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Potential roof area for photovoltaics in a Swedish municipality

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Abstract— The focus of this paper is on the estimation of building roof area for solar PV systems, potential solar PV installed capacity and power generation in Vasteras, a typical Swedish municipality. The following sectioning of different building types has been investigated: Residence, Industry, Social function, Business, Economy, Complement, and Others. In the following sections, an estimate of available roof area potential is calculated by considering factors such as rooftop orientation, shadows and obstacles. With appropriate rooftops covered with commercial solar cells, combined with the average solar irradiation, PV panel efficiencies and other system parameters, the total solar power potential PV peak power output from the region is considered and the potential annual energy production is calculated. This will give a picture of how much the electricity demand will be met by rooftop PV deployment. We get those new understanding of roof area distribution and potential outputs that can largely help solar energy policy formulation in the city.

Keywords—building rooftop area potential; installed capacity potential; solar power potential; GIS

I. Introduction

Solar photovoltaic (PV) technology has matured to become a technically viable largescale source of sustainable energy. In Sweden, the installed capacity of solar PV is 322.4 MW_p in 2018 but it is expected to increase to 32 GW_p in 2050 [1]. An interesting segment of solar PV markets is the one corresponding to building-integrated and building-applied projects. In this research work, a comprehensive methodology has been proposed to identify potential roofs using the geographic information system (GIS) tool. The roof geographical potential for solar PV installation is defined as the fraction of the theoretical potential that is usable, in other words, the solar irradiation received on the land available for the PV facility. A step-by-step procedure has been developed for estimating total roof PV potential which involves geographical data division and classification, gross area calculation, roof orientation analysis with sampling method, roof shadows and obstacles analysis with utilization factor, reduction for inter-row shading effects, installed capacity analysis, extrapolation with the use of roof area-population relationship, installed capacity, and energy yield calculation.

II. Methodology

A. Site description

The selected study area is Vasteras (59.61° N, 16.54° E, elevation = 21.00 m appx.), located around 100 kilometers west of capital Stockholm in Sweden (Fig. 1). Vasteras is predominantly known as an industrial city and the founder city of Asea Brown Boveri (ABB) electrical industries. At present, there were approximately 150,000 inhabitants in 2018. The study area includes Västerås city, Örtagården, Irsta, Tillberga and the other eight districts, representing the total built environment. This city has a total land area of around 65.34 km^2 covering both the compact, central parts of Vasteras and the remote countryside which is more suitable for distributed solar PV system. The population and district area plot is shown as Fig. 2.

Fig. 1. (a) The vector map of Vasteras municipality with all buildings. The blue lines represent the administrative boundaries. The light green areas are the urban areas with high population density and infrastructure of the built environment. The light orange polygons represent the building roofs outlines. (b) A zoom-in area, that is Stenby Tunbytorp, in Vasteras, and (c) its Google Earth Pro™ satellite image with the property boundaries from our dataset (purple lines represent the property boundaries and black dots represent the property break points).

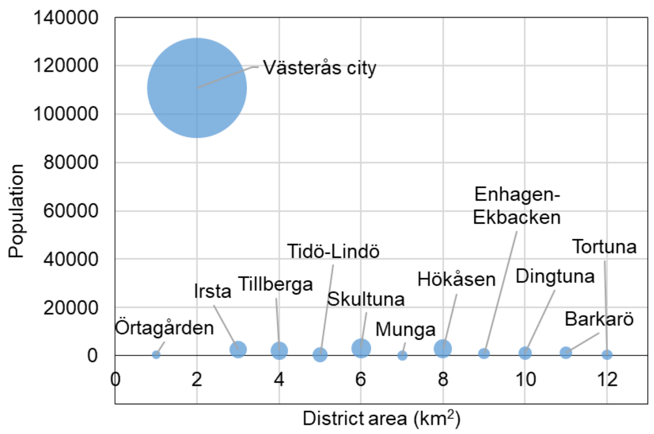

Fig. 2. The distribution of population and district area of 12 districts in Vasteras municipality.

