study additionally conducts a parameter test to identify the key factors that govern the feasibility of PV contribution to the zero-emission goal. The findings will provide evidence-based insights into the potential of household PV installations for achieving Bremens' climate neutrality goals.

Method

This study implemented an integrative approach to couple outputs from geometrical modules (in FreeCAD) with geographical information system (GIS) tools to analyze the feasibility of PV contribution by single households based on the building rooftop area. Integrated approach that couples geometrical features with urban built environment has been increasingly implemented for sustainability assessment (e.g., Tauscher & Wong, 2022). The approach for this study comprises of a few steps: data preparation, FreeCAD operations, solar irradiance values from PVGIS, and heating consumption of Bremen city. The codes used for data preparation, calculation, and visualization are shown in a workflow notebook (Appendix I).

Data preparation

For this study, data from Open Street Map was used to obtain building footprint. Six old residential districts were selected: Ostertor, Steintor, Fesenfeld, Östliche Vorstadt, Huisberg, and Peterswerder (Figure 1). These areas are characterized by a high density of Old Bremen Houses, a typical singled-household structure with 2-3 storeys and equipped with an underground storage (around half a level below the ground, known commonly as souterrain) and a backyard at the same level. These houses usually neighbour closely or pack with each other along the street (Figure 1). They do not have a standard height but ranges between 8 and 12 m. For this study, a height of 10 m was assumed for all buildings. Due to the size of the areas, it needed two separate osm files to be exported. These files were combined based on the latitude and longitude coordinates of each node. Duplicated nodes were excluded. Only objects (called 'way' in osm) tagged with 'building' and registered with a house number were considered. Geometric polygons were created and exported as dxf.

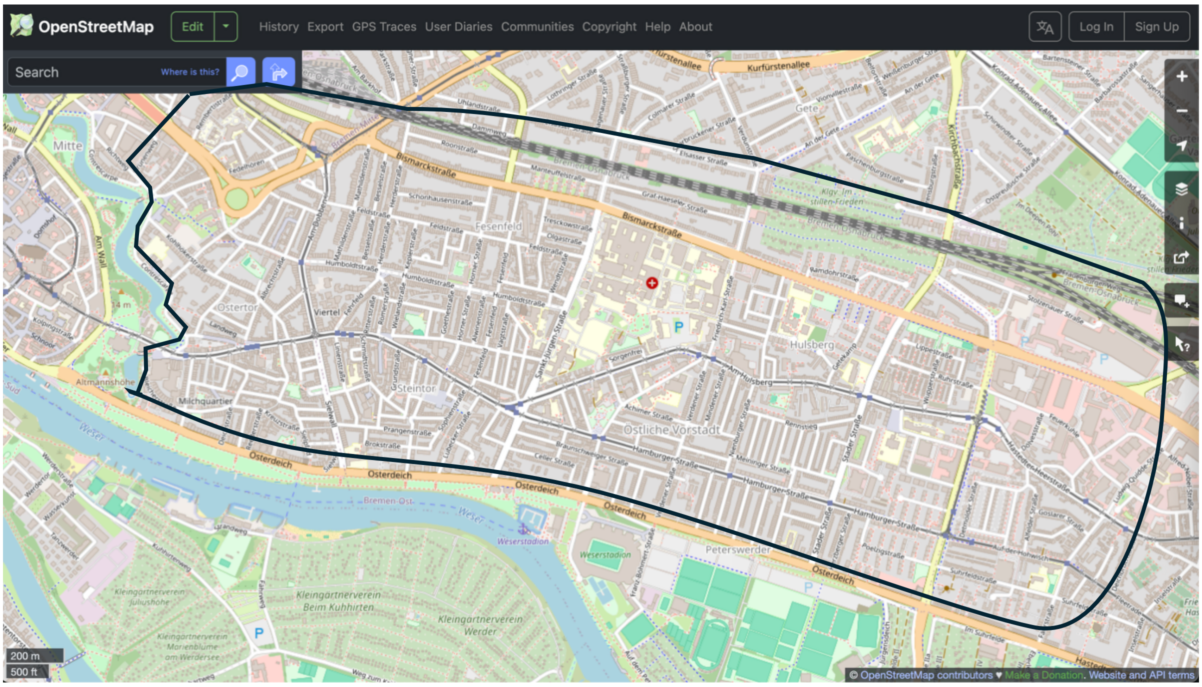

Figure 1 Open Street Map showing the selected area for analysis of this study (dark line).

