Applied Energy 279 (2020) 115786

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Potential analysis of roof-mounted solar photovoltaics in Sweden☆

Ying Yang [a,*], Pietro Elia Campana [a], Bengt Stridh [a], Jinyue Yan [a,b,*]

[a] School of Business, Society & Engineering, Mälardalen University, Västerås 72123, Sweden
[b] Department of Chemical Engineering, KTH Royal Institute of Technology, Stockholm 10044, Sweden

HIGHLIGHTS

- A comprehensive analysis framework for roof-mounted solar PV systems is developed.
- The estimated roof area for Västerås municipality is 5.74 km^2.
- Different scenarios are considered for the potential installation of PV systems.
- The potential capacity is 727-956 MWp and annual yield is 626-801 GWh for Västerås.
- 504 km^2 usable roof area and 65-84 GWp installed capacity are estimated for Sweden.

ARTICLE INFO

Keywords:
Roof-mounted solar photovoltaic systems
Building roof area
Installed capacity potential
Subsidy scales
Geographic information system

ABSTRACT

Solar photovoltaic energy, driven mostly by the residential and commercial market segments, has been growing a lot in recent years in Sweden. In response to the commitment towards sustainability goals, this paper explores the potential of roof-mounted solar photovoltaic projects. This paper focuses on: roof area estimation, potential installed capacity, and potential electricity generation, at the single municipal scale and at the national scale. The following categories of different building types have been investigated: residential buildings, industrial buildings, buildings of social function, buildings of business function, buildings of economic/agricultural function, buildings of complementary function, and buildings of other unknown functions. The analysis starts from Västerås, a typical Swedish municipality and ranking seventh among the largest cities in Sweden. An estimate of 5.74 km^2 available roof area potential is calculated, by considering factors such as building purposes, roof orientations, shadows and obstacles. The total potential installed capacity is calculated, assuming the installation of commercial photovoltaic modules, and design parameters for flat roofs such as inter-row distances and tilt angles. With the inputs of meteorological parameters and geographical information, the potential yearly electricity generation is calculated. The results reveal 727, 848, and 956 MW$_p$ potential installed capacity and 626, 720, and 801 GWh annual electricity production for Västerås on pitched roofs and flat roofs with three scenarios, respectively. The extrapolation of the methodology to the entire of Sweden yields a total of 504 km^2 usable roof area and 65, 75, and 84 GW$_p$ installed capacity. Finally, we reveal a new understanding of usable roof area distribution and of potential installed capacity of roof-mounted solar photovoltaic systems, which can largely help evaluate subsidy scale and solar energy policy formulation in Sweden.

1. Introduction

Solar applications in Sweden have matured to become technically viable and economically feasible sources of sustainable energy [1]. This is due to the development of global solar applications, and subsidy stimulation from the authorities. In Sweden, there are various national subsidy schemes to encourage new installations that implement photovoltaic (PV) technology as part of the goal of zero net greenhouse gas emissions by 2045; the introduction of the direct capital subsidy system in 2009 is worth highlighting here [2]. This national incentive programme has also been fueled by declining solar system prices, high popularity among the public, growing interest from utilities, and ongoing reformation work by the authorities to simplify the rules for

☆ The short version of the paper was presented at Applied Energy Symposium: MIT A+ B, May 22–24, 2019, Boston. This paper is a substantial extension of the short version of the conference paper.

* Corresponding authors at: School of Business, Society & Engineering, Mälardalen University, Västerås 72123, Sweden (J. Yan).
E-mail addresses: ying.yang@mdh.se (Y. Yang), jinyue@kth.se (J. Yan).

https://doi.org/10.1016/j.apenergy.2020.115786
Received 16 January 2020; Received in revised form 18 August 2020; Accepted 25 August 2020
Available online 1 October 2020

Nomenclature

α^{roof}	slope angle of the roof (°)
α^{flat}	slope angle of the flat roofs (°)
α^{pit}	slope angle of the pitched roofs (°)
A_{roof}	surface roof area (km^2)
A_{base}	base area (km^2)
A^{m}_{base}	building base area of the m^{th} municipality (m^2)
A^{SE}_{pv}	usable area for roof-mounted PV systems in Sweden (km^2)
m	length of the ridge (m)
p	length of counter beam (m)
q	length of the hanging beam (m)
U_{ori}	utilization factor of orientation
U^{ind}_{ori}	utilization factor of orientation for industrial buildings
$U^{non_ind}_{ori}$	utilization factor of orientation for non-industrial buildings
R_{fla}	flat roof percentage (%)
r_{fla}	orientation role for flat roofs
R_{u_pit}	applicable orientations for solar PV installations (%)
r_{u_pit}	orientation role for applicable orientations
R_{n_pit}	not-applicable orientations for solar PV installations (%)
r_{n_pit}	orientation role for not-applicable orientations
R_s, R_{sw}, R_{se}, R_w, R_e	orientation of South, South West, South East, West, and East, respectively (%)
R_n, R_{ne}, R_{nw}	orientation of North, North East, and North West, respectively (%)
U_{so}	utilization factor due to shadows and obstacles
U^{ind}_{so}	utilization factor due to shadows and obstacles for industrial buildings
$U^{no_ind}_{so}$	utilization factor due to shadows and obstacles for non-industrial buildings
$U^{non_ind}_{abs}$	absolute reduction on non-industrial buildings (%)
U^{ind}_{abs}	absolute reduction on industrial buildings (%)
β	tilt angle of PV module (°)
β_{opt}	optimal tilt angle of PV module (°) in scenario A
θ_z	solar zenith angle (°)
α	solar altitude (or elevation) angle (°)
γ	solar azimuth angle (°)
δ	earth's declination (°)
ϕ	latitude (°)
ω	hour angle (°)
l	width of a solar PV panel (m)
d	distance between the front row and the back row of PV panels (m)
mu	municipality, $\mathrm{mu} = 1, 2, 3 \cdots, 290$

Acronym

DSM	Digital Surface Models
GIS	Geographical Information System
LiDAR	Light Detection and Ranging
HVAC	Heating, ventilation, and air conditioning
PF	Packing Factor
PV	Photovoltaic
SCB	Statistics Sweden
ZIP	Zoning Improvement Plan

micro-producers. The 2019 installed capacity of solar PV was 698 MW_p [3], which accounted for 0.4% of total electricity consumption. A strategy proposed by the Swedish Energy Agency suggested that 5–10% of electricity consumption could come from PV in 2040 [4]. Given this scenario, an increased focus on research and development within the solar PV sector is anticipated.

In 2018, the residential single-family houses and commercial facilities were the biggest market segments (65% of the market share of installed capacity) in Sweden. Meanwhile, centralized solar stations represented a very small share (8%) [5]. An interesting segment of solar PV markets is the one corresponding to building-integrated and building-applied projects. Installing solar PV systems on building rooftops increases the generation of renewable electricity without occupying additional land area [6]. Furthermore, due to Sweden's vast territory and sparse population, many of the roofs might be large enough to fit solar PV systems. Understanding the potential of roof solar PV generation and its spatial variations is critical for utility planning, accommodating grid capacity, deploying financing schemes, and formulating future adaptive energy policies [7].

Policymaking for the successful development of solar markets relies heavily on the assessment of the roof surface area available for equipment installation. Energy policymakers use this information to evaluate opportunities and challenges, and to decide if more and new types of subsides are needed. For example, in the early stage, incentives on a large scale drive a sharp increase in PV capacity, which in turn leads to fiscal deficit, and forces governments to slash renewable energy subsidies. Examples are Greece [8], Spain [9], and China [10]. To avoid these negative consequences in Sweden—although the solar PV industry "boom-and-burst cycle" [9] would less likely happen here, considering the less desirable meteorological conditions—a rational evaluation of available roof area and subsidy scale is still necessary.

To integrate the potential geographical evaluation, technical evaluation, and subsidy feasibility analysis for solar PV systems, this study presents a Geographical Information System (GIS)-based comprehensive methodology with energy system modeling techniques. The paper is organized as follows: Section 2 describes previous related studies. Section 3 describes the study area and data input. Section 4 presents the methods of estimating the geographical potential of roof-mounted solar PV, as well as the technical potential, which includes the estimation of potential installed capacity, and solar PV energy conversion. The method of extrapolating from Västerås scale to Sweden scale is shown as well. Section 5 reveals the results and discusses the historical incentives scale as well as potential challenges. Thereafter, the scope and limitations of the paper are presented. Section 6 draws conclusions. It is worth noting that solar cells can be integrated into building façades as well, but this is not considered in this research. The potential of ground-based PV parks is not included in this study either.

2. Literature review of related work

Spatial information technologies, particularly GIS, have been widely used in evaluating the feasibility of solar power stations in a given region, and in identifying optimal locations. GIS is a powerful tool for performing spatial analysis integrating geographical spatial data for a comprehensive feasibility assessment of solar energy potential at the regional scale. Estimation of PV potential is challenging, but indispensable for relevant renewable energy policymaking. The evaluation of adequate available roof surfaces is one of the most crucial stages in the implementation of roof-integrated PV applications [11].

Previous research studied the spatial distribution of PV applications and the determinants. Snape [12] revealed the evolution of the spatial and temporal distribution of PV adoption in the UK. The spatial distribution highlighted the number of systems installed, the capacity of systems, the percentage of households with rooftop PV for every spatial unit, and the evolution over time. The pronounced pattern of distribution was found to coincide with announcements of feed-in tariff policy.

Balta-Ozkan et al. [13] investigated the regional distribution of PV deployment in the UK and its determinants, by employing the spatial econometric method. Their research showed that accumulated capital (represented by home ownership) and financial savings—rather than income—were the key drivers for PV uptake in the UK. Kwan [14] used Zoning Improvement Plan (ZIP) code level data to examine the influence of local environmental, social, economic, and political variables on the distribution of residential solar PV arrays across the US. In terms of spatial performance, the south-western region and the state of Florida underperformed in number of housing units with solar PV installations. California was expected to have an ideal combination of environmental, economic, social, and political characteristics for promoting solar PV. The author indicated that solar insolation, cost of electricity, and amount of available financial incentives were important factors influencing adoption of residential solar PV systems. Sun et al. [15] used a high-resolution grid map of solar radiation combined with geographical restriction factors to evaluate the comprehensive potential of solar PV generation in Fujian province, China. This study presented a GIS-based approach to facilitate the feasibility analysis of geographical and technical potential, based on which the economic feasibility was studied under two feed-in tariff scenarios. He and Kammen [16] used the hourly solar radiation data from 2001 to 2010 from 200 representative locations to develop provincial solar availability profiles. The authors combined GIS modeling and solar photovoltaic simulation. The results found a potential stationary solar capacity from 4,700 GW_p to 39,300 GW_p, distributed solar of about 200 GW_p, and annual solar output reaching 6,900 TWh to 70,100 TWh. With a homogeneous approach, considerable efforts have been made in the case of Israel [17], Slovakia [18], Andalusia (Spain) [19], Bangladesh [20], Piedmont Region (Italy) [21], Pennsylvania (USA) [22], Germany [23,24], Greece [25], and Karachi (Pakistan) [26].

