Harnessing the Sunlight on Facades – an Approach for Determining Vertical Photovoltaic Potential

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Abstract

The paper deals with the calculation of the photovoltaic potential of vertical structures. Photovoltaic systems are a core technology for producing renewable energy. As roughly 50% of the population on planet Earth lives in urban environments, the production of renewable energy in urban contexts is of particular interest. As several papers have elaborated on the photovoltaic potential of roofs, this paper focuses on vertical structures. Hence, we present a methodology to extract facades suitable for photovoltaic installation, calculate their southness and percentage of shaded areas. The approach is successfully tested, based on a dataset located in the city of Graz, Styria (Austria). The results show the wall structures of each building, the respective shadow depth, and their score based on a multi-criteria analysis that represents the suitability for the installation of a photovoltaic system.

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1 Introduction

Renewable energy resources are crucial for sustainable development and mitigating the impact of climate change to achieve carbon neutrality. Solar energy is the largest inexhaustible source of clean energy in the world [12]. Solar photovoltaic (PV) systems play a vital role in harnessing solar energy and account for 10% of the world's electricity in the year 2022 [13].

The utilization of solar energy requires the assessment of the solar energy potential that quantifies the physically available solar radiation on the earth's surface [1]. Of special interest is the assessment of solar energy potential in urban environments, as almost 50% of the world's population currently lives in urban areas. Buildings are key structures in urban settings and understanding their solar potential is essential for the optimal utilization of solar

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energy in urban environments. Aside from rooftop [6] or ground mounted [8] PVs, there is an emerging interest in the solar potential of vertical structures (vertical PV) in recent years [4, 11]. Building facades provide additional space for the installation of PV systems that can complement the PVs installed on rooftops increasing the solar potential by 10-15% [2].

However, the assessment of the solar potential of building facades at a large scale (e.g. city level) is a challenging task. Most of the current solutions use complex radiation and shadow computation models that are computationally intensive and are not scalable from a few buildings to city level [2]. So, one of the major challenges for the assessment of vertical PV potential is the reasonable computational time [12]. Thus, computing the solar potential of building facades in urban areas needs to address the following challenges:

1. *Extraction of Facades*: Facades are vertical surfaces that show discontinuities in elevation models. Extracting vertical surfaces (facades) from elevation models is a complicated task. In addition, all facades of a building will not receive the same amount of solar radiation.
2. *Shadow Analysis*: Mutual shadowing due to the surrounding environment (other neighboring buildings, trees, etc) will reduce the solar radiation and this temporally varies.

In this paper, we address the aforementioned challenges by providing a novel approach for the assessment of vertical PV potential. The solution is computationally viable as it uses simple radiation and shadow computation models. The work takes the following simplifications and assumptions. (1) Only direct sunlight is considered for the radiation model. (2) We only consider facades with a minimum height of 3m and an area over $50m^2$.

This paper has the following major contributions. (1) It presents a novel approach for the assessment of the PV potential of building facades that uses an efficient technique for shadow computation without using sky maps. (2) It provides an analysis of the important features for the vertical PV including southness, shading, height and width of building facades.

The remaining sections of the paper are organized as follows. In section 2 we provide an overview of existing approaches for assessing PV potential. Section 3 explains our proposed approach. In section 4 we demonstrate our approach on a small dataset. Finally, section 5 concludes this paper with a discussion of the contributions and an outlook of future work.

2 Related work

It is possible to estimate PV potential with statistical data, as [7] did on a country level (Austria) by describing the feasible potential of facades including physical/theoretical, technical, economic, and ecological/social limitations. However, approaches on a building level are more precise, but require a spatial data basis such as light detection and ranging (LiDAR) [4, 10], CityGML [14], aerial photogrammetry [9], or cadastral data where 2D to 3D objects can be extracted. E.g., a combination of LiDAR data, 2D, and 2.5D cadastral data was used by Desthieux et al. [4] to analyze the PV potential on rooftops and facades.

To handle the third dimension, shadow casting and solar radiation modeling were applied to 3D hyper-points covering the facade areas grid-like. Similar point-cloud-based methods were used in [11, 10], by calculating the sky view factor values for each point of a facade. The density of the points determines the accuracy and computational costs. Our approach uses 3D building data for vertical PV estimation too but it avoids computationally demanding point-cloud-based methods. This makes it applicable to large areas. We also introduce the southness indicator for building facades which was not addressed by literature yet.

3 Methodology

The approach proposed in this paper determines the PV potential of vertical surfaces (e.g. buildings facades). The developed workflow uses a raster containing shadow depth information to determine the PV potential of vertical structures (e.g. buildings). The shadow depth describes the height of a shadow cast by surrounding structures (e.g. trees, etc.).

The developed approach consists of six major steps. (1) Split into segments, (2) orientate geometries, (3) compute southness, (4) compute the wall area, (5) map shadow raster to wall segments and (6) the multi-criteria-analysis (MCA).