B. *Geographic data input*

The availability of high quality GIS data played the strongest role in determining the methodology used for this research. The data in this study was obtained from Lantmäteriet[2], the land survey authority of Sweden. The data collection and updating is done by Lantmäteriet performing photogrammetric measurements in aerial photos and through collaboration agreements with the municipalities. The dataset includes the real estate classification, building, land use, and urban maps. All the data are saved as the vector format with the specified geographical information. In this study, the buildings data (bebyggelse) are the main focus. The buildings in the Real Estate Register's Building section (Fastighetsregistrets Byggnadsdel) are defined according to the Planning and Building Act (Plan- och bygglag 2010: 900) as "A durable construction consisting of roofs or roofs and walls and which is permanently placed on land or partly or completely underground or is permanently placed on a certain place in water and is intended to be designed so that people can stay in it." There are 59,403 buildings with the location and shape information, e.g. attribute name, data type, data length, MapInfo type and length, and description in our database.

Each one of the buildings was measured on the roof edge or the façade, and stored as a closed polygon that represents the building as it looks in reality. All polygons are surface-shaped and they have a collection position and a mean error in the plane and in height if there is a height value. The building layer shows the extent of the buildings as polygons on the horizontal plane. The properties were measured with satellite positioning which can have an accuracy of a few centimeters. Depending on the altitude and image quality, the measurement accuracy may vary slightly, but in general the position in plane has an average accuracy of 5 m. About 4% deviations exist in the form of deficiency or redundancy at the national level.

Building types indicate which purpose the building is used for. A building can have several different building purposes, for example, residence or business. Detailed building purposes in this study include: Residence, Industry, Social function, Business, Economy, Complement, and Others. In order to reduce the gross surface area to the realistic usable surface area for solar PV systems, both absolute and relative reductions are made. The absolute reductions, such as the religious buildings and cultural buildings, have been subtracted directly from the base area. The relative reductions, such as due to orientation, shadows and obstacles, snow and dirt, have been processed with different utilization factors. The following Fig. 3 shows the different building types and their numbers.

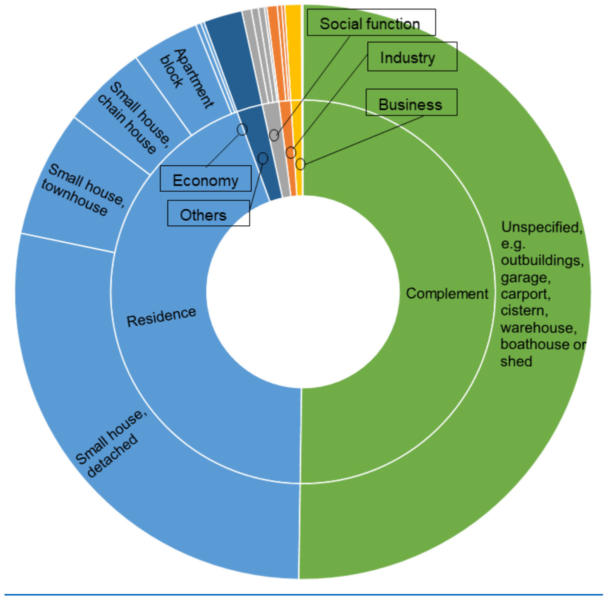

Fig. 3. Different building types and their numbers in Vasteras municipality.

III. ROOF UTILIZATION FACTORS AND TOTAL AVAILABLE AREA

A. *Roof base area and surface area*

For every building polygon with the unique code, we use the "Calculate Geometry" tool in ArcGIS (ESRI, 2015) to calculate its area. This tool allows to access the geometry of the features in a layer based on the coordinate values and lengths. The gross base area of all types of buildings are calculated to be 9.58 km^2 and the structure is summarized as Fig. 4 below.

Fig. 4. Different building types and their gross base area in Vasteras municipality.