In addition, several researchers have demonstrated that the use of Light Detection and Ranging (LiDAR) point cloud data significantly improved the identification of rooftop geometries and thus the estimation of PV electricity generation. Nguyen et al. [27] provided a methodology for the application of LiDAR point cloud data to analyze PV deployment on the regional scale. Based on the proposed methodology, the authors determined and quantified the challenges in solar PV deployment assessment. Szabo et al. [28] extracted the building and roof models of buildings from LiDAR data and drone surveys. The multi-resolution segmentation of the digital surface models (DSM) and orthophoto coverage were conducted to identify buildings and roof planes. This approach was then validated and applied to 50 buildings in Debrecen, Hungary. A similar study was also applied in the Chao Yang District of Beijing, China, by Song et al. [29]. To estimate solar PV potential, the authors developed an approach to simulate the monthly and annual solar radiation on rooftops at an hourly time step. The approach combined rooftop retrieval from remote sensing images and DSM. Then the approach was applied in one Chinese district to calculate the usable rooftop numbers, available rooftop area, and the annual PV electricity potential. Similar research, with the use of LiDAR data to model buildings and energy systems, was conducted in Georgetown (Malaysia) [30], Arizona (USA) [31], and Seoul (South Korea) [32].

Vector cartographic maps, digital cadastral services, and state geographic information systems are reference sources used in evaluating potential buildings for the installation of PV systems [33]. These resources provide information about buildings' footprints and certain useful data such as height or classification of building type (e.g. residential, commercial, or industrial buildings). In some cases, all these data are used together with digital surface models of the urban area. Moreover, aerial images are a good complement for checking objects, which form the urban model [28]. When the solar potential is calculated, the results are influenced not only by each building's situation, but also by the size and typology of the roof (flat or tilted). In this sense, these data can be adequate to provide an overview of the study area, with proper assumptions. Considering the general characteristics of the buildings, it is possible to estimate the number of roofs of different types, determine the parameters which are needed to determine solar PV capacity potential. In order to evaluate building roofs at the city scale, it is fundamental to have a 3D urban model with LiDAR point cloud data [34]. However, an important aspect to consider is that the extent of the studied area is sometimes limited by the available data [33,35]. Researchers such as Lingfors and Widén studied the Swedish counties of Blekinge [36], Skåne [37], and Dalarna [38]. They used the consistent methodology through these reports to estimate usable area and potential solar energy conversion for Västmanland County where Västerås municipality belongs to. The authors presented the order of magnitude of the potential [39]. To our knowledge, a rigorous and comprehensive assessment of roof PV geographical and technical potential in our studied region has not been published. Furthermore, how to evaluate the current solar PV policies and how to optimally use money is still not self-evident. Sweden's problems and experiences are by no means unique. Indeed, necessary and sufficient information, in particular scientific and technical information, is needed as a firm ground to create evidence-based policies about the appropriate investment of public funds. To address these inadequacies, a two-step procedure is conducted in this paper. First, this paper estimates the potential for exploiting solar energy resources in urban environments, including the geographical and technical potential of the suitable area with the aid of GIS spatial analysis functions. Second, this paper discusses subsidies for PV projects, to facilitate the feasibility analysis of investments for policymakers, investors, and energy planners in Sweden.

3. Study area and data input

3.1. Site description

The selected study area is Västerås (59.61° N, 16.54° E, elevation = 21 m appx.), located around 100 km west of Sweden's capital, Stockholm (Fig. 1). Västerås is predominantly known as an industrial city, and the founder city of ASEA (predecessor of ABB) electrical industries. In 2019, there were approximately 154,000 inhabitants [40]. The study area includes Västerås city, Irsta, Tillberga and the other fourteen localities, representing the total built environment. This municipality has a total land area of around 69 km^2 [41], covering both the compact and central parts of Västerås as well as the remote countryside, which might be more suitable for distributed solar PV systems.

3.2. Data input

The availability of high-quality GIS data plays the strongest role in determining the methodology used for this research. The geographic data in the case of Västerås are obtained from Lantmäteriet [42], the land survey authority of Sweden. The data collection and updating are conducted by Lantmäteriet performing photogrammetric measurements in aerial photos and through collaboration agreements with the municipalities. The datasets include real estate classification, building, land use, and urban maps. All the data are saved in vector format with the specified geographical information. In this study, the building data are the main focus. A "building" in the Real Estate Register's Building section is defined according to the Planning and Building Act as "a durable construction consisting of roofs or roofs and walls, 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" [42]. Our dataset contains 59,403 buildings, with location and shape information, e.g. attribute name, data type, data length, and description. The gross land area of buildings is 9.67 km^2.

The measurement data of buildings were stored as closed polygons, representing the building as they look 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.

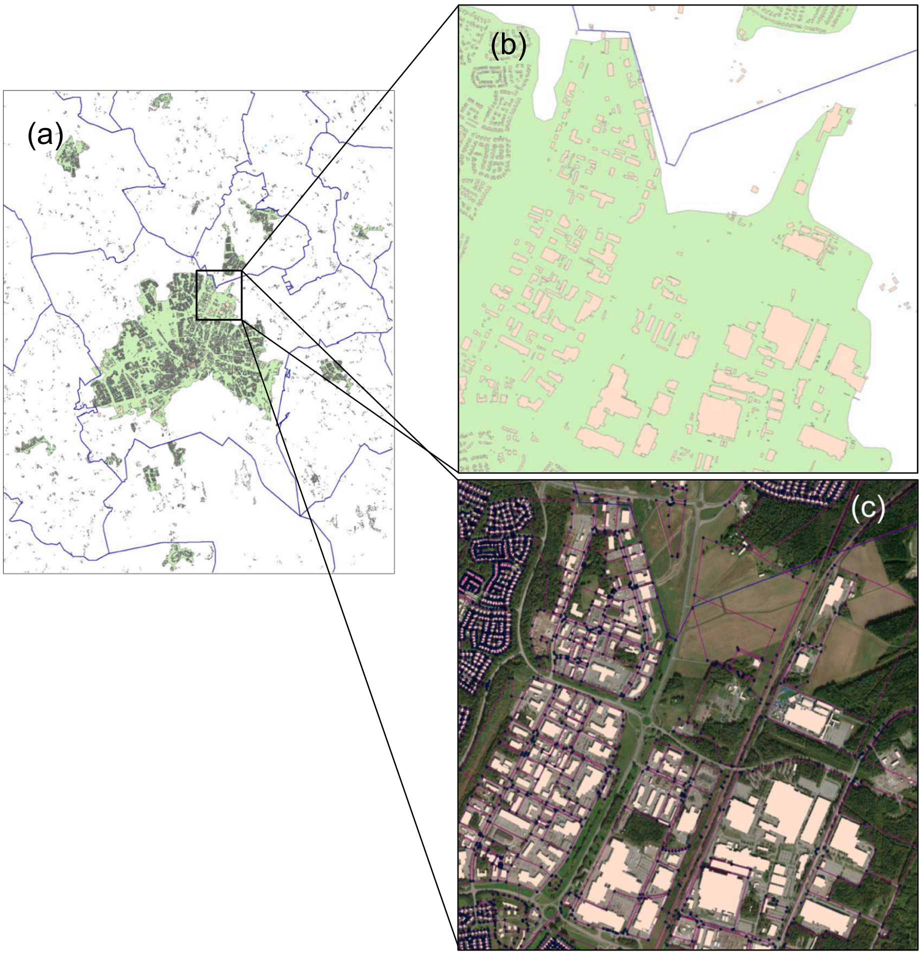

Fig. 1. (a) The vector map of Västerås with all buildings (The blue lines represent the administrative boundaries. The light green areas are the urban areas with high population density and infrastructure of the built environment. The light orange polygons represent the building roofs outlines), (b) A zoom-in area, i.e. Stenby Tunbytorp, in Västerås, 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).

The properties were measured with satellite positioning, which can be accurate to within a few centimeters [43]. Depending on altitude and image quality, measurement accuracy may vary slightly, but in general the position in plane has an average accuracy of 5 m [43]. About 4% deviation exists in the form of deficiency or redundancy at the national level [43].

Building types indicate which purpose the building is used for. Detailed building purposes in this study include: residential buildings, industrial buildings, buildings of social function, buildings of business function, buildings of economic/agricultural function, buildings of complementary function, and buildings of other unknown functions [43]. Residential buildings are predominantly used for permanent or leisure living, e.g. detached houses, chain houses, townhouses, and apartments. Industrial buildings predominantly contain the manufacture of products or processing of raw materials. Buildings of social function predominantly contain activities used by citizens in society, e.g. fire station, defense construction, health center, or religious community. Buildings of business function are mainly used for business, e.g. hotel, office, trade, restaurant, or parking garage. Buildings of economic/agricultural function are predominantly used for agriculture. Buildings of complementary function are buildings belonging to other buildings for residential purposes, community function, business or industry, e.g. outbuildings, garage, carport, cistern, warehouse, boathouse, or shed. Other buildings are those with unknown purposes.

The data used for area extrapolation are obtained from Statistics Sweden (SCB) and are freely accessible. PVsyst software (V6.87) is used for calculating solar PV electricity generation. Other data related to this study are specified in the corresponding context.

4. Methodology

This study presents a GIS-based approach combined with energy system modeling to facilitate the feasibility analysis of geographical and technical potential for roof-mounted solar PV systems. The methodology is comprised of three phases. The first phase is to evaluate the geographical potential for exploiting solar energy sources of building rooftops, including residential buildings, industrial buildings, buildings of social function, buildings of business function, buildings of economic/agricultural function, buildings of complementary function, and buildings of other unknown functions, in a Swedish municipality, Västerås. A step-by-step procedure has been developed for estimating total rooftop solar PV potential, which involves geographical data division and classification, gross area calculation, roof orientation analysis with sampling method, and roof shadows and obstacles analysis with utilization factors. The second phase is to evaluate the technical potential for installing solar PV systems. For flat roofs, the solar panels inter-row distance and the tilt angles are designed based on three scenarios. The third phase is to extrapolate the methodology from a municipal scale to the national scale, to reveal the potentially usable roof area and installed capacity of the entire country. A methodology flowchart can be found below (Fig. 2).