In more detail this means (1) we split buildings into wall segments and (2) orientate their geometries to ensure the outside of the building is to the left of the wall. (3) We then use this orientation to determine the southness of the wall segments, which is a value derived from the geographic direction that the outside of the wall segments is facing (see Section 3.2). (4) Based on the height and the length of the wall segments, their areas are derived. (5) To determine the shadowed area of the facade we map the shadow depth raster to vertical walls. This is done by computing the mean shadow depth in front of the wall segment (see Section 3.3). Consequently, the sun area of the facade is calculated by subtracting the shadowed area from the overall facade area. We also derive the percentage of the wall that is shadowed or non-shadowed from these values. Finally, (6) the PV potential of the walls is determined with an MCA. Scores and weights are assigned to the attributes *percentage of sun area*, *normalized southness indicator*, and *facade area* (see Section 3.4).

3.1 Preparation of vertical structures

Calculating vertical PV potential for a high quantity of buildings over large datasets can be computationally demanding and can be simplified by applying additional measures to the buildings. Firstly, instead of analyzing individual buildings, they can be dissolved into larger blocks. We propose a weighted average height for the dissolved building blocks. The weight is derived from the ratio of the area of the individual building to the total area of the block.

Secondly, once the buildings are dissolved into larger blocks they can be simplified further with line simplification algorithms such as the Douglas-Peucker algorithm [5]. This algorithm simplifies lines by excluding points based on a distance threshold.

3.2 Southness of the facades

One of the most important features that determines how much sunlight exposure a facade will get is its orientation. The facade facing south is likely to receive more sunlight than the one facing north, while facades facing east and west are expected to fall in between. To capture and quantify this feature, we have come up with a normalized southness indicator that ranges from 0 for north-facing facades to 1 for south-facing facades and graduates equally between them regardless if the facade is facing east or west. Firstly, the azimuth of the facade is reduced to a value between 0°and 180°, and this value is then normalized. The reduction process differs depending on the azimuth and the exact formulae are shown in Table 1.

3.3 Mapping 2D-shadow raster to vertical walls

One step of assessing the potential of vertical areas is gaining information on the area covered by shadow. We map a 2D-Shadow-Raster to the wall segments by (1) buffering the outside of the walls, (2) intersecting the buffered wall with the shadow-raster and (3) deriving the mean shadow depth in front of the wall from the mean of the intersecting pixel values. The mean shadow depth is a negative value thus it is inversed to receive the mean shadow height.

Table 1 Calculation of the normalized southness indicator depending on the azimuth of the line.

Azimuth [α]	$\alpha < 90°$	$90° \leq \alpha < 180°$	$180° \leq \alpha < 270°$	$270° \leq \alpha < 360°$
Reduced Azimuth [α_r]	$90° - \alpha$	$\alpha - 90°$	$\alpha - 90°$	$180° - (\alpha - 270°)$
Southness Indicator			$\alpha_r/180°$	

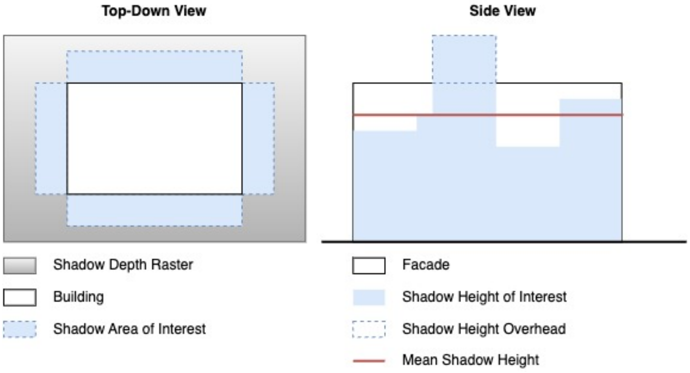

Figure 1 The top-down view shows the buffers in front of the walls that mark the shadow area of interest. The side view shows the different shadow heights in front of the facade covering up the facade area. To compute the mean shadow height, the shadow height must be reduced to the facade height to avoid shadow overhead.

We compute the shadow depth raster with an adjusted version of the QGIS Terrain shading plugin [3]. It uses the vertical angle and the horizontal angle (azimuth) of the sun to compute the shadow depth over the elevation model. We use an average shadow depth raster built from 12 rasters which represent 4 different days of the year with 3 times around noon for each day.

Figure 1 shows the problem at hand from two perspectives. To avoid a false mean shadow height we reduce the intersected height values to the wall's height. Without this, the shadow height overhead can cause mean shadow height to exceed the wall height. By multiplying the mean shadow height with the length of the facade, the shadowed area is determined.

The wall buffer which is meant to capture the area in front of the building can intersect with the roof of the building itself or nearby treetops, leading to false shadow depth values. This is solved by filtering false shadow depth values with a threshold as they are considerably lower than the correct shadow depth values due to the height of these structures.

