Target-based visibility assessment on building envelopes: Applications to PV and cultural-heritage values

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Abstract

Solar energy applications have, in recent years, become a common element in the urban landscape, especially on roofs and facades. However, it is important that the integration of solar energy in the built environment do not distort the fabric or expression of the existing building envelope, not at least in areas of high cultural-heritage values. The aesthetics depend, to a large extent, on how visible the new technology, such as photovoltaic (PV) panels, is. This paper describes a method for visibility assessment of building envelopes. It is referred to as target-based as it, in contrast to previously reported methods, bases the assessment from the perspective of the building envelope itself, rather than possible vantage points on the ground. The method was evaluated for two Swedish cities; Stockholm and Visby. In Stockholm, each building was evaluated based on its cultural-heritage values, solar irradiation and visibility. Deploying PV only on the roofs with the lowest cultural-heritage values, with insolation >900 kWh/m^2, and with no visibility from ground, results in a total PV yield of up to 2% of the total electricity demand. In Visby, various definitions of the vantage area were evaluated, from which the building envelope can be seen. It was found that the choice of vantage area greatly impacts the solar energy potential. If the vantage area is defined by the public domain, i.e., streets and other public open spaces, the non-visible roof area doubles compared to if all ground/terrain defines it. Compared to previous studies, the use of a vantage area, instead of discrete vantage points, seems to result in higher visibility of the roofs.

Keywords: Visibility assessment, Photovoltaics, Building preservation

1. Introduction

As solar energy applications, especially photovoltaics (PV), have become an attractive alternative to conventional power supply in recent years, solar panels are becoming an increasingly common element in the urban landscape. For historic buildings the installations may have a strong impact on visual appearance not only of the single building but of the whole district (see Figure 1).

The historic building stock is a non-renewable cultural and material resource for which we must find ways to reduce energy demand and greenhouse gas emissions without unacceptable effects on the heritage values (CEN, 2017).

A sustainable use and preservation of historic buildings requires broad and long term compromises between social, economic and environmental aspects. The decision context is multi-disciplinary and involves both qualitative and quantitative analysis (Broström and Svahnström, 2011). The present paper is part of the development of a method to determine the solar energy potential in historical districts given three constraints:

1. shading,
2. visibility,
3. cultural-heritage values.

This is an iterative process where the effects of different thresholds in all three stages must be investigated.

Solar panels may have a physical impact on the historic building fabric, such as damage of his-

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Figure 1: Photo montage of roof-mounted PV panels in Visby, Sweden. PV panels may have a strong impact on the visual appearance of historic buildings and districts.

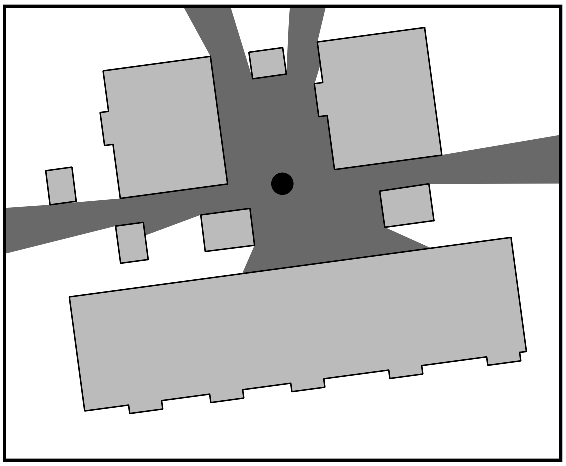


Figure 2: Illustration of an isovist, defined by the visible area from a vantage point (black marker). Rework of the property map from the Swedish Land Survey (2018).

toric roofs, i.e., some *documentary values* are lost (Swedish National Heritage Board, 1998). But the main controversy related to installing solar panels is the effect on the architectonic and aesthetic expression of the buildings, i.e., the *experience values* (Swedish National Heritage Board, 1998). Thus the estimation of visibility is crucial in planning and decision making.

Hence, an important aspect, that mainly impacts the experience values, is to what extent a solar energy application is visible for people residing nearby. It may be acceptable, as long as the visibility is low, the integration with the present architecture is high and there is no risk of damaging or distorting the building material of the building envelope (Munari Probst and Roecker, 2015).

Some attention has been given in the literature to find tools or methods that can help in decision making when considering solar energy applications on buildings with high cultural-heritage values (Munari Probst and Roecker, 2015; Munari Probst, 2012; Munari Probst and Roecker, 2007; Florio, 2018). This paper mainly focuses on assessing the visibility of potential solar energy applications. Florio (2018) gives, in his thesis, an excellent review on the current literature on visibility assessment with emphasis on renewable energy technology. He concludes that the visibility can be assessed by (i) inquiring experts, (ii) the general public, or (iii) by spatial modelling. Similar to this study, he focuses his thesis on the latter, but with a different approach than here.

As soon will be explained, the method proposed in this paper differs from the visibility assessment methods previously reported in literature. The vast majority bases the analysis from the perspective of the vantage point or the actual observer (see chapter 3 of Florio (2018) for a thorough review). Thus, these kind of methods can be categorised as observer-based methods.