FreeCAD operations

The imported dxf file contained a total of 9456 polygons. Data clean-up was conducted to exclude small objects that are small community garden structures in the north and south (across the river) of the map. The screening, done via visual inspection, was followed by identifying non-residential structures like supermarket (Rewe), schools, cultural facilities (museums), industrial services (Bauhaus, Deutsche Telekom) and public services (hospital, fire station). Eventually, 9333 polygon household buildings remained and were extruded to a height of 10m (Figure 3). The rooftop area of each building was calculated in FreeCAD.

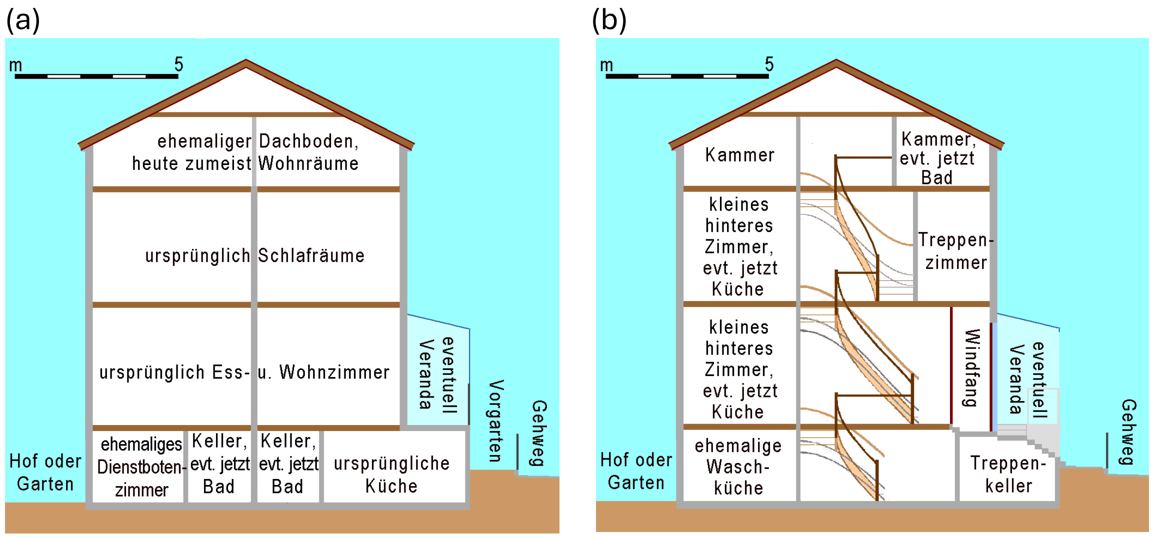

Figure 2 A simple illustration on the building design of typical Old Bremen Houses from side view (a) and (b). The building height was approximated as 10 meters. Source: https://de.wikipedia.org/wiki/Bremer_Haus

Solar irradiance values from PVGIS

PVGIS is a web-based, open-access API tool developed by the European Commission to estimate worldwide (except North and South Poles) PV generation potentials based on the information of solar radiation and PV system performance. The performance computation is specific to a grid-connected PV system and is location-based, with a built-in horizon data, and the solar radiation is based on a typical meteorological year (*PVGIS*, 2025). Since the solar irradiance values provided in PVGIS (Version 5.3) do not vary within the selected area, this study adopted one standard set of PV generation data for all buildings. The output was based on the specific parameterizations on the PV products and installation (Table 1). An area loss for installation of 25% due to, for example, architectural irregularities, product size and technical limitations was considered in the analysis. Other default setting for this study includes: 1.) An elevation at 10m; 2.) default solar radiation database PVGIS-SARAH3 (Satellite data at 5km resolution, time spanned across 2005-2023); 3.) PV technology for Crystalline Silicon wafer ; and 4.) Mounting position at rooftop. The standard set of parametrizations used for describing PV performance is listed in Table 1 and detailed in the information sheets in Appendix II.

Table 1 The standard parameter values for describing PV performance.