The buildings have different roof shapes, such as the saddle roof, the mansard roof, pulp roof, counter roof, and flat roof. Since the available vector data are not three-dimensional, some assumptions about the pitched-roof slope angle must be made. In Sweden, the saddle roofs are the most common ones for residence buildings (e.g. single-family and multi-family houses, and apartment buildings), complementary buildings and economy buildings, which have the average slope angle of 24-31°. The mansard roofs rank the second widely-used roof types, which have the average slope angle of 19-30°. The other types have the slope angle between 0-9° [3]. To simplify the calculations, the assumption about pitched-roof slope angle is obtained from [4], that is we assume that all buildings with pitched-roofs have an ideal shape (Fig. 5). Their average slope angles are assumed to be 30°. In addition, the Industrial buildings, which are 0.99% of the total numbers and 16.67% of total base area, are assumed to be flat.

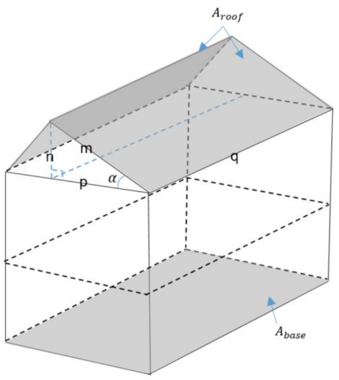

Fig. 5. The ideal building that is assumed in the calculation. The estimated roof surface area (A_{roof}) is the total base area of a building (A_{base}) divided by the angle of inclination of the roof (α).

Therefore, the roof surface area is calculated as (Equation (1)).

$$A_{roof} = 2 \cdot m \cdot q = 2 \cdot \frac{p}{\cos\alpha} \cdot d = \frac{A_{base}}{\cos\alpha} \quad (1)$$

Where A_{base} is the base area, α is the slope angle of the roof. The calculations give the total ideal ceiling surface.

From this formula, the gross surface area can be calculated by the type of buildings (Fig. 6). The gross roof surface area is 10.82 km2. The Residence buildings and Complement buildings account for 47.07% and 20.28% of the total surface area. Industry buildings and Business buildings account for 14.77% and 9.11%. It is common that the average area per Industrial buildings to be considerably larger than Residential buildings. (Fig. 6)

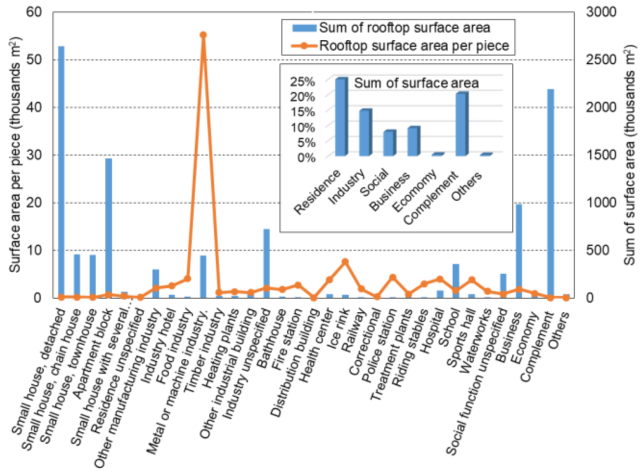

Fig. 6. Roof area per piece and surface area by building types in Vasteras municipality.

In practice, the roof surface is limited by the shadows and various obstacles such as skylights and chimneys. Not all the roofs are usable due to the orientation. Analysis for reducing the ideal roof surface are used to calculate the total usable roof surface.

B. *Roof orientation, shadows and obstacles*

The vector data in our study can be used to determine the available roof area because it identifies the different types of buildings, their surface outlines, numbers and other attributes. However, different from the three-dimensional remote sensing technologies, e.g. airborne LIDAR, the vector data fails to automatically identify the 1) the orientations of the pitched roofs; 2) the shadow casts by neighboring structures, buildings, trees or other parts of the roof itself; and 3) the roof obstacles e.g. chimneys, ventilation, HVAC, elevator shafts, dormers, antennas or other elements (Fig. 7). Quantifying these factors is essential to evaluate its influence on the availability of radiation and consequently on the potential of solar system installation.

Fig. 7. The above image, as part of Vasteras city center, shows (a) the shadow cast by the surrounding tall building, (b) the roof obstacles, (c) the different building slopes, and (d) the different building orientations.