One common concept used by observer-based methods is the isovist, illustrated in Figure 2. It is defined as the area in the urban landscape, which is visible from a specific vantage point (Tandy, 1967). If considering the isovist for multiple vantage points (red dots in Figure 3), one will achieve a measure of the number of times an isovist touches a certain building. This is referred to as the *cumulative isovist* and could be understood as the number of locations that a building is seen from (Llobera, 2003). Since roof-tops and facades are of interest for solar energy applications, it is natural to extend the isovist to 3D, which spans a volume in the urban landscape (Morello and Ratti, 2009).

Bartie et al. (2010) focuse, to some extent, more on the target as it evaluates the visibility of a specific feature of interest (FOI), e.g., a characteristic architectonic element of a building. They evaluate the *visual exposure* of the FOI based on five criteria; field of view, perceived visible area, distance from observer, clearness index and skyline ratio. However, the analytic method itself in Bartie et al. (2010) is yet, in accordance with the majority of the literature, based on the vantage point and can thus be classified as an observer-based method.

In this paper, a methodology for visibility assessment is presented that is based on the point-of-view

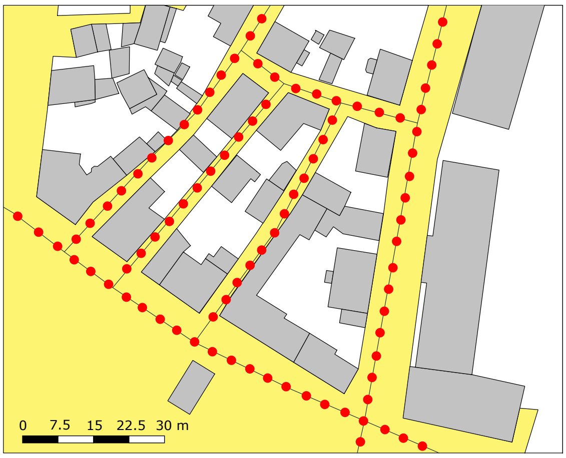


Figure 3: Example of vantage point samples (red dots) along a street network from OpenStreetMap. The yellow area represents the public domain, defined by the Property Map from the Swedish Land Survey (2018).

of the building envelope, i.e., what is visible from the location of a potential solar energy application, either applied to or integrated in the building envelope. This is hereafter referred to as the *target-based* method.

The paper is structured as follows. Section 2 describes the proposed method and two case studies on which the method has been applied. Section 3 presents the results from the case studies and in Section 4 the implications of the results are discussed. Section 5 gives some conclusions and an outlook.

2. Methodology

In this chapter, the methodology of the study is presented. After a brief overview of the methodology, the data used in the study is presented in Section 2.1. In Section 2.2 the proposed methodology for visibility assessment is described in detail, and in Section 2.3 the two cases studies for Stockholm and Visby, Sweden, are presented, in which the methodology was evaluated.

The target-based approach is a development from the method reported in Lingfors et al. (2017), in which viewshed analysis is performed on a vectorised building model to determine the impact of shading on the total insolation onto the building envelope. Here, the viewshed analysis is extended below the horizon (see Figure 4c). Hence, below the horizon only the visibility is assessed, while above it, both the shading and visibility are assessed simultaneously for a set of azimuth and elevation angles (see Figures 4a and 4b, respectively).

The visibility assessment also requires that the type of object that lies closest the roof under evaluation, in a given direction, is determined (Figure 5b), while for the shading assessment this is not important (assuming trees to be opaque) (Lingfors et al., 2017). If the closest object represents ground the building can be seen from here, while if it is a tree one may assume the building is not visible in this direction. Additionally, the distance or the angle-of-incidence (AOI) to the object may be of interest, as these will impact the visual perception (see Figures 5d and 5c, respectively).

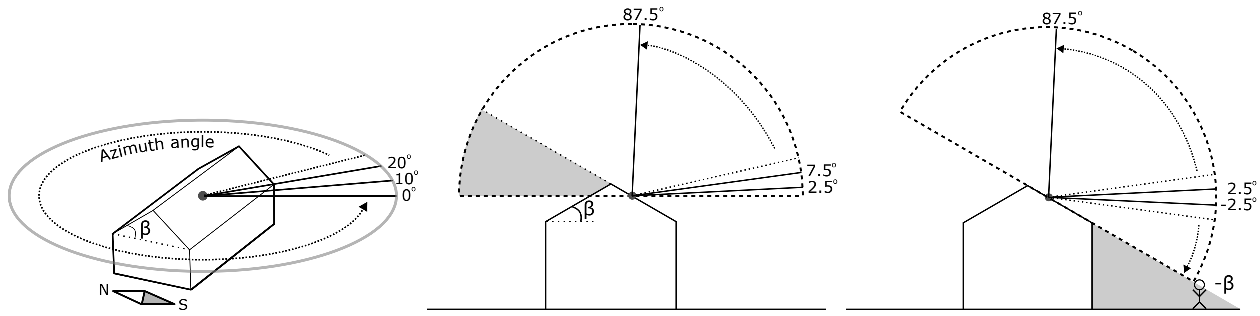
Moreover, to save computational power, only building surfaces that theoretically would be interesting for solar energy applications could be considered, i.e., those with such favourable orientation that, if unshaded, would have a solar irradiance that will make a solar energy application economically viable. This filtering would preferably be done before the joint shading and visibility assessment. The methodology can therefore be summarised as follows:

1. Import existing or create new building models following the method of Lingfors et al. (2017).
2. List buildings that have roofs with an economically viable orientation, assuming no shading.
3. From this list compute the solar exposure, now considering shading, and the visibility (optionally including the distance and AOI) of these buildings simultaneously.
4. Eliminate buildings:
   - of non-viable solar exposure, or
   - that have such cultural-heritage values that the visual impact would be deemed unacceptable.

2.1. Data requirements

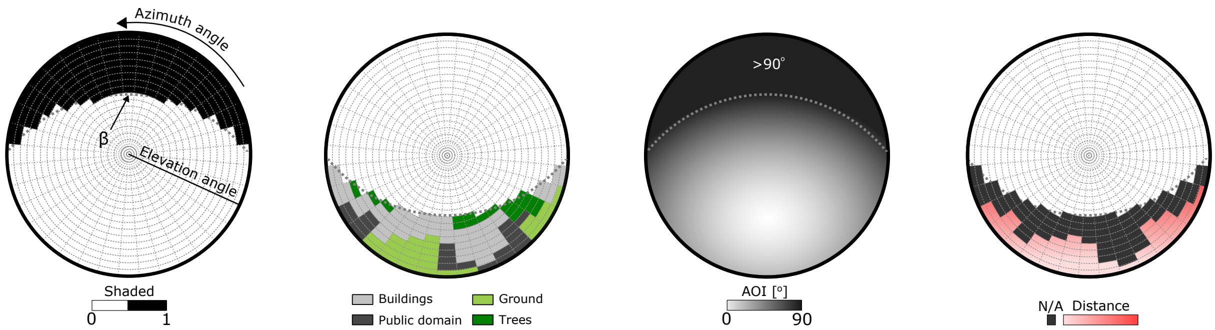
Building footprints were taken from the "GSD-Property Map", provided by the Swedish Land Survey (2018), to define the location and shape of buildings. From the same map, the property borders were used to define the public domain of one of the evaluated case cities, Visby.

LiDAR data were also provided by the Swedish Land Survey (2015). The data set covers the whole Sweden and is therefore of lower resolution (0.5-1 pts/m^2) than most LiDAR data sets, which only



(a) (b) (c)

Figure 4: Angles for which the shading and visibility of a building facet point (gray dot) are considered, i.e., the azimuth angle (a), and the elevation angles for the shading (b) and visibility (c) assessment, respectively.



(a) (b) (c) (d)

Figure 5: Polar diagrams representing the shading and visibility properties of a south facing building facet with tilt β (see Figure 4a) and free horizon (no shading); in (a) the viewshed, (b) the type of visible object, (c) angle-of-incidence (AOI) with respect to the visible object and (d) the distance to the visible object.

covers a specific urban area. The LiDAR data set is classified into *ground* and *unassigned* according to the standard protocol for LiDAR data (Heideman, 2014). The LiDAR data set was initially filtered before being used in the modelling (see Lingfors et al. (2017) for details). Noise, in terms of sparse outliers, was removed using the Matlab® function *pcdenoise* (Rusu et al., 2008). Points classed as unassigned within the building footprints where classed as building points. Unassigned points 1 m outside building polygons were removed, since these may represent parts of the building due to misalignment between the LiDAR data and the property map. Hence, removing them limited the risk of incorrectly classifying building points as, for instance, trees. Unassigned points less than 0.5 m above ground was removed, partly because they often represent high grass, but more importantly to save computational time in the shading/visibility analysis as these would neither contribute to the shading assessment, nor the visibility assessment.

2.2. Target-based visibility assessment

In this section, the proposed visibility assessment method is described. As mentioned in the introduction, the method is an extension of a method for shading analysis, developed by Lingfors et al. (2017). That method is summarised in section 2.2.1 and in the consecutive section (2.2.2), the visibility assessment method is outlined.