Installed peak PV power [kWp][i]	System loss (%)[ii]	Mounting slope[°]	Azimuth[°][iii]
0.25 per m^2	14	25	0

[i] Calculated as *area * efficiency / 100* (as per PVGIS manual). A cell efficiency of ca. 25% per 1cm^2 in laboratory condition was suggested by Fraunhofer Institute for Solar Energy System (Fraunhofer ISE, 2024). kWp stands for kilowatt peak and describes the maximum output a specific system can produce. For Germany, a PV system generates around 1,000 kilowatts of electricity per kWp per year. A common range of kWp for monocrystalline solar panel is 0.22-0.30 kWp per m^2 (Source: Tritec Energy, https://www.tritec-energy.com/en/guidebook/kwp-kwh-pv-key-figures/)
[ii] PVGIS default value for all overall losses.
[iii] the angle of the PV modules relative to the direction due South

Parameters explorations

Due to a number of simplifications in this study, some parameters on the PV performance were assumed. To better understand their effects on the PV generation, the parameters for mounting slope and azimuth were additionally examined with, respectively, ±100% (50°, 0°) and 45° (facing south-west), 90° (facing west). The values between 45 and -45 were relatively similar throughout the year (±) so they were not explored. The changes in parameter value were examined based on the standard set of parameters. Exploring these parameter values are meaningful for understanding to what extent the roof slope and roof direction can impact the potential rooftop PV energy generation.

Table 2 Parameter configurations for test cases

Test cases	Mounting slope[°]	Azimuth[°]
25_0_m	25	0
50_0_m	50	0
0_0_m	0	0
25_45_m	25	45
25_90_m	25	90

Heating consumption of Bremen city

Based on a report on households' energy consumption for heating (Behr et al., 2024), Bremen's average consumption in kWh per square meter of heated living space for the year 2021, 2022, and 2023 were, respectively, 140.37, 132.12, and 125.84. A three-year mean of 132.7 kWh km^{-2} was used for comparison with the PV generation.

Results

Standard configuration

Based on the geometrical calculations in FreeCAD (Figure 3), the rooftop area from a total of 9295 residential buildings (i.e., Bremen houses) is 0.95km^2. Based on the energy values exported from PVGIS (Figure S2), the total maximum annual output of PV modules per square meter is 236 kWh m^{-2} (Figure S3). Under the assumption of installation area loss (25%), the total usable rooftop area is 0.72km^2. Lastly, the maximum total energy generation based on the standard configuration is 168.9 kWh km^{-2} (Figure 4). Due to year-to-year fluctuations in solar conditions, standard deivation estimates were provided by PVGIS and shown as the error bars in Figure 4. Given the three-year mean of heating consumption of 132.7 kWh km^{-2}, the standard configuration showed a positive balance of 36.2 kWh km^{-2} rooftop PV panel installation for the Bremen city. The result suggested that, assuming an identical configuration on the PV panel installation across the evaluated areas, the Bremen household is likely capable to sustain their heat consumption by rooftop photovoltaic installation.

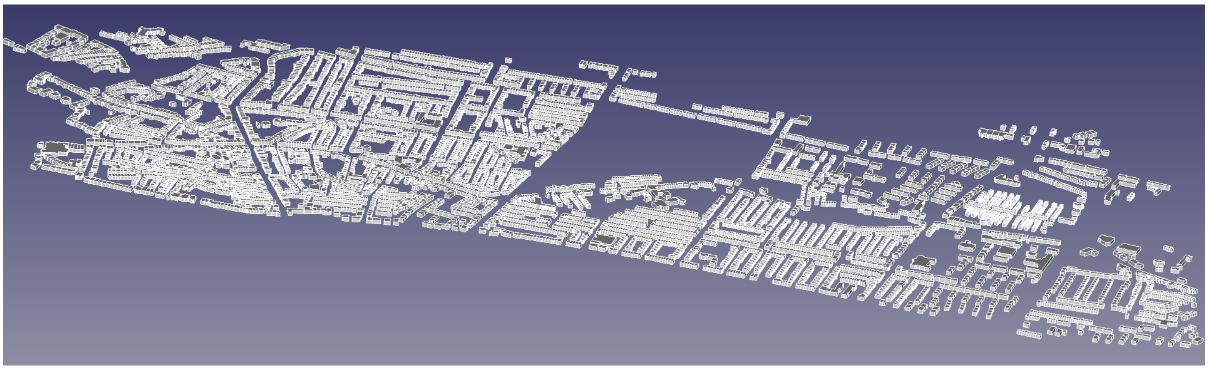

Figure 3 A bird view on the extruded buildings in the model. The blank area at the center is a hospital in Bremen (Klinikum Bremen Mitte) excluded from the study.