4.1. Roof surface area and utilization factors

4.1.1. Roof base area and surface area

The geographical potential for solar PV installation is defined as the usable roof area, that receive the solar radiation for the PV facility. In order to reduce the gross surface area to the realistic usable surface area

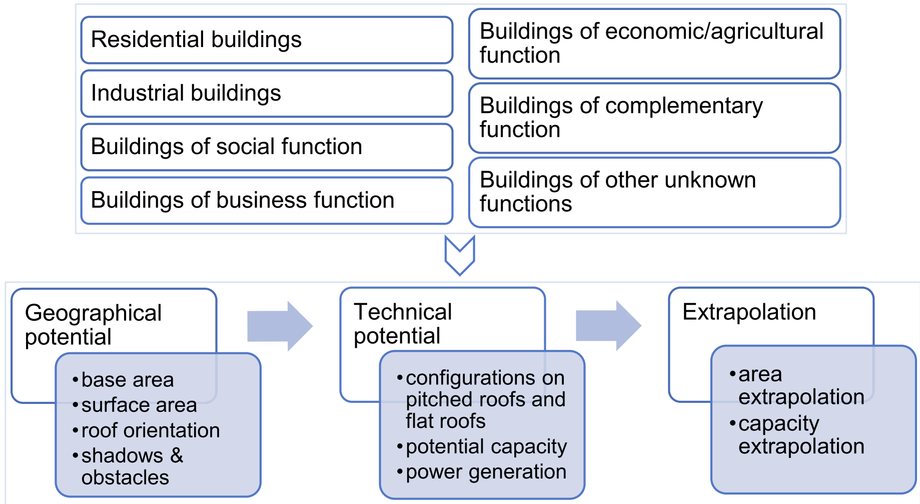

Fig. 2. The methodology flowchart in this study.

for solar PV systems, both absolute reductions and relative reductions are made. Absolute reductions apply to the area that should be subtracted directly from the surface area. This is due to their special purposes (cultural-heritage values) and difficulty of getting building permits. Relative reductions—such as those due to orientation, shadows and obstacles—should be processed with different utilization factors (see Sections 4.1.2 to 4.1.3).

For every building polygon with a unique code, we use the "Calculate Geometry" tool in ArcGIS software to calculate its base area. This tool allows us to access the geometry of the features in a layer, based on the coordinate values and lengths.

The buildings in Sweden have different roof shapes, such as gable roof, mansard roof, flat roof, shed roof, and butterfly roof [44,45]. Since the available vector data are not three-dimensional, some assumptions about the pitched-roof slope angle must be made. In Sweden, gable roofs are the most common roof type for residential buildings, buildings of complementary function, and buildings of economic/agricultural function; gable roofs have an average slope angle of 24-31°. Mansard roofs rank second most widely-used, with an average slope angle of 28–30° [45]. The other types have a slope angle between 0 and 9°. To simplify the calculations, an assumption about pitched-roof slope angle is obtained from Lingfors and Widén [36,37] and Kamp [45]. We assume that all buildings with pitched roofs have an ideal shape (Fig. 3). Their average slope angles are assumed to be 30°. In addition, industrial buildings, which are 0.99% of the total building number and 16.67% of the total base area in our dataset, are assumed to be flat [36,37,45]. Therefore, the roof surface area for the pitched roofs is calculated as follows.

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

where A_{roof} is the surface roof area, A_{base} is the base area, α^{roof} is the slope angle of the roof. m, p, and q are the length of the roof ridge, counter beam, and hanging beam. The calculations give the total area of ideal ceiling surfaces.

In practice, not all roofs are usable, due to orientation. Moreover, roof surfaces are limited by shadows and various obstacles such as skylights and chimneys. 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, unlike three-dimensional remote sensing technologies (e.g. airborne LiDAR), the vector data fail to automatically identify: (1) the orientations of the pitched roofs; (2) the shadows cast by neighboring structures, buildings, trees, or other parts of the roof itself; and (3) the

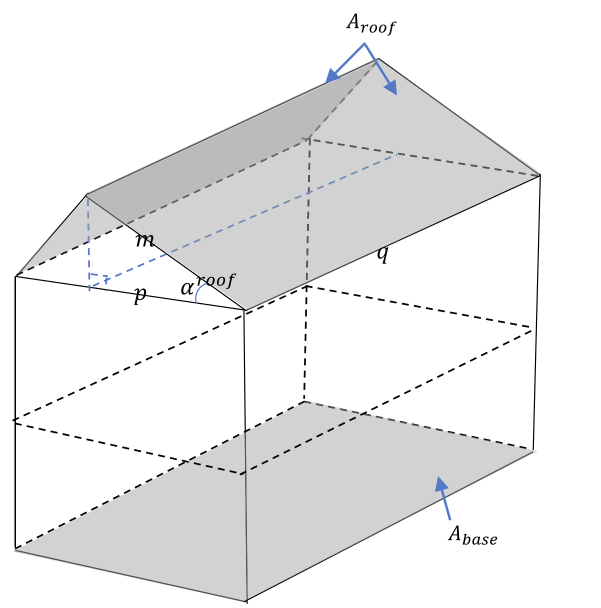

Fig. 3. The ideal building that is assumed as non-industrial building in the calculation.

roof obstacles, e.g. chimneys, heating, ventilation, and air conditioning (HVAC), elevator shafts, dormers, antennas, or other elements. Quantifying these factors is essential to evaluate their influence on the availability of radiation and consequently on the potential for solar PV system installation. Analysis for reducing ideal roof surface (see Sections 4.1.2 to 4.1.3) is conducted to calculate the total usable roof surface.

4.1.2. Roof orientation

In this study, we employ the sampling method to determine roof orientations. To obtain the orientation data, we take the district within the First Ring Road of Västerås municipality as the sample. In this district, the buildings have the function of residential, social, business, economic and complementary. Industrial buildings are excluded because there are no industrial buildings within the First Ring Road of Västerås municipality. First, we separate the whole sampling area into

Table 1
The roof orientation statistics within the First Ring Road district of Västerås municipality (excl. industrial buildings).

Roof orientation	Number of buildings	Percentage (%)
North (0°)	207	16.96
North East (45°)	57	4.67
East (90°)	206	16.88
South East (135°)	30.5	2.50
South (180°)	210	17.20
South West (225°)	60	4.92
West (270°)	208	17.04
North West (315°)	30.5	2.50
Flat	211.6	17.34

22 sub-areas by district, and assign a code to each satellite image from Google Earth Pro™. Second, we separate the roofs into units, i.e. one 30 m * 10 m roof area is one sample unit. Third, we count units by different orientations. The length and angle are measured based on the Google Earth Pro™ measurement feature. The roof azimuth values are measured clockwise. The orientation statistics are shown in Table 1. As the roof orientations are obtained from sampling, the sampling error could unavoidably incur.

In the case of pitched roofs, 58.54% usable pitched roofs ($R_{u_pit} = 0.59$) (including the orientation of South, South West, South East, West, and East) and 17.34% flat roofs ($R_{fla} = 0.17$) are considered for solar PV system installation. Their orientation roles are considered to be $r_{fla} = 1$, $r_{u_pit} = 1$, since they are usable for further calculations. North-facing ($R_{n_pit} = 0.24$) (including North, North West, and North East orientation) roofs are disregarded for solar PV system installations. Thus, considering building orientations, the fraction of oriented roof area can be computed as follows, using the following approach [46]:

$$U_{ori} = R_{fla} \cdot r_{fla} + R_{u\_pit} \cdot r_{u\_pit} + R_{n\_pit} \cdot r_{n\_pit} \quad (2)$$

where U_{ori} is the utilization factor of orientation, R_{fla} is the flat roof percent, r_{fla} is the orientation role for flat roofs, R_{u_pit} is the percent of applicable orientations for solar PV installations, r_{u_pit} is the orientation role for roofs with applicable orientations, R_{n_pit} is the percent of not-applicable orientations for solar PV installations, and r_{n_pit} is the orientation role for roofs with not-applicable orientations. $R_{u_pit} = R_s + R_{sw} + R_{se} + R_w + R_e$, and $R_{n_pit} = R_n + R_{ne} + R_{nw}$; R_s, R_{sw}, R_{se}, R_w, R_e, R_n, R_{ne}, R_{nw} are the percent with the orientation of South, South West, South East, West, East, North, North East, and North West, respectively. Notably, the sampling takes place only on non-industrial buildings.

4.1.3. Shadows and obstacles

Shadows and obstacles analysis is the second essential step of solar PV system potential estimation. The shadings caused by nearby buildings and/or vegetation, and the presence of obstacles such as chimneys, HVAC, and elevator shafts, should be eliminated as much as possible to minimize calculation inaccuracies [47]. Different researchers used different utilization factors employed in different regions; utilization factors as summarized in Table 2. The utilization factor is described and calculated as the total usable roof area for solar PV system installation divided by the total roof surface area. Values may range from 0.5 to 0.8, as shown in several studies (Table 2).

The studies on Swedish cases showed that approximately 25–30% [36,37] of total roof area is reserved for dormers and other uses, considering the effect of shading from nearby trees and buildings. Taking a conservative estimate, the fraction of industrial buildings and non-industrial buildings for solar PV system are given by Eqs. (3) and (4) [45]:

$$U_{so}^{ind} = 1 - 0.3 = 0.7 \quad (3)$$

$$U_{so}^{no-ind} = 1 - 0.25 = 0.75 \quad (4)$$

where U_{so}^{ind} is the utilization factor due to shadows and obstacles for industrial buildings. U_{so}^{no-ind} is the utilization factor due to shadows and obstacles for non-industrial buildings.

4.2. Installed capacity potential

4.2.1. Configurations on pitched roofs and flat roofs

When designing a solar PV system that is installed on pitched roofs,

Table 2
The fraction of usable roof areas for solar PV system in previous studies (non-exhaustive).