2.2.1. Shading analysis of PV systems

Figure 6 is a simple illustration of some essential features of the shading analysis. The shading analysis is consecutively performed for every flat segment of a building envelope, hereafter referred to as a building *facet* (Figure 6a). Both the buildings and the objects surrounding it, are derived from the LiDAR data set, the former by using linear regression (see Lingfors et al. (2017) for details). For the surrounding features, the LiDAR data are first filtered (see Lingfors et al. (2018)) before triangulated irregular networks (TINs) are derived using Delaunay triangulation. A TIN makes up a surface model connecting all points of a LiDAR subset to form triangles, with no points enclosed by any triangle. These TINs are the basis of the viewshed analysis. There is a distinction between the ground and terrain TINs (light green in Figure 6) as the resolution of the ground is higher (10 m), representing nearby ground features (within 50 m radius of the building), while the resolution of the terrain TIN was set to 50 m (within 1000 m radius). The non-ground features (dark green in Figure 6) impact the shading the most and the TIN resolution is therefore set to 5 m for the zone 20-50 m from the building and 2 m within a 20 m radius of the building. Higher resolution improves the result negligibly, but impacts the computational time considerably (Lingfors et al., 2017).

Since the TIN is a continuous surface, patches of trees will be connected in an unnatural way (e.g., there will be triangles connecting tree tops, which may lead to the shading being overestimated). In the latest version of the model, this problem was fixed by introducing a maximum threshold on the catheter length. Triangles surpassing this threshold are removed and instead new vertical triangles are created connected to the ground.

The TINs and building facet polygon are projected along a sky vector (dashed black line in Figure 6b), directed at, in this study, 18 × 36 segments of the sky, representing the altitude (in steps of 5°) and azimuth (in steps of 10°) dimensions, respectively (Figure 4). While CIE recommends an equal-angle subdivision of the sky into 145 segments (Freitas et al., 2015), based on the work by Tregenza (1987), here an equal-angle subdivision was chosen due to its symmetry and computational simplicity. The resolution of the sky segments is, however, user-defined. The building facet may not be fully obscured by a triangle along the sky vector, therefore the facet is discretised into a regular grid of *facet points* (see Figure 6a) separated by 0.5 m according to the methodology of Martínez-Rubio et al. (2016) to consider partial shading/visibility of a potential solar energy application. This means that some facet points may be flagged as shaded (black dots in Figure 6a) and some may not be.

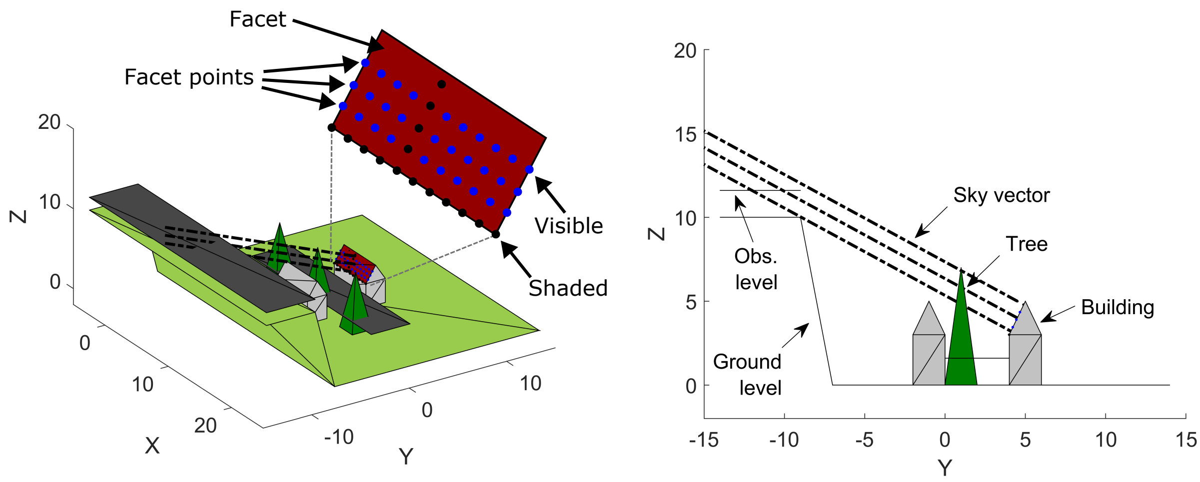
The dark gray areas of Figure 6 represents the *public domain*, which is used for the visibility assessment and further explained in Section 2.2.2. The analysis is thus repeated for each sky vector and a unique shading map or *viewshed* is produced for each facet point (Figure 5a). The viewshed is used as input for the computation of the solar irradiance on the building facet when shading is considered (Lingfors et al., 2017).

2.2.2. Visibility assessment method

In this work, the methodology described in the previous section is extended below the horizon line as is illustrated in Figure 4c. In the shading analysis it is only important to determine if the sky vector is intersecting a feature or not. However, in the visibility assessment it is also important to keep track of what type of feature projected along the sky vector (see Figure 6b) lies closest to the building facet (Figure 5b). If, for instance, a tree is closer than a ground or terrain feature, then the roof is nonvisible from this angle. It may also be interesting to know the distance to the closest feature (Figure 5d), since the perception of an object decreases with distance, or from what angle the building facet is visible (Figure 5c) (Groß, 1991). However, these aspects will not be further evaluated in this paper.