Parameter test cases

This study also investigated the effects of mounting slope and azimuth on the PV generation based on several sets of parameters (Table 2). The results on the maximum production capacity of the PV panel showed that a flat-mounted PV panel (0_0_m) has lower total annual PV generation than tilted panels (25_0_m and 50_0_m). A horizontally-mounted panel produced 144.7 kWh km^{-2} annually, almost 25 kWh km^{-2} less than that from tilted panels, which produced close to 170 kWh km^{-2} (Figure 4). Given a default mounting slope of 25 degree, the PV panel facing south-west (25_45_m) can produce at least 15 kWh km^{-2} more energy than that facing south (25_0_m) and west (25_90_m). The one with the lowest production is the tilting 25-degree and facing west panel, generating 139.3 kWh km^{-2} annually (Figure 4). While all the test cases cover the average heating consumption of 132.7 kWh km^{-2}, when considering year-to-year fluctuations (error bars, Figure 4), the annual production from the test cases would not, or only closely, compensate the heating consumption sufficiently. In sum, the parameter exploration showed the importance of the mounting slope and azimuth and the margins for achieving self-sufficiency on heating consumption.

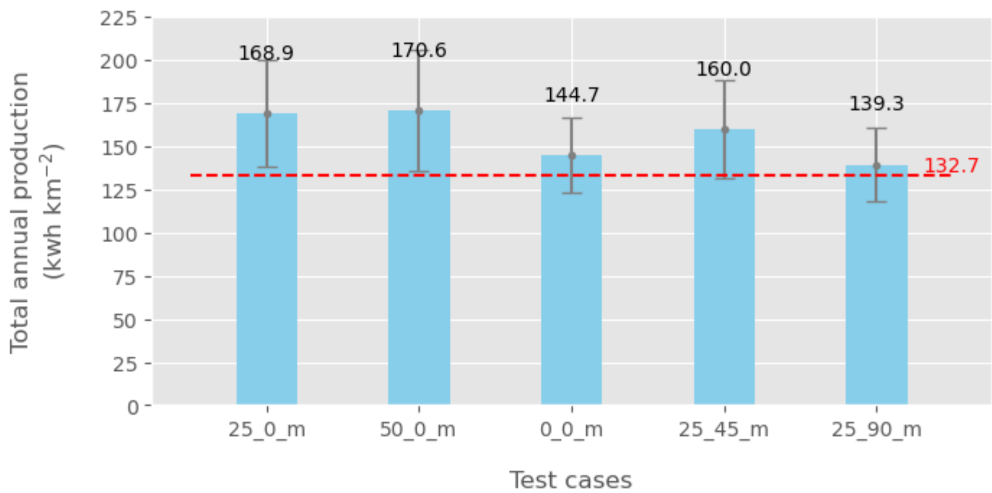

Figure 4 The comparison between energy production and heating consumption in terms of kilowatt hour per square kilometer for different test cases. 25_0_m is the default case. Error bars

indicate the standard deviation of the monthly energy generation due to year-to-year variations. The values are provided by PVGIS. The red stripped line represents the 3-year averaged heating consumption in Bremen city i.e., 132.7 kWh km^{-2} (Behr et al., 2024).

A consideration for maximum heating demand

The above showed energy generation and demand per kilometers. It is important to consider the heating areas to estimate the total heating demand. Assuming all budlings are 3 story and 20% of the building footprints are wall or structures that are excluded from heating consumptions, the total annual heating consumed is 302.6 kWh. Without specifying any consumption patterns, the PV production evaluated in this study, in all test cases, is not sufficient to cover the demand (Figure 5). The demand approximately doubles the amount producible by the PV panels.