3.4 Multi-Criteria-Analysis

We derive the attributes that play a key role in the assessment of the PV potential of vertical structures by interviewing stakeholders and experts. Aside from binary filtering attributes like a *minimum height* or a *minimum area*, we determine the *percentage of sun area*, the *normalized southness indicator*, and the *total area* as properties for the assessment of the PV potential. With the *percentage of sun area* being the non-shadowed part of the facade area.

For the MCA it is required to assign the same score range to each property. Further, the three properties *percentage of sun area*, *normalized southness indicator* and *total facade area* are assigned weights based on their importance. This importance is gained from the knowledge of stakeholders and experts. The sum of all weights must be 1. By multiplying the weights with the assigned scores and building the sum of the weighted scores a total score is obtained that describes the PV potential of the vertical structure.

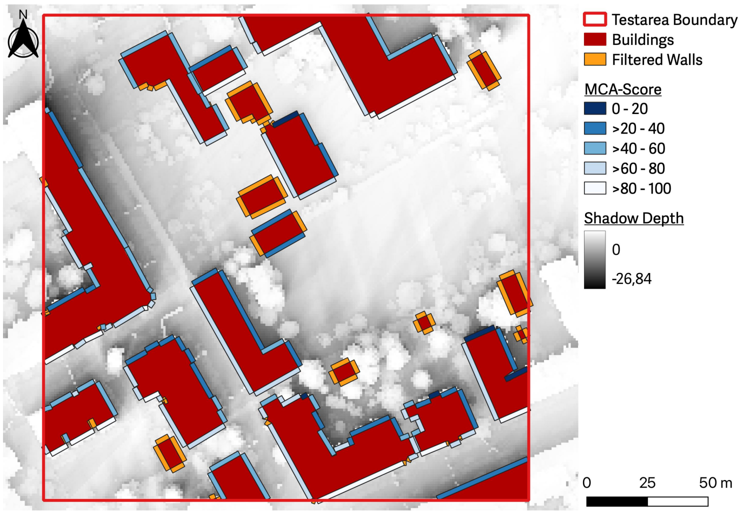

Figure 2 The 200m by 200m test area consisting of 217 walls of which 117 walls are suitable for PVs depending on their MCA score.

Table 2 The number of walls and the mean of the MCA attributes, as well as the mean total score by direction.

	Count	Mean Southness Indicator	Mean Sun Area Percentage (%)	Mean Total Score
North	35	0.16	43	39.76
West/East	40	0.43	47	48.19
South	42	0.79	74	73.82

4 Experiment

We test the proposed approach on a set of buildings in Graz, Styria (Austria). The test area is selected based on the even distribution of north, east/west and south facing faccades (see 2). It has a size of $200m \times 200m$. It consists of 63 buildings, which we split into 217 walls. Of these walls, we determine 117 walls suitable for PVs based on the binary attributes. These are a minimum height of 3m and a minimum facade area of 50m^2 . By applying weights to the scores of the three properties we receive an overall PV suitability score ranging from 0 - 100. The used weights are 0.7 for *percentage of sun area*, 0.2 for *normalized southness indicator*, and 0.1 for *total facade area*.

Figure 2 visualizes the result for the test area. It shows the walls filtered by the binary attributes and the ones suited for PVs colored by their MCA score. It is visible that southward-facing walls tend to have a higher suitability score, than the ones facing northwards or east/west. A look at table 2 supports this. With an average total score of 73.82 southern walls tend to have the highest suitability, while northern walls have the lowest with 39.76. One aspect of interest is that the average percentage of the non-shadowed areas between north-facing walls and east-/west-facing walls only differs by 4%. As expected south-facing walls have the highest percentage of sun-covered area with a value of 74%.

5 Discussion and Outlook

In this paper, we present a novel approach for determining the PV potential of vertical surfaces. Further, we discuss the necessary pre-processing steps for the building data at hand. We highlight the normalized southness indicator as an attribute of assessing the PV potential of vertical surfaces. Additionally, we discuss our approach for determining the shadowed / non-shadowed area of vertical surfaces. The normalized southness indicator as well as the percentage of non-shadowed surface area play a vital role in multi-criteria-analysis of the PV potential of the vertical surfaces.

The key contributions of this paper are (1) the approach of assessing the PV potential of vertical surfaces, (2) the analysis of the relevant measures and indicators for vertical PV potential such as southness, shading, height and width of the facades. Further, (3) the findings may support the energy transition by finding potential facades for renewable energy production, and (4) it enables stakeholders and administration to make informed decisions concerning vertical PV areas which is of particular interest in urban contexts.

Future research aspects consist of evaluating the performance of the proposed approach by comparing it to existing methodologies. Further, it could be extended with additional attributes such as window surface area.

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