Reference	Year	Location	Factor and building types (UF = Utilization Factor; RF = Reduction Factor)
Kjellsson [48]	1999	Sweden	Obstacle RF = 0.1 and Shading RF = 0.1 (Small houses, private facilities, and unspecified). Obstacle RF = 0.1 and Shading RF = 0.15 (Apartment buildings and public facilities). Obstacle RF = 0.2 and Shading RF = 0.1 (Industry).
IEA [49]	2002	Selected IEA countries	UF = 0.4 for roof area, UF = 0.15 for façade area (Residential, agriculture, industry, commercial, and other buildings).
Ghosh, S., Vale, R., & Vale, B. [50]	2006	Auckland, New Zealand	UF = 0.296, 0.231, 0.296, 0.218, 0.468 (Five residential blocks).
Pillai, I. R., & Banerjee, R. [51]	2007	Pune, India	UF = 0.3 (Residential area having hospitals, nursing homes and hotels).
Izquierdo, S., Rodrigues, M., & Fueyo, N. [52]	2008	Spain	UF = 0.216 ~ 0.4335, Mean = 0.346 (All urban buildings).
Ordóñez, J., Jadraque, E., Alegre, J., & Martínez, G. [19]	2010	Andalusia, Spain	UF = 0.740 for flat roof, 0.974 for pitched roof (Detached and semi-detached houses). UF = 0.796 for flat roof, 0.983 for pitched roof (Town houses or row houses). UF 0.654 for flat roof, 0.789 for pitched roof (High-rise buildings).
Wiginton, L. K., Nguyen, H. T., & Pearce, J. M. [7]	2010	Ontario, Canada	UF = 0.3 (Urban and suburban areas: residential, commercial, and institutions).
Vardimon [17]	2011	Israel	UF = 0.3 (all buildings) UF = 0.5 (large buildings only)
Bergamasco, L., & Asinari, P. [21]	2011	Piedmont Region, Italy	Obstacle UF = 0.7 and shadowing UF = 0.46 (Residential and industrial buildings). Obstacle UF = 0.9 and shadowing UF = 1 (Industrial buildings).
Yue, C. D., & Huang, G. R. [53]	2011	Taiwan	UF = 0.4 (Urban areas: residence, commerce, industry, gas station, school, civic institute, health services, and admin agency).
Karteris, M., Slini, T., & Papadopoulos, A. M. [54]	2013	Thessaloniki, Greece	UF = 0.5 ~ 0.75 (Urban area).
Singh, R., & Banerjee, R. [55]	2015	Mumbai, India	UF = 0.28 (Urban sites: residential buildings, commercial buildings, offices, educational amenities, medical amenities, social amenities, transport and communication, and industrial use).
Khan, J., & Arsalan, M. H. [26]	2016	Karachi, Pakistan	RF = 0.35 (Urban area: residential buildings, commercial buildings, mosque, and educational institutes etc.).

the solar PV modules' angle is supposed to be parallel to the roof plane [24]. For the pitched roofs in five different orientations, a 30° tilt angle is applied for solar PV modules, which equals to the assumed roof angle. Different orientations give different electricity yields (kWh/kW$_p$).

However, for PV modules that are free-standing on flat roofs, determining the appropriate spacing between each row of PV modules is important, since the electricity yield can be affected by mutual-shading. In this study, 17.34% of the non-industrial buildings and 100% of the industrial buildings have flat roofs, where the mutual-shading effects should be considered, by setting appropriate PV panel tilt angles and inter-row spacing distances. Therefore, three scenarios, i.e. scenario A, scenario B, and scenario C, are investigated for flat roofs. In scenario A and scenario B, the PV modules are mounted in rows and oriented to true South. In scenario C, the PV modules are installed with East-West orientation and low tilt angle.

For solar modules mounted facing south, mutual-shading effects are caused by the preceding row of PV modules, and this effect applies to all rows except the first row. At a high latitudes like Västerås, the sun is relatively low in the sky, which causes a longer shadow between adjacent solar rows. This means that the land area needed for PV installations of a given capacity is larger than that needed at lower latitudes, if shading is to be avoided. On the winter solstice in the northern hemisphere, solar radiation is at its minimum, which requires a theoretically maximum inter-row distance, to avoid mutual shading (Fig. 4(a)). On the summer solstice in the northern hemisphere, solar radiation is at its maximum, which requires a theoretically minimum inter-row distance (Fig. 4(b)). Scenario A and scenario B investigate two different combinations of tilt angle and row distance, in response to different inter-row shading effects.

In scenario A, the mutual-shading effect is minimized by employing a longer row distance. The solar panels are assumed to mount at a fixed tilt on flat roofs. The tilt angle is determined in order to maximize the incidence of solar radiation exposed on the PV array for a specific period of time. Then the distance between two consecutive rows is calculated to avoid the mutual shading in winter solstice at noon. When this prerequisite is respected, mutual shading would never occur throughout the year at noon. The following equation (Eq. (5)) gives the optimal tilt angles in scenario A [56], which was developed based on the SMHI mesoscale model STRÅNG [57].

$$\beta_{opt} = -0.1101\phi^2 + 14.003\phi - 404.77 \tag{5}$$

where β_{opt} is the optimal tilt angle of PV module. ϕ is the latitude.

The Packing Factor (PF) used in the literature [58] defines the ratio between the PV array and the total ground area required for PV array installation (Fig. 5). It considers the aforementioned mutual-shading effects and determines the distance between rows in each case. However, rule-of-thumb PFs cannot be used, because they vary widely depending on specific location and mode of installation [59].

According to Martín-Chivelet [58], the PF is given by the following Equation (6):

$$PF = \frac{l}{d} = \left(cos\beta + \frac{sin\beta}{tan\alpha}cos\gamma\right)^{-1} \tag{6}$$

where β is the tilt angle of the PV array, α is the solar elevation defined by Eq. (7) and γ is the solar azimuth.

$$cos\alpha = sin\delta sin\phi + cos\delta cos\phi cos\omega \tag{7}$$

where δ is the earth's declination, and ω is the hour angle.

These two equations are applied at noon of the winter solstice. Consequently, the row distance in scenario A can be defined. The estimated optimal module tilt angles, the PFs for winter design, and the latitudes exhibit the following relationships (Fig. 6).

In scenario B, we look for the combination of tilt angle and row distance that gives the higher electricity generation per roof area (higher value of kWh/m^2 for a given area), higher potential installed capacity (tighter inter-row distance), and lower shading losses. With the same meteorological parameters and latitude, when the module tilt angle is decreased, the shadow cast by the front row is decreased. Therefore, a smaller row distance can be achieved which indicates greater potential installed capacity on a given area (kW$_p$/m^2). However, a smaller tilt angle does not necessarily give a higher annual electricity generation i.e, specific yield (kWh/kW$_p$). In order to get the optimal combination of tilt angle and row distance, a 35 kW$_p$ solar PV system in 10 rows is predefined as the reference system. Parametric simulations are run in PVsyst software (V6.87) using the most accurate simulation method that

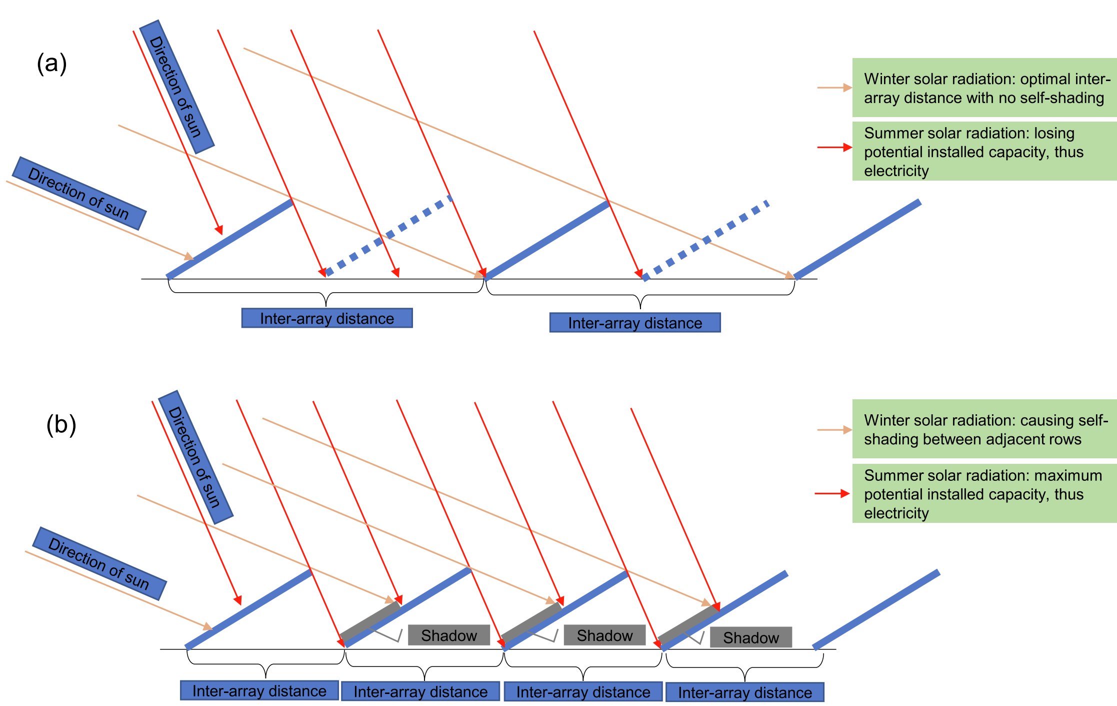

Fig. 4. (a) (b). Different inter-row distance designs and the mutual-shading effects during winter and summer season.

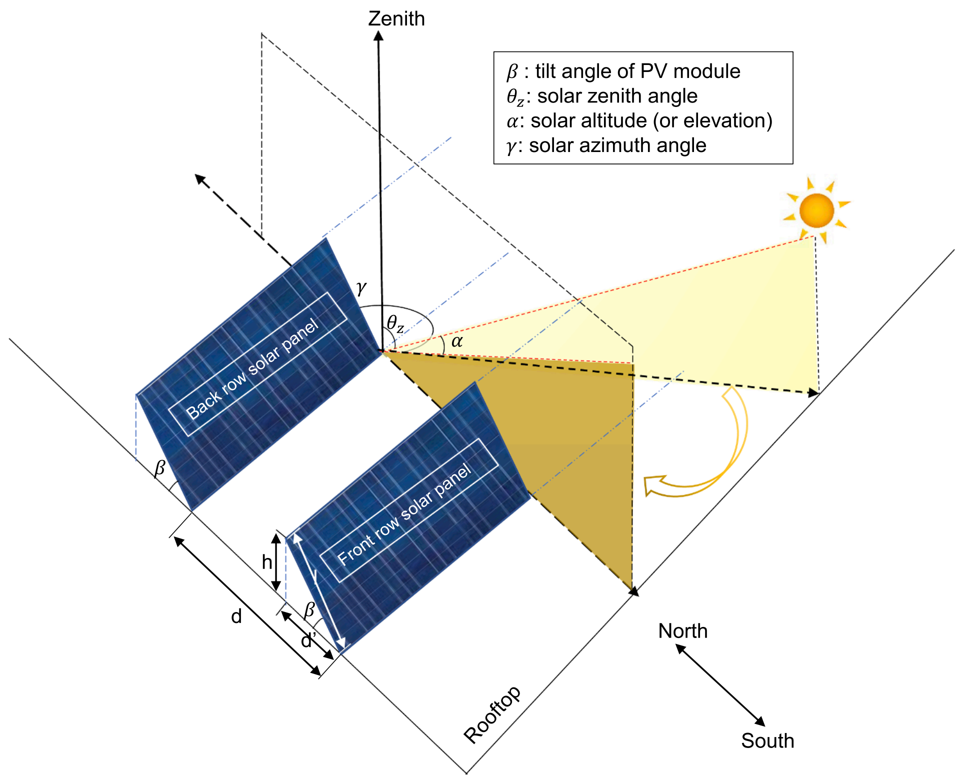

Fig. 5. Schematic diagram of the required distance between rows of solar panels in scenario A. The light and dark yellow parts represent the solar elevation angles.