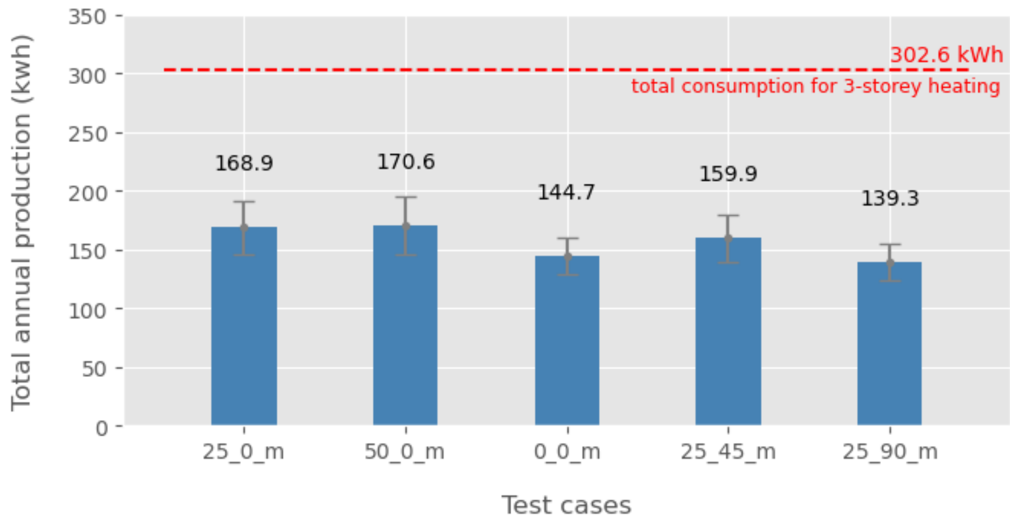

Figure 5 Total annual energy production per kilowatt hour across different test cases versus total consumption in the case where all buildings (3-storey) are in maximum heating demands. Error bars indicate the standard deviation of the monthly energy generation due to year-to-year variations. The standard deviation values are provided by PVGIS.

Discussion

The results suggested a low possibility for Bremen's household achieving complete self-sufficiency on heating consumption by rooftop PV system, assuming a standard configuration implemented for all selected buildings in this study. Notably, this result represented a first-order approximation and depended on multiple assumptions and idealizations. First, for simplification, the study omitted architectural and structural details like the specific height and roof shapes. In reality, roof shapes determine not only the installable areas for PV panels but also the mounting slope of the panel (Mohajeri et al., 2016). In the parameter test, the slope of the PV panel determined the annual PV output. Second, the angle of houses to the sun (i.e., Azimuth) was not calibrated. Such calibration is crucial for evaluating annual and seasonal PV generation and for matching individual households' consumption patterns based on a more refined temporal and spatial scale. Lastly, the screening of building was done manually by visual inspection. Some registered buildings might not function completely as a residential housing (e.g., private clinics). This likely overestimated the usable rooftop areas in this study. A more comprehensive geographical data that involves specific labeling on the building type can facilitate a more systematic and effective data screening.

The results from parameter testing showed that both the mounting angle and orientation of the PV panel can vary annual energy production. The parametrization of both factors is important to achieve an optimized configuration, in agreement with a number of case studies on PV installations (Ebhota & Tabakov, 2025; Wirth, 2025). Apart from system and module specifications, additional factors can affect PV output like the variabilities in solar irradiance, the ambient temperature and humidity, the atmospheric conditions, and extreme climatic events (Dewi et al., 2019; Bamisile et al., 2025). Scenario analyses on these factors shall be included into considerations for a more comprehensive evaluation on the PV self-sufficiency among Bremen household. To conclude, this is a preliminary study focusing on Bremen houses in 6 old residential districts. While heating consumption constitutes a major fraction of domestic energy demand, household energy consumption contributes only to a small fraction to the energy demand of the Bremen city (Statistisches Landesamt Bremen, 2025). To address the ambitious goal of energy neutrality, PV energy generation shall be considered in other sectors than single households. In Bremen, a large fraction of area attributed also to industries and manufacturing where PV installations are of huge potential.