More importantly, the way the *vantage area* is defined, from which the buildings can be observed, has a significant impact on the results of the visibility assessment. The most conservative definition would be to treat all ground and facades (i.e., possibly populated by windows) as the vantage area. However, private space, such as gardens, courtyards, windows from residential dwellings, etc., would be reserved for a limited number of observers and should logically not be given the same weight as the public space. Therefore, two different definitions of the vantage area are evaluated here. In the first, all ground/terrain (GT) features of the model are included. Building facades are, however, excluded, since windows would only populate a small fraction of the facade and may have curtains, and therefore the visibility would probably be over-estimated. In the second, only the public domain is considered, i.e., streets, squares and parks, which anyone can access.

The public domain is represented as dark gray in Figure 6. It has been raised by 1.7 m to represent the eye level of the observer (see *observation level* in Figure 6b). The yellow area of Figure 6 represents GT and if this layer is used to define the vantage area, a copy of it is created and raised by 1.7 m. This layer is only used for the visibility assessment, and not the shading analysis.



(a) (b)

Figure 6: Illustration of the combined shading and visibility assessment from two different angles. Black, dashed lines represent sky vectors, starting at the top, middle and bottom of the building facet (red) under evaluation. On this facet, black dots represent shaded facet points and dark blue dots facet points visible from the public domain (dark gray area) for the specific sky vectors. Non-colored facet points (top-row) are not shaded, nor visible along the projected sky vector. Light green, light gray and dark green areas represent ground, buildings and trees, respectively.

2.3. Case studies

The proposed methodology was evaluated in two case studies for the Swedish cities Stockholm and Visby, respectively, as described below.

2.3.1. Case study 1: Stockholm

In this case study the method was applied on 90’000 buildings within the municipality of Stockholm, Sweden. This area was chosen since about half of the buildings have been evaluated with respect to their cultural-heritage values by the Stockholm City Museum, where *Blue* corresponds to the highest values, followed by *Green* and *Yellow*. Buildings that are considered to have no cultural-heritage values are classed as *Gray* and correspond to a very small part of the total building stock (0.3%). The reason that so few buildings are classed as gray is that according to Swedish law, all changes to a building, no matter its age, need to be done carefully without distorting its originality (SFS, 2010). This means that gray buildings have no values that are worth preserving and could as well be demolished. It is therefore likely, that the small fraction of gray buildings is representative for the whole building stock (i.e., including the non-classed). This classification is combined with the solar irradiation and visibility assessments and presented in Section 3.1.

2.3.2. Case study 2: Visby

In this case study, a more detailed analysis of the proposed method was performed. In total, 3388 buildings were studied, located within the city wall of the medieval part of Visby. Solar energy applications are currently prohibited within the city wall, making the classification done for Stockholm obsolete in this case. Two different methods for defining the public domain were evaluated.

The first utilises the property borders of the Property Map from the Swedish Land Survey (2018). In this context, it was convenient, as all streets, parking lots, squares and parks are tagged *INNERSTADEN VISBY* in the Property Map, i.e., the public domain is well defined and do not overlap other features, such as buildings in the Property Map.

In the second method, the public domain is defined from features in OpenStreetMap (OSM). Polygons in OSM are often classed, e.g., as buildings, parking lots, parks, etc., and features that are not considered part of the public domain could thus be excluded from it. Naturally, building polygons should always be excluded, since these occupy the ground, but other features classed as, for instance, residential or industrial may also be excluded, depending on how conservative the public domain is defined. In this case study, no residential, nor in-

Table 1: Number of and assumed width of lines tagged as "highway" within the OSM of the Visby case study area.

	Count	Width
cycleway	18	3
footway	53	2
living_street	5	6
path	1	2
pedestrian	6	6
residential	140	6
service	16	6
steps	13	2
unclassified	14	6

dustrial areas were present within the city wall.

The streets in OSM are represented by lines, therefore they need to be translated when defining the public domain. This was achieved by creating a buffer around the streets of different width, depending on the type of street (see Table 1). These widths are context-specific, and to a large extent they depend on the age of the city district and what region in the world is studied. Table 1 presents the assumptions made for the different street types tagged as "highway" in OSM within the city wall of Visby.

Figure 7 illustrates the difference between the public domain if the Property Map or OSM is used to define it. The difference in terms of visibility across the city is presented in Section 3.2.

3. Results

In this chapter, the results of the two case studies in Stockholm and Visby are presented.

3.1. Case study 1: Stockholm

Table 2 presents the main results from the Stockholm case study. The columns represent three different classes of cultural-heritage values, defined by the Stockholm City Museum. The threshold for *some visibility* here corresponds to that the facet points of a facet are seen in average 3.7 times from the vantage area. The threshold was chosen so that it represented the same ratio of a test sample district as *no visibility* did using ground/terrain as vantage area. The table shows that only 2.4% of the total roof area (which was 18 km^2) is represented by buildings that have the highest classification, *Blue*. If thresholds for solar irradiation and visibility are applied, the potential for solar energy applications