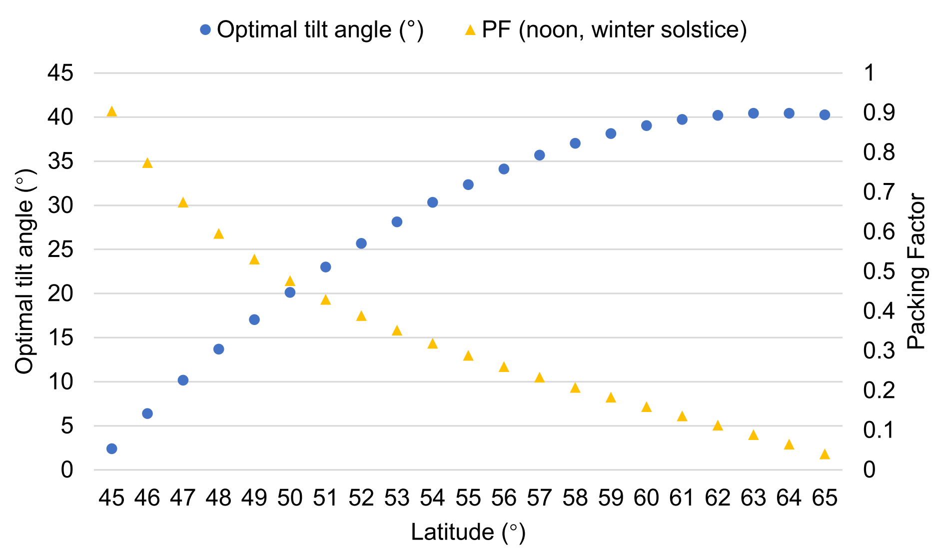

Fig. 6. The scatter plot of latitudes with the optimal module tilt angles and Packing Factors in scenario A.

considers shadings according to modules orientation and strings definition.

The south-facing configuration is generally suitable for maximizing the electricity generation by PV modules; meanwhile the effects of inter-row shading are presumed to be great. To realize effective electricity production with less shading, an East-West orientation with low tilt angle (scenario C) is designed as a comparison to scenario A and scenario B. As studied by [60,61], a combination of East-West orientation with low tilt angle is becoming a growing trend on flat roofs, which allows for a more economic land-use and greater installations on a given ground area. In the design of scenario C, the PV modules are mounted on flat roofs with low tilt and East-West orientation (Fig. 7).

This configuration can generate less electricity per installed kW_p comparing to South-oriented system, because it receives lower radiation on PV modules. However, East-West oriented PV installation can be fitted more tightly together on flat roofs, compared to South-oriented PV installation that requires to be spaced further apart to avoid mutual shading. Therefore, such installation allows for a maximum coverage of roof area with insignificant mutual shading. It is of interest to compared scenario B and scenario C as two commercial solutions; meanwhile, scenario A is more likely to be employed in theoretical design.

4.2.2. Potential capacity and energy conversion

Solar PV electricity production is determined based on three main

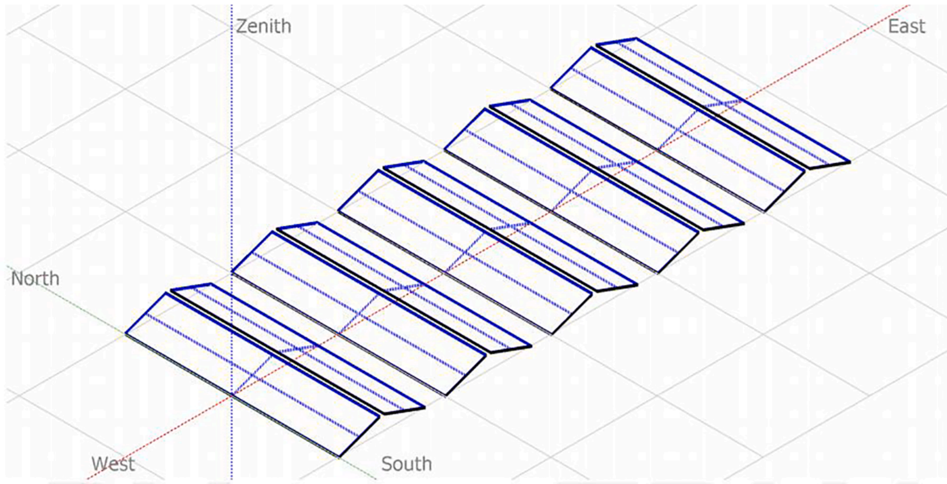

Fig. 7. East-West orientation configuration with low tilt angle in scenario C (screenshoot from PVsyst).

Table 3
Jinko Solar PV modules (JKMS 350M-72V Maxim) technical parameters.

Characteristics of a PV module (Jinko Solar, JKMS 350M-72V Maxim)	
STC Power Rating	$350W_p$
Technology	Si-mono
Module size (Width × Length)	0.992 × 1956 m^2
Rough module area	1.94 m^2
Number of cells	72
Max. power point voltage	39.3 V
Max. power point current	8.89 A
Power temper. coefficient	−0.38%/°C
Efficiency (/ Module area)	18.03%
Efficiency (/ Cells area)	20.5%

Table 4
Technical assumptions for solar PV energy generation in PVsyst (V6.87).

Ohmic losses	1.50%
Soiling losses	3.00%
Balance-of-System efficiency	86.46%
Module quality loss	−0.8%
Inverter efficiency	98.26% (ABB PRO-33.0-TL-OUTD-400)

parameters: solar radiation of the area, size of the solar PV system, and the performance ratio of the system. In this paper, Jinko Solar PV modules (JKMS 350M-72V Maxim) are employed. The size and technology of the modules and cells are given in Table 3 (PVsyst V6.87).

To minimize the mutual shading in the bottom and achieve greater electricity output, panels are assumed to be in landscape orientation [62,63]. Based on the module data (Table 3), geographical data, and technical assumptions (Table 4), the potential installed capacity and the total potential electricity generation of Västerås municipality can be calculated for different scenarios, and summarized in Section 5.1.

We employ a 5% reduction on yearly electricity production in Sweden, due to the snow on PV panels [45,64].

4.2.3. Extrapolation for the entire country

From SCB, we extract the data of building numbers and ground space area of buildings of different building types. The data from the land survey authority of Sweden (Lantmäteriet) and SCB suggest minor differences.

Based on the method in Section 4.1, the total usable roof area of different building types in Sweden can be calculated based on Eq. (8).

$$A_{pv}^{SE} = \sum_{mu=1}^{290}\left(\frac{A_{base}^{m}\cdot U_{abs}}{\cos\alpha^{roof}}\cdot U_{ori}\cdot U_{so}\right) \tag{8}$$

Table 5
The summarized parameter values and their applicable building types.

Parameter	Value	Apply to building type
$U_{abs}^{non_ind}$	90% (Section 4.1.1)	100% of non-industrial buildings
U_{abs}^{ind}	100% (Section 4.1.1)	100% of industrial buildings
α^{flat}	0° [36,37,45]	100% of industrial buildings and 17.34% of non-industrial buildings
α^{pit}	30° [36,37,45]	82.66% of non-industrial buildings
U_{ori}^{ind}	100% (Section 4.1.2)	100% of industrial buildings
$U_{ori}^{non_ind}$	75.88% (Section 4.1.2)	100% of non-industrial buildings
U_{so}^{ind}	70% (Section 4.1.3)	100% of industrial buildings
$U_{so}^{no_ind}$	75% (Section 4.1.3)	100% of non-industrial buildings

where A_{pv}^{SE} is the usable area for roof-mounted PV systems in Sweden, $mu = 1, 2, 3\cdots, 290$ (290 municipalities), A_{base}^{m} is the building base area of the m^{th} municipality, U_{abs} is the absolute reduction factor due to the cultural and religious purpose of buildings, α^{roof} is the slope angle of the roof, U_{ori} is the utilization factor of orientation, U_{so} is the shadows and obstacles factor. The values of the above parameters and the applicable building types can be found in Table 5.

Table 6
The usable area, potential installed capacity, and electricity generation for pitched roofs.

Roof type: pitched roofs	Usable area (km^2)	Tilt angle of PV modules (°)	Specific yield (kWh/ kW_p)	Potential installed capacity (MW_p)	Potential yearly electricity generation (GWh)
East	1.06	30	820	191	149
South East	0.16	30	966	28	26
South	1.08	30	1023	195	190
South West	0.31	30	966	56	51
West	1.07	30	814	193	150
Total	3.68	N/A	N/A	664	565

Table 7
The usable area, potential installed capacity, and electricity generation for flat roofs in three scenarios.

Roof type: flat roofs	Usable area (km^2)	Tilt angle of PV modules (°)	PV module orientation	Row distance (m)	Specific yield (kWh/kW_p)	Potential installed capacity (MW_p)	Potential yearly electricity generation (GWh)
Scenario A	2.06	39	South	5.9	1010	63	60
Scenario B	2.06	20	South	2	933	184	155
Scenario C	2.06	10	East-West	2.5	849	292	235

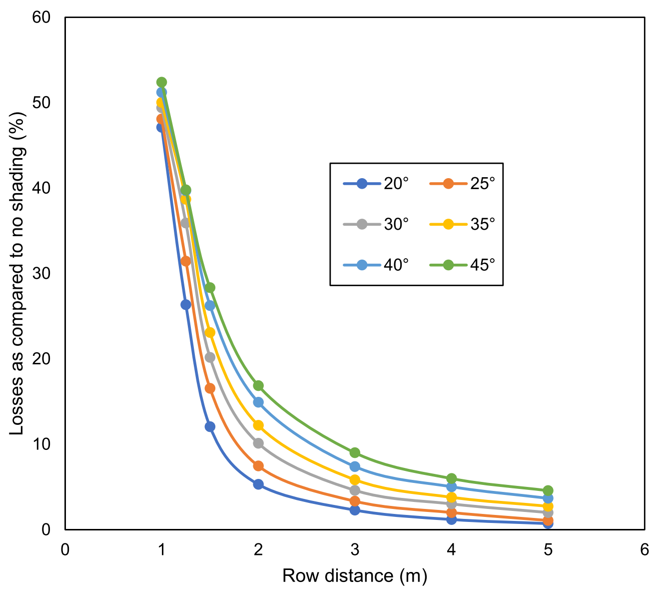

Fig. 8. The percent of electricity losses using different row distances and tilt angles due to mutual shading. Conducted for a 35 kW_p PV system mounted in rows. Calculated with PVsyst.