Conclusion

This feasibility study presented a preliminary investigation on the potential of photovoltaic installations in Bremen houses for supporting their own heating consumption. Methodologically, this study also demonstrated an integrative approach to couple outputs from geometrical features to analyze real-world problems. Essentially, this study offers a first-order approximation for future fine-tuning and assessment in deeper and wider aspects. That includes to investigate based on finer architectural configurations and building footprints like a specific height and room types, on more realistic scenarios and consumption patterns for the household that consider, for example, an energy system with battery storage (e.g., Galvin, 2022), and to conduct energy cost analysis or life cycle impact assessment for rooftop PV system installation. With proper data, tools and computational power, this approximation can also scale up to the city level as a valuable overview for policy- and decision-making purposes. Lastly, the success of carbon neutrality for Bremen will require widening the understanding and participation to independent sources of renewable energy generation from different parties.

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AI Usage Disclosure: The data processing codes (osm2def.py) for this project was created with assistance from AI tools. The code has been reviewed and edited by the author.

Supplementary Figures

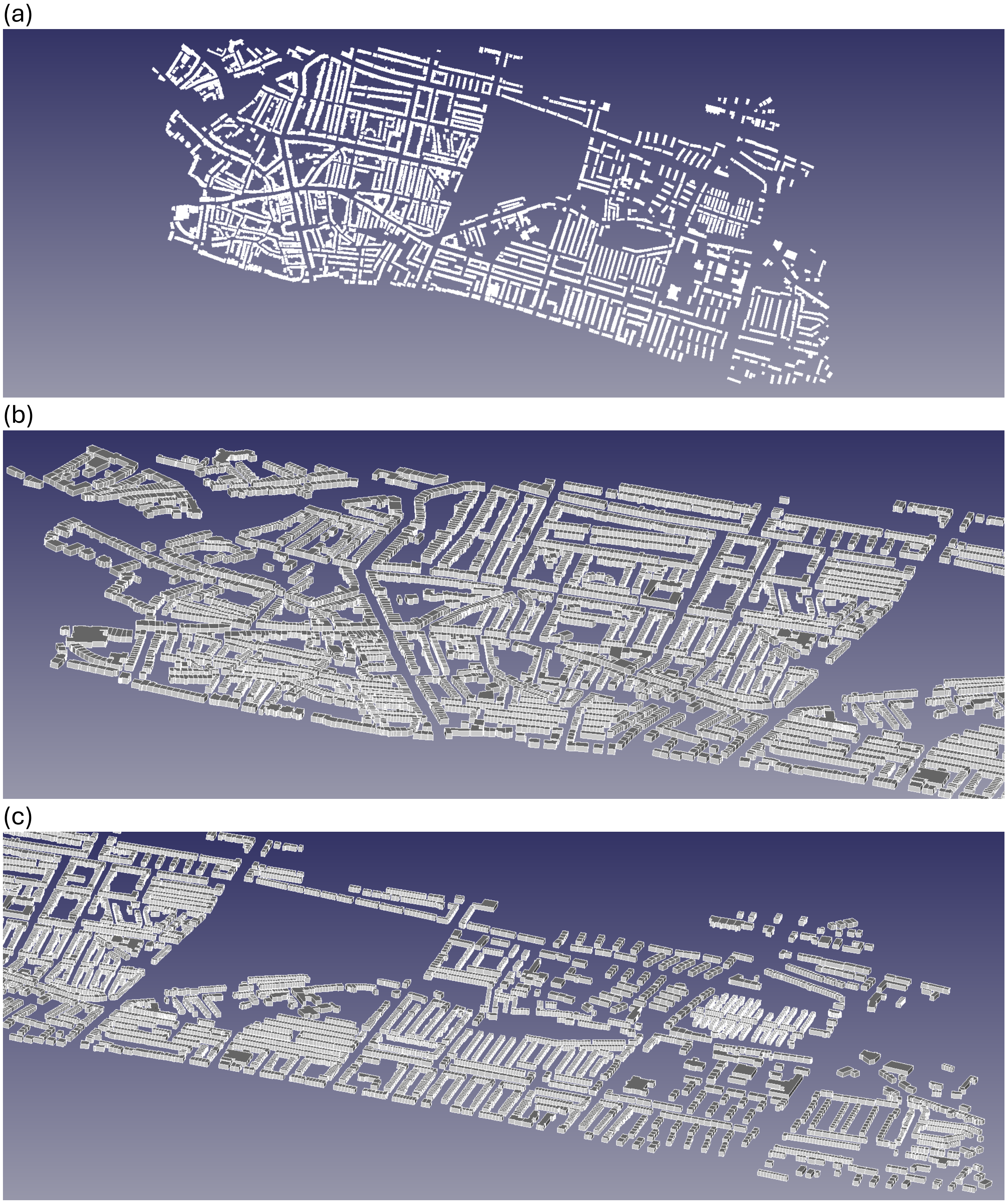

Figure S1 Different aspects on the 3D model of the selected areas in this study. (a) top-view; (b) bird-view on the western part; and (c) bird-view on the eastern part. All buildings were extruded to 10 meters.