Previous studies used the "Calculate Polygon Main angle" function in ArcGIS to calculate the roof orientation. The angle of the longest collection of segments that have similar orientation is therefore assumed as the dominant angle of a polygon. However, there are several technical shortcomings when using this method. First, many inter-connected roof polygons can be recognized as one. These buildings are so called composite buildings, which a building object consists of several building parts (Fig. 8). Second, the main angle of the longest collection is not accurate. That method could give the polygon main angle values with the total extension of 180°, using three different rotation ways (i.e. clockwise with 0 at top/north, counterclockwise with 0 at the right/east, and counterclockwise with 0 at top/north). Each value corresponds to two directions, e.g. 0° may correspond to either north or south, 45° may correspond to either southeast or northwest. The "Calculate Polygon Min angle" function fails to distinguish these without more assumptions.

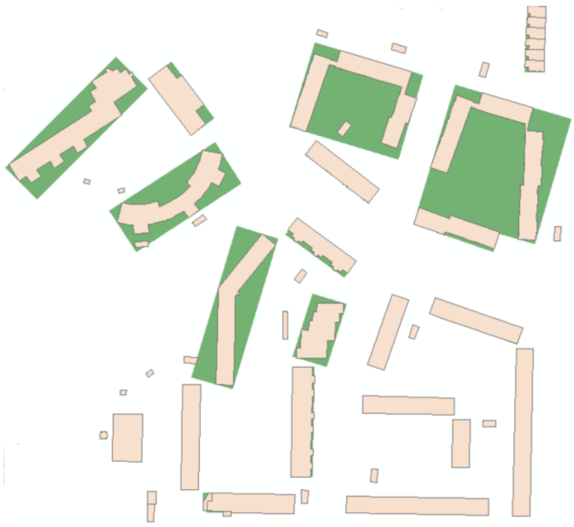

Fig. 8. Several polygons are recognized as one when calculating the longest collection of segments.

In this study, we employ the sampling method to determine the roof orientations. To obtain the orientation data, we take the district within the First Ring Road as the sample. In this district, the buildings have the function of Residence, Social function, Business, Economy and Complement, where the Industry buildings are excluded. First, we separate the whole sampling area into 22 sub-areas by districts and code each satellite image from Google Earth ProTM. Second, we disintegrate the roofs into unites, that is. one 30m*10m roof area as one sample piece. Third, we count units by different orientations. The length and angle can be accurate based on the Google Earth Pro™ measurement feature (Fig. 9). The roof azimuth values were measured clockwise, from 0 that defines north to 360° which again indicates north.

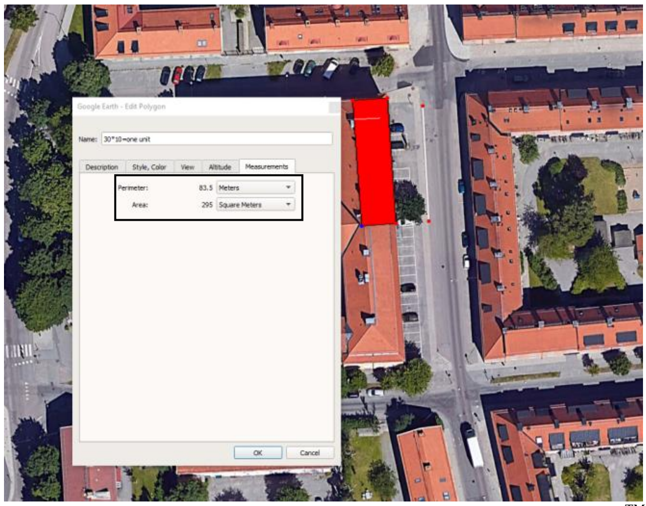

Fig. 9. The orientation sample and measurement of the Google Earth Pro™ measurement feature.