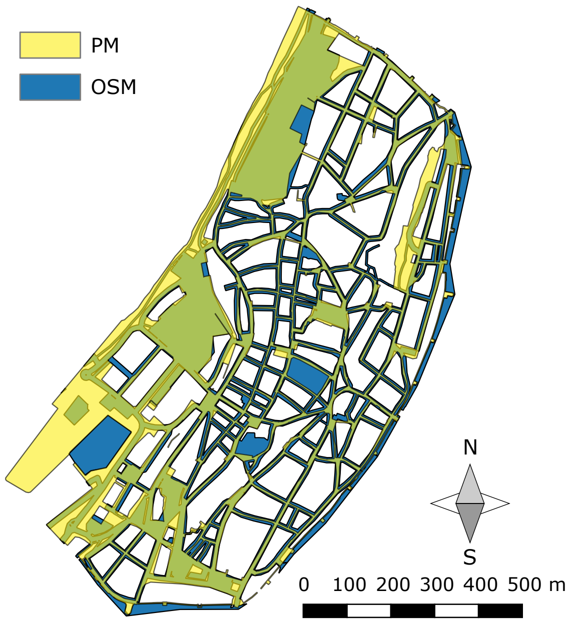


Figure 7: Public domain in one of the case study areas, the medieval city of Visby, Sweden, defined by the property map (PM) from the Swedish Land Survey (2018) (yellow) and OpenStreetMap (OSM) (blue), respectively. Green represents the overlap of the two datasets.

of these roofs is insignificant. For instance, only 0.27% of the total area is available if no visibility is allowed, and an irradiation level of >900 kWh/m^2 is used (combination 2 in Table 2). Hence, the total solar energy potential in Stockholm is almost not affected if these roofs are ruled out from solar energy applications.

On the other hand, a significant share of the building stock is classified with lower heritage values, i.e., *Green* (23.5%) and *Yellow* (35.2%). For combination 2 in Table 2, 2.57% of the total roof area is represented by buildings classed as yellow, which for instance would correspond to 70 GWh of annual electricity production if all these roofs were covered by PV panels (1% of the annual electricity demand in Stockholm (Statistics Sweden, 2017)). If assuming that the classified buildings are representative for the whole building stock, the potential for solar energy on yellow-classed roofs may approximately double (i.e., 2% of the electricity demand). Of course, there are several other parameters that further limit this potential, e.g., obstacles on the roofs, such as chimneys, ladders and bay windows, and the strength of the roof.

An illustrative example of the annual solar irradiation, visibility and heritage classification is given

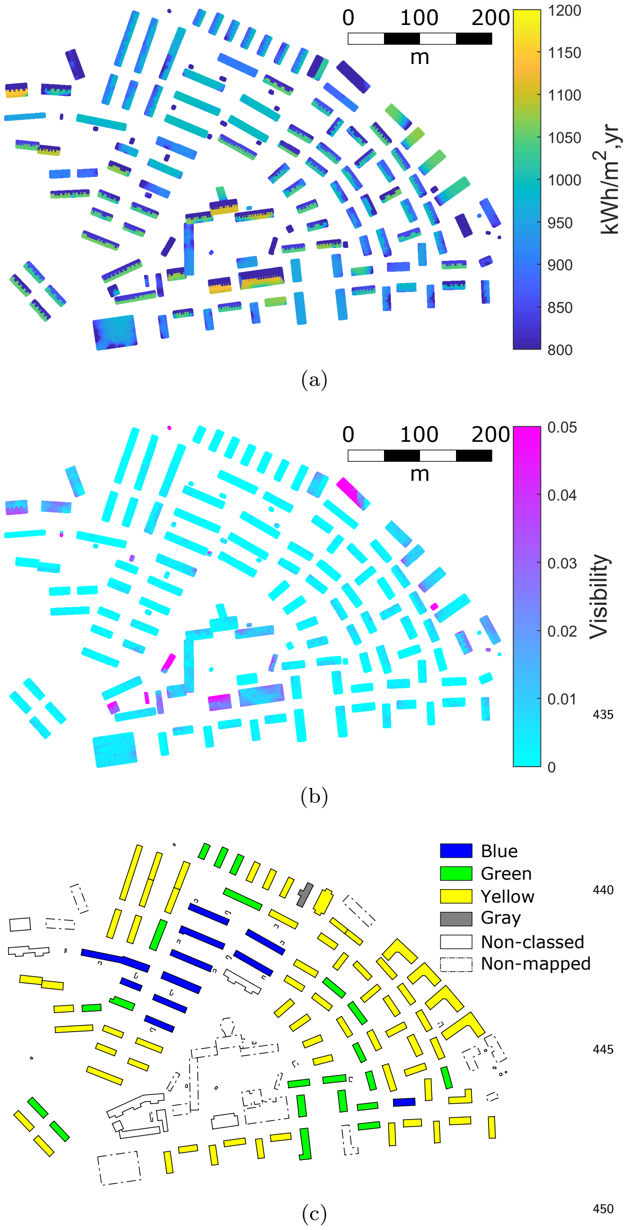


Figure 8: Application example from the city district Hammarby, Stockholm (N59.3,E18.1). In (a), annual irradiation on roofs, in (b) the visibility assessed for ground/terrain and in (c) classification of buildings. Buildings that were by the time of extraction non-mapped in the Stockholm museum database are marked by dashed lines.

in Figure 8, representing the city district Hammarby in Stockholm.