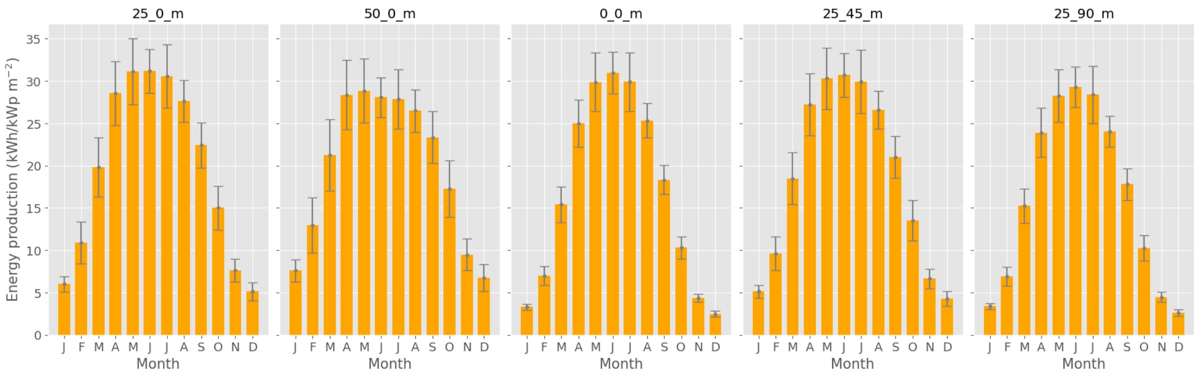

Figure S2 The annual distribution of energy production across different test cases. Different mounting and orientation configurations result in peak production in different months. These configurations differ more strongly mainly during spring and autumn months. Error bars indicate the standard deviation of the monthly energy generation due to year-to-year variations. The standard deviation values are provided by PVGIS.

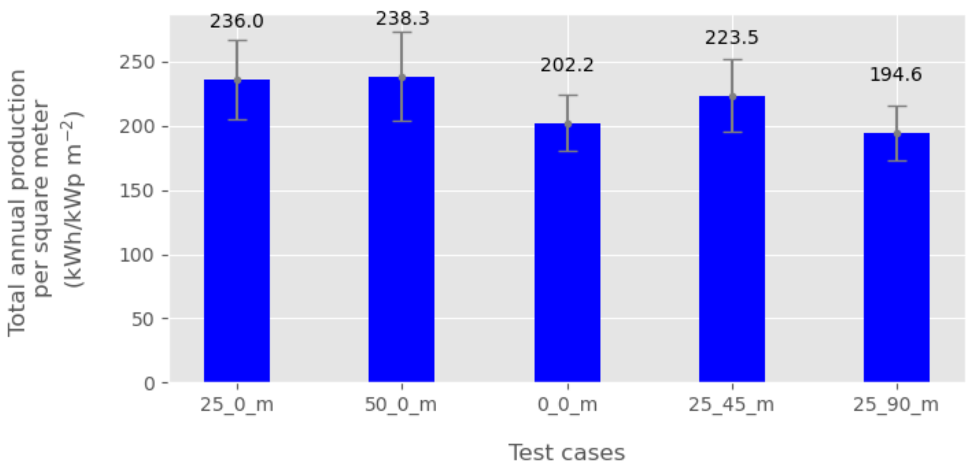

Figure S3 Total annual energy production per kilowatt peak per square meter across different test cases. Error bars indicate the standard deviation of the monthly energy generation due to year-to-year variations. The standard deviation values are provided by PVGIS.

Appendix I – A Jupyter Notebook outlining the workflow for data preparation, calculation, and visualization (in attachments: "Workflow.ipynb")

Appendix II – the generated reports from PVGIS for the five test cases