Shadows and obstacles analysis is the second essential step in phase of solar photovoltaic system design or analysis. The shadings caused by the near buildings and/or vegetation and the presence of obstacles such as chimneys, HVAC, elevator shafts should be eliminated as much as possible to minimize the inaccuracy. Different researchers used different utilization factors employed in different regions and scenarios[5][6][7]. In this paper, we take 0.7 as the shadow and obstacle utilization factor for Industrial buildings and 0.74 as for non-Industrial buildings.

C. *Estimation of usable area*

Suitable locations for the placement of PV panels possess particular attributes. Various criteria for selecting suitable roof planes based on their slope (tilt), aspect (azimuth), minimum amount of contiguous area, and received incident solar radiation were applied.

The usable area is assumed to be occupied 100% by the PV systems which is called the direct land area. The usable roof area for PV installations is the total roof area reduced by shading and building orientation factors (Equation (2)).

$$A_{pv} = A_{roof} \cdot U_{ori} \cdot U_{so} = A_{roof}^{non\_ind} \cdot 0.7587 \cdot 0.74 \cdot 0.9 + A_{roof}^{ind} \cdot 1 \cdot 0.7 \cdot 0.9 \quad (2)$$

Where, $A_{roof}^{no\_ind}$ are the non-Industrial buildings area, and A_{roof}^{ind} are the Industrial buildings area.

IV. Estimation of Installed Capacity Potential

In this paper, the Yingli Solar PV modules (YL310P-35b) are employed. The size and technology of the modules and cells are in Table I.

TABLE I. Yingli Solar PV modules (YL310P-35b) technical parameters.

Characteristics of Yingli Solar, YL310P-35b	
STC power (manufacturer)	
STC Power Rating	310W
Technology	Polycrystalline Silicon
Module size (W x L)	0.990 x 1.960 m²
Rough module area	1.94 m²
Number of cells	1 x 72

Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)	
Max. power point voltage	36.7 V
Max. power point current	8.44 A
Maximum power	310.0 Wc
Power temper. coefficient	- 0.42 %/°C
Efficiency(/ Module area)	16.00%
Efficiency(/ Cells area)	17.70%
Fill factor	0.755

For all the pitched-roofs, we use the roof angle as the desirable angles of solar PV modules. For all the flat-roofs, we use the optimal angle as the desirable angles of solar PV modules, with the consideration of PV array distance. The solar power generation is calculated based on solar resource data from Meteonorm© using PVSYST© software with the technical assumptions as Table 2 [8].

TABLE II. TECHNICAL ASSUMPTIONS FOR SOLAR PV POWER GENERATION.

Optimal tilt angle	30° for pitched-roofs and 38.85° for the flat-roofs [9]
PV module efficiency	16.00%
Ohmic losses	1.50%
Soiling losses	2.00%
Balance-of-System efficiency	85.00%
Inverter efficiency	97.50% (ABB_ UNO-8.6-OUTD-US-S-A)

The simulation shows that 629.87 MWp potential can be explored in Vasteras municipality based on the available roof area of Residence, Industry, Social function, Business, Economy, Complement, and Other buildings. This can yield 586.50 GWh electricity per year.

V. CONCLUSION

Solar energy deployment is gaining greater attention as a suitable source of energy that could alleviate aspects of the current climate crisis. Increasing the development of solar PV is mostly due to improving competitiveness and cost parity with other technologies, new government plans, increasing awareness of the potentials of this technology, and rising electricity demand. Substantial increases in roof solar PV installation resulted in buildings becoming the largest available urban source of space for deployment. In fact, globally, about half of the PVs presently installed capacity is composed of distributed PV system. However, in Sweden, a large capacity is still untapped.

In this paper, a comprehensive methodology has been proposed to identify the potential roof area for solar PV installation in a Swedish municipality, using the GIS tool. The results show that there are approximately 630 MWp potential can be explored in Vasteras municipality. There is a significant potential for utilizing solar energy on building surfaces in Vasteras and other municipalities in Sweden. These findings can provide an established reference point for roof PV in the region and be used by energy and building sectors, and policy makers to assess new development opportunities and guide investments towards clean energy technologies. Future work can extrapolate the methodology to the entire Sweden and further focus on the potential solar PV market evaluation in Sweden, by integrating the different market stakeholders together.

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