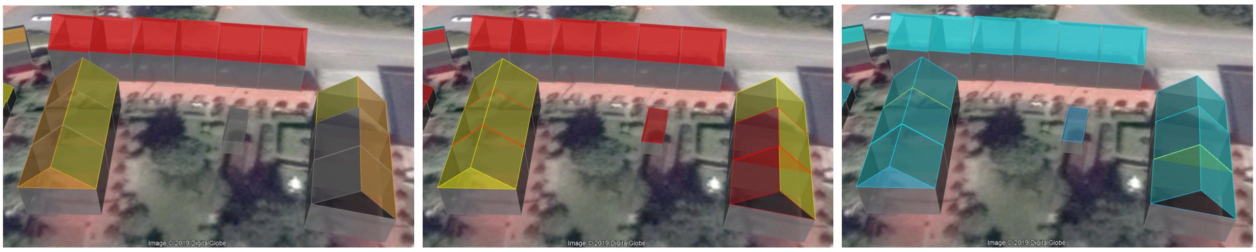
Table 2: Percentage of total roof top area for different annual irradiation and visibility levels and for buildings of different cultural-heritage classes (B=blue, G=green, Y=yellow). *All* refers to all buildings, including the non-classed. The visibility is assessed with respect to ground/terrain. At the bottom, three combinations of criteria are presented.

Class		B	G	Y	All
			Area [%]		
Annual irradiation [kWh/m^2]					
a	>1100	0.06	0.90	0.96	2.6
b	1000-1100	0.19	2.26	3.63	9.7
c	900-1000	0.46	4.65	7.23	19.2
Visibility					
d	no visibility	0.36	2.74	3.07	8.6
e	some visibility	0.41	5.55	8.87	21.4
Combinations					
1	a+b // d	0.05	0.33	0.32	1.0
2	a+b+c // d	0.27	2.23	2.57	7.0
3	a+b+c // d+e	0.48	5.38	7.93	19.3
	Total	2.39	23.5	35.2	100

3.2. Case study 2: Visby

Figure 9 illustrates the results from the case study in Visby, in which the model output has been integrated in Google Earth. Figure 9a presents the color coded annual solar irradiation. The roofs of the six attached buildings in the back of the illustrations are facing south, thus having the highest possible solar irradiation. Figure 9b shows that these roofs are not visible from the public domain, while Figure 9c shows that they are visible if all ground/terrain is included in the analysis. Hence, this illustrates that the model effectively captures the difference between using only the public domain or all ground/terrain as vantage area, as roofs are visible from the courtyard in the center of the illustrations, but not from the street behind the buildings.

Table 3 presents statistics for the all buildings in Visby. From the table it is clear that there are significantly more roofs that have no or some visibility when only the public domain is considered, compared to when all ground/terrain is included as possible vantage area, in line with the illustration in Figure 9. For instance, Table 3 shows that 36% of the total modelled roof area in Visby is non-visible from the public domain, but only 16% from ground/terrain. It should be stressed that the topography has a strong impact on the visibility. Visby lies on a slope with a height difference of

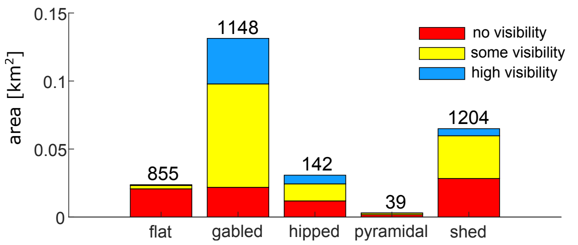


(a) (b) (c)

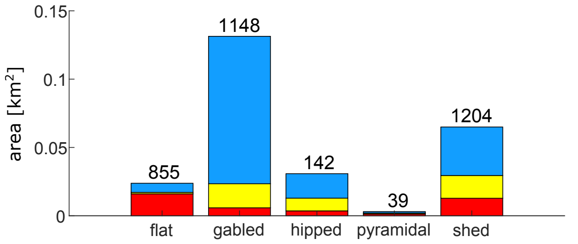
Figure 9: In (a), annual irradiation on roofs color coded as red (>1100 kWh/m^2), orange (>1000) and yellow (>900). In (b) and (c), the visibility assessed for the public domain (b) and for all ground/terrain (c), respectively, color coded as red (no visibility), yellow (some visibility), blue/purple-scale (relatively high visibility).

Table 3: Percentage of total roof top area for different annual irradiation- and visibility levels. The visibility is assessed with respect to the public domain (PD), and ground/terrain (GT), respectively. PD is defined by the property map (PM) from the Swedish Land Survey (2018) and OpenStreetMap (OSM), respectively. At the bottom, three combinations of criteria are presented.