5. Results and discussion

5.1. Estimation of solar photovoltaic potential in Västerås

The estimated roof area for solar PV systems in Västerås is 5.74 km^2, with 1.12 km^2 area of industrial buildings and 4.63 km^2 area of non-industrial buildings. For building types, it is investigated that 3.68 km^2 are pitched roofs, and 2.06 km^2 are flat roofs.

For the pitched roofs, different orientation gives different electricity yields, which range from 814 kWh/kW_p (West-oriented) to 1023 kWh/kW_p (South-oriented). The total potential installed capacity is estimated to be 664 MW_p and yearly electricity generation 565 GWh. The results are presented in Table 6.

For scenario A of the flat roofs, a 5.9-meter row distance is calculated with 39° tilt angle. The potential installed capacity is estimated to be 63 MW_p and yearly electricity generation 60 GWh (Table 7).

For scenario B of the flat roofs, the simulation results of a 35 kW_p system (Fig. 8) suggest a 20° tilt angle and 2-meter row distance that gives the lowest shading losses. This design is also consistent with existing commercial solutions, for example, IBC Solar suggested 1.6-meter and 10°, 1.8-meter and 15° on flat roofs for the South-oriented solar PV systems in Germany [65]. In this particular scenario, the losses due to mutual-shading effect are estimated to be 5.3%. The potential installed capacity is estimated to be 184 MW_p and yearly electricity generation 155 GWh (Table 7).

For scenario C of the flat roofs (see Fig. 7), a 2.5-meter row distance and 0.05-meter top spacing are employed. Suggested by [66,65], we use the 10° as tilt angle. With the same module parameters (Table 3) and technical assumptions (Table 4), the potential installed capacity is estimated to be 292 MW_p and yearly electricity generation 235 GWh (Table 7).

To sum up, 5.74 km^2 usable area in Västerås gives potential installed capacity as 727 MW_p, 848 MW_p, and 956 MW_p, and potential yearly electricity generation as 626 GWh, 720 GWh, and 801 GWh on pitched roofs and flat roofs with three scenarios, respectively. This potential generation corresponds to 55%-70% of Västerås' annual electricity demand [67]. It is noteworthy that this does not consider the hourly or seasonal electricity supply and demand balance. Around noon in summer, there would be an excess of PV electricity that has to be exported. According to the statistics from Swedish Energy Agency, 14.46 MW_p of grid-connected systems was installed in Västerås municipality at the end of 2019 [68]. Comparing with the potential, this is still a very small share.

5.2. Estimation of solar photovoltaic potential in Sweden

After applying the method in Section 4.1 to all types of buildings, the overall results of roof area of Sweden and the geographical distribution of each municipality can be found in Fig. 9(a). The total usable roof area of different building types in Sweden is estimated to be 504 km^2, with 327 km^2 pitched roofs and 178 km^2 flat roofs.

Based on the method in Sections 4.2.1 and 4.2.2, the potential installed capacity across 290 municipalities is calculated. Three scenarios (scenario A, B, and C) are designed on the flat roofs. On the national scale, the total potential installed capacity of solar PV systems are 65, 75, and 84 GW_p on pitched roofs and flat roofs with three scenarios. The geographical distribution of potential installed capacity of roof-mounted solar PV systems can be found in Fig. 9(b)–(d). To the greatest extent possible, this study employs updated geographical data and statistical data to calculate solar PV capacity potential, and employs technical software to simulate solar energy conversion.

The usable roof area for solar PV installation per capita is 49 m^2 for Sweden on average, and 38 m^2 for Västerås municipality, which are within the range of results obtained by other authors. Izquierdo et al. [52] reported an available roof area per capita to be 14.0 ± 4.5 m^2/capita for Spain. The values ranged from 6.2 m^2/capita to 76.4 m^2/capita. Wiginton et al. [7], reported a roof area per capita of 70.0 m^2/ca ± 6.2% in the Canadian context, after reduction of constraint factors. Analysis of potential installed capacity yielded a value of 6–8 kW_p/capita for Sweden and 5–6 kW_p/capita for Västerås municipality. Considering the total city area and potential installed capacity, 10.5–13.9 MW_p/km^2 is estimated as potential capacity density of rooftop PV in Västerås. These values are generally higher than results such as 2.9 MW_p/km^2 for Wrocław (Poland) [69], 4.78 MW_p/km^2 for Mumbai (India) [55], and 1.75 MW_p/km^2 for Lethbridge (Canada) [46]. This is because, for example, we use the high-efficiency modules, lower tilt angles and shorter array distances in the scenarios of flat roofs. By the end of 2019, a record of 287 MW_p annual installation was made, which brought the total capacity to 698 MW_p [3]. However, compared with the potential, there is still huge space for the solar PV market in Sweden to grow.

5.3. Discussion: direct capital subsidy

Since 2009, Sweden offers a direct capital subsidy for the installation of grid-connected PV systems, which covered 60% of the installation cost in 2009 and 20% in 2020. In parallel to this direct capital subsidy, a 0.6 SEK/kWh tax deduction for sold electricity was introduced in 2015,

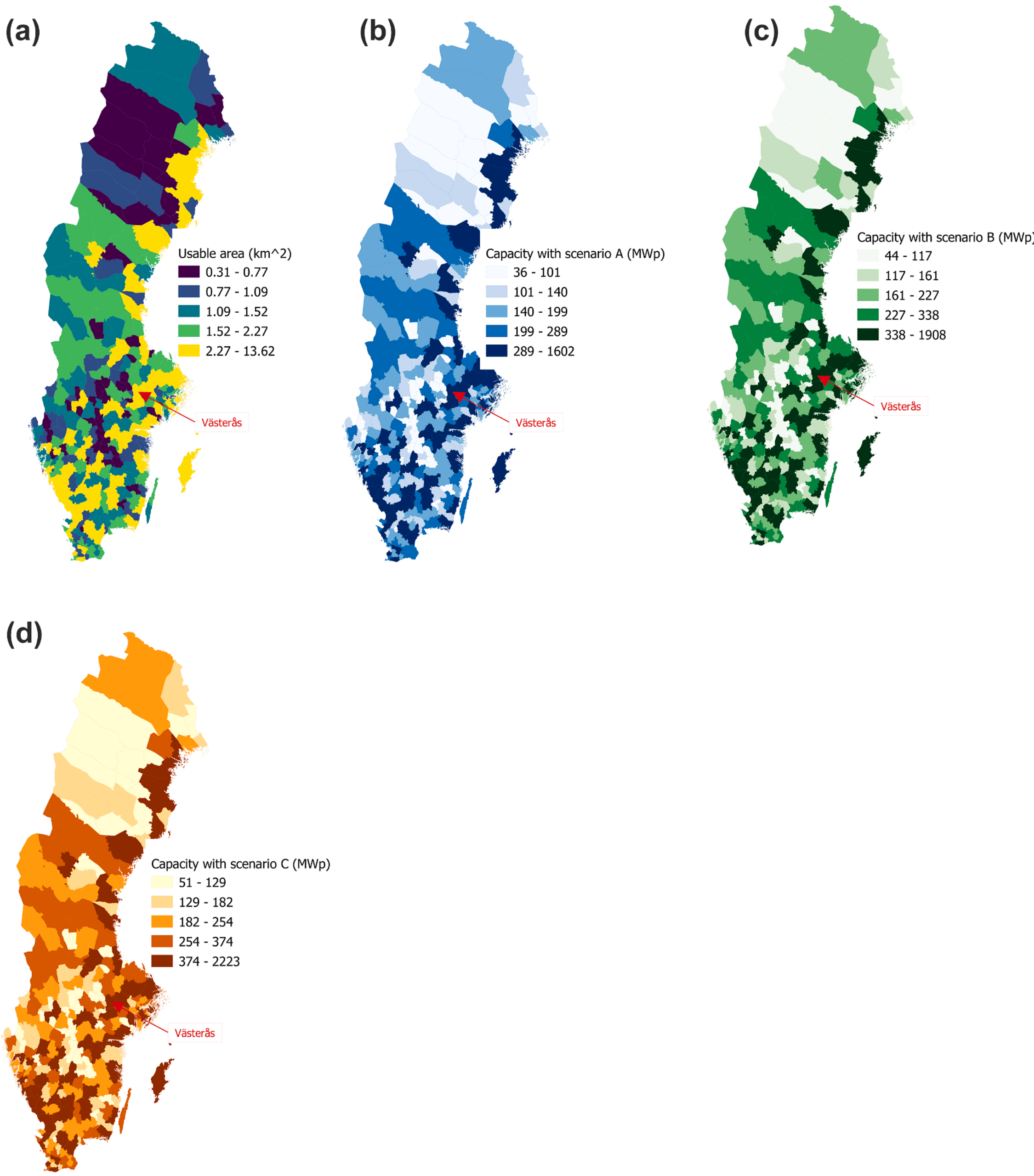

Fig. 9. (a) The potential area for roof-mounted solar PV systems, and (b) (c) (d) the potential installed capacity on pitched roofs and flat roofs with three scenarios.

for up to 30,000 kWh or so much electricity that is purchased per year [70]. To meet the increased interest in solar PV in Sweden, the current authorities decided in the autumn of 2015 to greatly increase the annual budget for the years 2016–2019, by 235, 390, 390, and 390 million SEK, respectively. In 2017, the budget was decided to increase even more to 585.6 million and 1.085 billion SEK to 2017 and 2018. After the revision in autumn 2018 and spring 2019, a total of 1.2 billion SEK was allocated for 2019. The budget over the years and the historical direct capital subsidies are summarized in Fig. 10 [5].

As a young and growing industry, the solar PV industry still needs access to external funding at various times in Sweden. Subsidization is an important tool available within the arsenals of governments for supporting their renewable energy industries. By using careful policy measures, policymakers have the means to increase the uptake of PV, thereby spurring associated innovation and increasing economic competitiveness through economies of scale.

The ambition of Sweden is to become one of the world's fossil-free welfare states. The Government will continue to boost the expansion of solar power, serving as a suitable source of energy that could alleviate aspects of the current climate crisis [2]. Based on the results in this study, the maximum installed capacity on roofs in Sweden has a theoretical potential of 65 GW_p to 84 GW_p. These not-yet-achievable amounts highlight critical issues for investors and authorities, despite the fact that it is not possible to fully exploit the theoretically available roof resources. Meanwhile, the arousing of interest in and the increasing of awareness of solar PV projects are substantially accelerating deployment. The direct capital subsidy program has attracted many investors since 2009, which makes the allocated budget from authorities always less than the amounts that were applied by solar PV owners. For example, an average waiting time of 722 days occurred in 2016.

As in the early stage, subsidies (particularly in the form of direct capital subsidies) are sufficient and necessary to strengthen a newborn industry. Examples such as China, Greece, and Spain have shown how strong endorsement by the authorities strengthened the solar PV

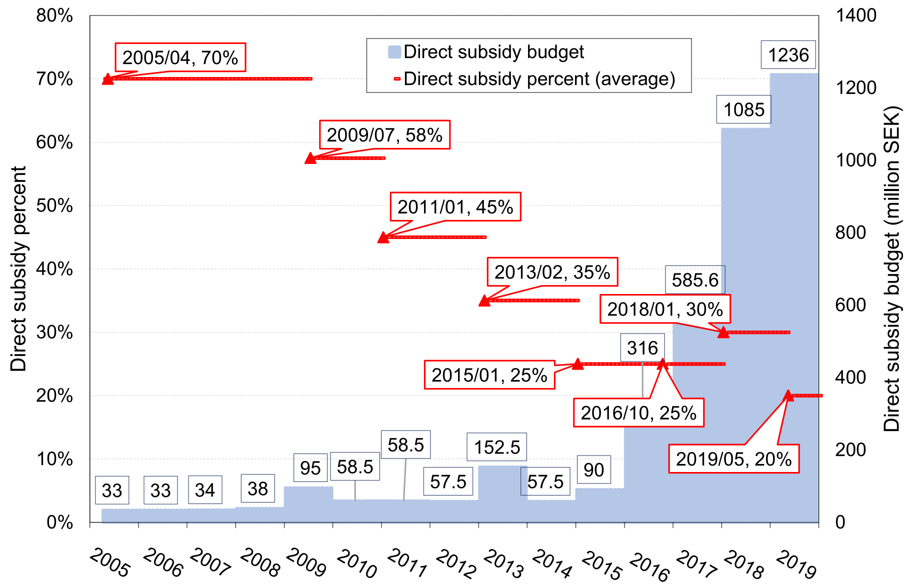

Fig. 10. The historical direct subsidy percent and the budgets for solar industry [5].

industry. In Sweden, similar effects are occurring in the solar PV industry in recent years. Subsidies have supported approximately 79% (337 MW_p) of total installed capacity until 2018 [5]. However, subsidies should be designed to be realistic and controllable. In the later stage, the authorities should gradually withdraw direct financial subsidies. More focus should be placed on other forms of incentives, for example, strengthen self-consumption by reducing or removing energy taxes for prosumers owning a PV system larger than 255 kW_p and strengthen tax deduction for "green" investments as proposed by some [71]. Otherwise, the policy risks brought by the policy might lead to overcapacity and subsidy gaps.

5.4. The scope and limitations

This study investigates the usable roof area for solar PV systems, potential installed capacity, and yearly solar electricity production in Västerås municipality. With the extrapolation of methodology, the usable area and potential installed capacity for entire Sweden are estimated as well.

This study only investigates the theoretical designs and values, which do not indicate the actual installations. In fact, to reflect the actual installation, more factors should be integrated and analyzed, e.g. grid capacity and economic factors. The peak power of Mälarenergi (city-owned power provider based in Västerås) in winter is around 200 MW. Vattenfall (Government-owned power provider) owns part of the grid and has a peak power of less than 50 MW. In total, the peak power shall be less than 250 MW in winter. This value is much lower in summer. Nevertheless, the estimated solar PV capacity in this study is higher than 700 MW, which is far greater than the grid capacity. However, it is out of the scope of this work to model how much solar electricity could be allocated in the power grid. Moreover, a threshold of 255 kW_p system could influence if the roofs could be effectively used or not. Solar PV systems below 255 kW_p are exempt from paying full energy tax (0.353 SEK/kWh) on the self-consumed electricity in Sweden. Several smaller systems owned by one actor, that together passes 255 kW_p installed capacity, are expected to pay 0.005 SEK/kWh energy tax on the self-consumed electricity. For this reason, most installations on roofs are smaller than 255 kW_p, thereby not effectively making use of all usable roof area. Furthermore, a large supply of solar electricity affects the intraday trading in Nord Pool (power market for Nordic countries) and results in lower prices of the produced PV electricity. This economic factor should also be carefully taken into consideration when planning the actual installation. However, this work does not consider any factor that affects the profitability of PV owners. Future work will incorporate a more complex economic analysis.

In this study, the datasets are from Lantmäteriet (in the case of Västerås municipality) and SCB (in the case of entire Sweden). It is worth to mention that the sampling method on roof orientations relies on statistical data. That particular data is not available at high spatial resolutions. In extrapolation, roof orientations are assumed to be homogeneous for all municipalities in Sweden. The error might incur due to this assumption. Nevertheless, the exact measurement of sampling error is not feasible, since the true values of roof orientation are unknown. Besides, it is assumed that all available roofs, except for buildings for cultural and religious purposes, are legally suited for the solar PV systems. This could overestimate the total potential capacity.

Comparing to previous results, for instance the study conducted by Kamp in 2013 [45] (Table 8), similar methods were employed. However, we use the most updated data for building area, solar module efficiency, and solar module size. Furthermore, when dealing with the tilt angle and the production losses due to the inter-row shadings on flat roofs, we do the analysis based on three scenarios. These scenarios aim to minimize shadows over the year and maximize electricity generation per area. Last but not least, when calculating the useable area, Kamp [45] combined the reduction factors of area and reduction factors of production together, which resulted in an underestimation of the usable area. An even older study conducted by Kjellsson [48] in 1999 showed that a total area of 459 km^2 was usable for building integrated photovoltaics in Sweden. This area included detached houses, apartment

Table 8
Results comparison between this study and previous studies.

Results	Västerås case	Sweden case	Sweden case [45]	Kjellsson [48]
Base area (km^2)	9.66	975		
Surface area (km^2)	10.70	1086	1091	
Usable area (km^2)	5.74	504	319	459
Potential installed capacity (GW_p)	0.7–1	65–84	47.9	

buildings, premises, industrial buildings, agricultural buildings, and holiday houses.

6. Conclusion

In this study, results show a significant potential for utilizing solar energy on building surfaces in Västerås municipality. A total 5.74 km^2 roof area is identified for solar panels on building rooftops. Secondly, this study calculates the technical potential, which estimates the available solar PV electricity, and the geographical potential, by taking the technical characteristics into consideration. The amount of electricity that could be produced through the projected roof utilization is calculated, considering PV inter-row distance design and characteristics of panels. The usable roof area translates into a total of 727 MW_p - 956 MW_p capacity on pitched roofs and flat roofs with three scenarios, respectively. The potential PV annual electricity production from the roof-mounted solar applications of Västerås municipality is 626 GWh - 801 GWh, which corresponds to 55%-70% of Västerås' annual electricity demand. Notably, this is only in consideration of the total electricity amount. In order to achieve power balance in real time, hourly power demand and supply profiles shall be analyzed. Thirdly, this study extrapolates the methodology from a municipality level to a national level. Approximately 504 km^2 available roof area is identified, and a total of 65 GW_p - 84 GW_p potential capacity is calculated for Sweden. The current policies, especially Sweden's direct capital subsidy, have been helping to fulfill the prerequisites for further diffusion of solar PV technologies in Sweden. Analysis has shown great photovoltaic potential, which suggests the need for more careful, realistic, and controllable policy measures from the authorities. Further market formation should be time-bound and independent from subsidies, in order to stimulate market-based entrepreneurship.

These policy implications are transferable to other countries- both developed and developing countries - as well. Solar energy will continue to expand over the next few decades both globally and in Sweden. In the current stage, the technical barriers in the solar energy industry are significantly diminished due to the technology advancements. In countries where market infrastructure is relatively mature, more focus could be placed on the exploitation of potential solar energy resources. Countries as early adopters are recommended to continue with incentives from authorities. Policy instruments can be multi-forms, such as subsidies, loans, tax exemptions, and other financial and non-financial support.

The outcomes of this study will be helpful in providing an established reference point for roof PV exploitation at the regional and national levels. Further research might usefully consider the temporal diffusion patterns of PV uptake interacting with other socio-economic factors. Further research could also adopt a more local level analysis to explore how the potential of solar PV energy generation could be integrated with load profiles of different uses.

Data Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon request.

CRediT authorship contribution statement

Ying Yang: Conceptualization, Methodology, Software, Validation, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Pietro Elia Campana:** Methodology, Software, Validation, Resources, Data curation, Writing - review & editing. **Bengt Stridh:** Methodology, Validation, Formal analysis, Resources, Writing - review & editing. **Jinyue Yan:** Formal analysis, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has received funding from KKS through Future Energy Profile (Project iREST and Project FREE), and Swedish Research Council (VR). This study has also received funding from the European Community's H2020 Framework Programme under grant agreements No 646529 and 774309. Ying Yang acknowledges financial support from the China Scholarship Council (CSC).