		PD [%]		GT [%]
		PM	OSM	
Annual irradiation [kWh/m^2]				
a	>1100		33	
b	1000-1100		18	
c	900-1000		14	
Visibility				
d	no visibility	36	33	16
e	some visibility	48	49	18
Combinations				
1	a+b // d	20	19	11
2	a+b+c // d	27	26	14
3	a+b+c // d+e	58	57	28



(a)



(b)

Figure 10: Classification of visibility by roof type, when the public domain is defined according to OSM (a) and ground/terrain (b), respectively. The numbers on top of the bar indicate the number of buildings with each roof type.

about 25 m in the SE-NW direction across a distance of 500 m. This means that roofs are in general more visible then in the case of a flat topography.

In Figure 10, statistics of the visibility of each roof type are presented, using OSM and ground/terrain in (a) and (b), respectively. Naturally, the visibility of flat roofs is not affected as much as the visibility of the other roof types when expanding from OSM to ground/terrain.

4. Discussion

The results indicate that the proposed methodology accomplishes the main goal of this study, to assess the visibility of solar applications on building envelopes from the point-of-view of the building, referred to as a *target-based* approach. The study also shows the importance of making a well-informed decision when defining the vantage area, as the results of the visibility assessment have a high dependency on the choice. In urban planning processes it might actually be useful to study the visibility using different definitions (in line with this study), i.e., for all ground or the public domain. For some buildings, technical installations, such as PV panels, may not be suitable, even if they are non-visible from any perspective, due to documentary values (Swedish National Heritage Board, 1998). Other categories of buildings may be interesting, with no or low visibility from either the public domain or more strictly from ground/terrain, if the experiential values are most important. Furthermore, the weighting of the visibility from the public and private domain, respectively, could be assessed qualitatively by consulting experts on heritage values.

When visually inspecting the results of the building modelling for Visby, it was observed that many roofs were modelled as flat, when they were actually not. Flat roofs are, naturally, more likely to have low visibility Florio (2018), which means that in reality the roofs are probably more visible than Table 3 indicates. The reason for this is that the method for deriving the building models is quite simple (due its intended use of low-resolution LiDAR data), as it uses a template of roof types of very basic roof shapes (Lingfors et al., 2017). The simple model approach is a necessity for performing large-scale assessment studies, i.e., on city level. For detailed analysis of single buildings more accurate building models are required in combination with other parameters of the building, such as building material, strength of the roof construction, etc. Thus, the model performs well for buildings of simple roof topography but less so for more complex roof topographies. A priority for future studies should be to evaluate the accuracy of the building modelling.

The ratio of non-visible roofs is lower in Stockholm than in Visby (8.6% vs. 16%, see Tables 2 and 3, respectively). There may be several reasons for this. Visby is a medieval town with narrow streets, which means that the public domain is smaller than in Stockholm in average, Since Stockholm consists of both older districts in the city core and newer ones, in the periphery, with more spacing between the buildings. The complexity of the buildings in Visby is also higher in general, which means that the roofs are more likely incorrectly classified as flat.

The results could, however, be compared to those of Florio (2018), in which 50% of the roof top area in Geneva, Switzerland, was modelled as non-visible, which is higher than if the public domain is considered (36%) in the model proposed here. Remember that in Florio (2018), vantage points were sampled along the street network of the city (as in Figure 3), even further reducing the total area for which the visibility is assessed. This may partly explain the difference, but there might also be other factors such as differences in topography of the two cities and the height of the buildings.

Since discrete steps of azimuth and elevation are used for the sky vectors, there is a risk of missing objects which decrease with the distance from the roof under evaluation. On the other hand, while distant objects may still be important for the visibility assessment, the perception of an object is decreasing with the distance following the Beer-Bouguer-Lambert's law. Previous studies have shown that the shading is mainly affected by nearby objects within a radius of 50 m (Lingfors et al., 2017). Just as increasing the radius of the viewshed analysis, decreasing the discrete steps of the sky vectors will mean a longer computational time, i.e., there is a trade-off between accuracy and computational time. This matter will be further evaluated in a follow-up study, in which the visibility will be qualitatively assessed and compared to the model when applying different resolutions of the sky-vector steps and Delaunay triangulation.

5. Conclusions

In this study, a new method for assessing the visibility of features on building envelopes has been developed, with applications to solar energy technologies. It mainly differs from the majority of visibility assessment methods in that the analysis is based on the target, i.e., building envelope, rather than a set of vantage points. By flipping the perspective in this way, the visibility assessment is only required for those buildings that are of interest. The study illustrates the importance of the choice of *vantage area* from which the building envelope can be observed. If the public domain is chosen, non-visible roof surfaces doubled compared to if all ground/terrain was chosen. However, the most proper definition depends on the context. The study exemplifies the usability of the method for solar energy applications on historical buildings by combining the visibility with the solar irradiation onto and cultural-heritage values of a building. Furthermore, the target-based approach proposed here may be used in other contexts in which the visibility is important to assess.

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