References

[1] Sommerfeldt N, Madani H, Carlo M. Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems : Part two - Application. Renew Sustain Energy Rev 2017;74:1394–404. https://doi.org/10.1016/j.rser.2017.03.010.
[2] Ministry of the Environment - Government Offices of Sweden. Summary of the Government's budget initiatives in the areas of environment, climate and energy 2016. https://www.government.se/articles/2016/09/summary-of-the-governments-budget-initiatives-in-the-areas-of-environment-climate-and-energy/%3E (accessed April 17, 2020).
[3] Swedish Energy Agency (Energimyndigheten). Grid-connected solar power plants 2020. http://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/natanslutna-solcellsanlaggningar/ (accessed April 27, 2020).
[4] Lindahl J. National Survey Report of PV Power Applications in Sweden 2016. 2017.
[5] Lindahl J, Stoltz C, Oller-Westerberg A, Berard J. National Survey Report of PV Power Applications in Sweden 2018: Task 1 Strategic PV Analysis and Outreach 2019.
[6] Haegermark M, Kovacs P, Dalenb J. Economic feasibility of solar photovoltaic rooftop systems in a complex setting: A Swedish case study. Energy 2017;127:18–29. https://doi.org/10.1016/j.energy.2016.12.121.
[7] Wiginton LK, Nguyen HT, Pearce JM. Computers, Environment and Urban Systems Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. Comput Environ Urban Syst 2010;34:345–57. https://doi.org/10.1016/j.compenvurbsys.2010.01.001.
[8] Nikas A, Stavrakas V, Arsenopoulos A, Doukas H, Antosiewicz M, Witajewski-Baltvilks J, et al. Barriers to and consequences of a solar-based energy transition in Greece. Environ Innov Soc Transitions 2019. https://doi.org/10.1016/j.eist.2018.12.004.
[9] Del Río P, Mir-Artigues P. Support for solar PV deployment in Spain: Some policy lessons. Renew Sustain Energy Rev 2012. https://doi.org/10.1016/j.rser.2012.05.011.
[10] Yan J, Yang Y, Campana PE, He J. City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China. Nat Energy 2019;4:709–17. https://doi.org/10.1038/s41560-019-0441-z.
[11] Li Y, Liu C. Estimating solar energy potentials on pitched roofs. Energy Build 2017;139:101–7. https://doi.org/10.1016/j.enbuild.2016.12.070.
[12] Snape JR. Spatial and Temporal Characteristics of PV Adoption in the UK and Their Implications for the Smart Grid. Energies 2016:1–18. https://doi.org/10.3390/en9030210.
[13] Balta-ozkan N, Yildirim J, Connor PM. Regional distribution of photovoltaic deployment in the UK and its determinants: A spatial econometric approach. Energy Econ 2020;51:417–29. https://doi.org/10.1016/j.eneco.2015.08.003.
[14] Lee C. Influence of local environmental, social, economic and political variables on the spatial distribution of residential solar PV arrays across the United States. Energy Policy 2012;47:332–44. https://doi.org/10.1016/j.enpol.2012.04.074.
[15] Sun Ywei, Hof A, Wang R, Liu J, Lin Yjie, Yang Dwei. GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian Province. Energy Policy 2013;58:248–59. https://doi.org/10.1016/j.enpol.2013.03.002.
[16] He G, Kammen DM. Where, when and how much solar is available ? A provincial-scale solar resource assessment for China. Renew Energy 2016;85:74–82. https://doi.org/10.1016/j.renene.2015.06.027.
[17] Vardimon R. Assessment of the potential for distributed photovoltaic electricity production in Israel. Renew Energy 2011;36:591–4. https://doi.org/10.1016/j.renene.2010.07.030.
[18] Hofierka J, Kaňuk J. Assessment of photovoltaic potential in urban areas using open-source solar radiation tools. Renew Energy 2009;34:2206–14. https://doi.org/10.1016/j.renene.2009.02.021.
[19] Jadraque E, Alegre J, Martı G, Ordo J. Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain). Renew Sustain Energy Rev 2010;14:2122–30. https://doi.org/10.1016/j.rser.2010.01.001.
[20] Hossain A, Islam AKMS. Potential and viability of grid-connected solar PV system in Bangladesh. Renew Energy 2011;36:1869–74. https://doi.org/10.1016/j.renene.2010.11.033.

[21] Bergamasco L, Asinari P. Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area : Application to Piedmont Region (Italy). Sol Energy 2011;85:1041–55. https://doi.org/10.1016/j.solener.2011.02.022.
[22] Choi Y, Rayl J, Tammineedi C, Brownson JRS. PV Analyst: Coupling ArcGIS with TRNSYS to assess distributed photovoltaic potential in urban areas. Sol Energy 2011;85:2924–39. https://doi.org/10.1016/j.solener.2011.08.034.
[23] Strzalka A, Alam N, Duminil E, Coors V, Eicker U. Large scale integration of photovoltaics in cities. Appl Energy 2012;93:413–21. https://doi.org/10.1016/j.apenergy.2011.12.033.
[24] Mainzer K, Fath K, Mckenna R, Stengel J, Fichtner W, Schultmann F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. Sol Energy 2014;105:715–31. https://doi.org/10.1016/j.solener.2014.04.015.
[25] Theodoridou I, Karteris M, Mallinis G. Assessment of retrofitting measures and solar systems' potential in urban areas using Geographical Information Systems: Application to a Mediterranean city. Renew Sustain Energy Rev 2012;16:6239–61. https://doi.org/10.1016/j.rser.2012.03.075.
[26] Khan J, Arsalan MH. Implementation of Open Source GIS Tools to Identify Bright Rooftops for Solar Photovoltaic Applications – A Case Study of Creek Lanes, DHA. Karachi. J Basic Appl Sci 2016. https://doi.org/10.6000/1927-5129.2016.12.03.
[27] Nguyen HT, Pearce JM, Harrap R, Barber G, Engineering G. The Application of LiDAR to Assessment of Rooftop Solar Photovoltaic Deployment Potential in a Municipal District Unit. Sensors 2012:4534–58. https://doi.org/10.3390/s120404534.
[28] Szabo S, Enyedi P, Horvath M, Kovacs Z, Burai P, Csoknyai T, et al. Automated registration of potential locations for solar energy production with Light Detection And Ranging (LiDAR) and small format photogrammetry. J Clean Prod 2020;112:3820–9. https://doi.org/10.1016/j.jclepro.2015.07.117.
[29] Song X, Huang Y, Zhao C, Chang Y, Yang J. An Approach for Estimating Solar Photovoltaic Sensing Images. Energies 2018;11:3172. https://doi.org/10.3390/en11113172.
[30] Latif ZA, Zaki NAM, Salleh SA, Ain N, Zaki M, Salleh SA. GIS-based estimation of rooftop solar photovoltaic potential using LiDAR. In: 2012 IEEE 8th Int. Colloq. Signal Process. its Appl., 2012, p. 388–92. https://doi.org/10.1109/CSPA.2012.6194755.
[31] Kucuksari S, Khaleghi AM, Hamidi M, Zhang Y, Szidarovszky F, Bayraksan G, et al. An Integrated GIS, optimization and simulation framework for optimal PV size and location in campus area environments. Appl Energy 2014;113:1601–13. https://doi.org/10.1016/j.apenergy.2013.09.002.
[32] Byrne J, Taminiau J, Kurdgelashvili L, Nam K. A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. Renew Sustain Energy Rev 2015;41:830–44. https://doi.org/10.1016/j.rser.2014.08.023.
[33] Bu R, Grassi S, Raubal M. A scalable method for estimating rooftop solar irradiation potential over large regions. Appl Energy 2018;216:389–401. https://doi.org/10.1016/j.apenergy.2018.02.008.
[34] Machete R, Falcão AP, Gomes MG, Moret Rodrigues A. The use of 3D GIS to analyse the influence of urban context on buildings' solar energy potential. Energy Build 2018. https://doi.org/10.1016/j.enbuild.2018.07.064.
[35] Africani P, Bitelli G, Lambertini A, Minghetti A, Paselli E. Integration of Lidar Data Into a Municipal Gis To Study Solar Radiation. ISPRS - Int Arch Photogramm Remote Sens Spat Inf Sci 2013;XL-1/W1:1–6. https://doi.org/10.5194/isprsarchives-xl-1-w1-1-2013.
[36] Lingfors D, Widén J. The solar energy potential for Blekinge's development - according to two future scenarios. Blekinge Cty Adm Board-Sweden 2014. https://www.lansstyrelsen.se/blekinge/tjanster/publikationer/2014/201410-solenergipotentialen-for-blekinges-bebyggelse-enligt-tva-framtidsscenarier.html (accessed April 17, 2020).
[37] Lingfors D, Widén J. The solar energy potential for Skåne's development - according to two future scenarios. Blekinge Cty Adm Board-Sweden 2018. https://www.lansstyrelsen.se/blekinge/tjanster/publikationer/2014/201410-solenergipotentialen-for-blekinges-bebyggelse-enligt-tva-framtidsscenarier.html (accessed April 17, 2020).
[38] Widén J, Weiss P. Solar energy in Dalarna's development - Potential for 2020 and 2050. Dalarna Cty Adm Board-Sweden 2012. www.lansstyrelsen.se/dalarna (accessed April 17, 2020).
[39] Lingfors D, Widén J. The solar energy potential according to two future scenarios for the development in Västmanland County and the municipalities; Heby, Håbo, Katrineholm, Strängnäs, and Örebro. Uppsala-Sweden: n.d.
[40] Statistics Sweden (SCB). Population in the state, counties and municipalities December 31, 2019 and population changes 2019 2020. https://www.scb.se/hitta-statistik/statistik-efter-amne/befolkning/befolkningens-sammansattning/befolkningsstatistik/pong/tabell-och-diagram/helarsstatistik–kommun-lan-och-riket/folkmangd-i-riket-lan-och-kommuner-31-december-2019-och-befolkningsforandringar-2019/ (accessed April 27, 2020).
[41] Swedish Land Survey (Lantmäteriet). Aerial and satellite images 2019. https://www.lantmateriet.se/en/maps-and-geographic-information/Flyg–och-satellitbilder/ (accessed April 17, 2020).
[42] Swedish Land Survey (Lantmäteriet). Handbook of buildings (Version 3,0) 2017. https://www.lantmateriet.se/contentassets/b3510f87ca6648a0b64c725e946b90e7/handbok_byggnad.pdf.
[43] Swedish Land Survey (Lantmäteriet). Product description: GSD property map, vector (Version 7.4) 2017. https://www.lantmateriet.se/globalassets/kartor-och-geografisk-information/kartor/e_fastshmi.pdf.
[44] Swedish Wood (Svenskt Trä). Roof - shape, material and construction 2020. https://www.traguiden.se/konstruktion/konstruktiv-utformning/stomkomplettering/tak/form-material-och-konstruktion/ (accessed April 17, 2020).
[45] Kamp S. The electric potential for roof mounted solar panels in Sweden. Uppsala University; 2013.
[46] Mansouri F, James K, Dan B, Locke J, Paul S. Evaluating solar energy technical and economic potential on rooftops in an urban setting: the city of Lethbridge, Canada. Int J Energy Environ Eng 2019:13–32.
[47] Freitas S, Catita C, Redweik P, Brito MC. Modelling solar potential in the urban environment: State-of-the-art review. Renew Sustain Energy Rev 2015;41:915–31. https://doi.org/10.1016/j.rser.2014.08.060.
[48] Kjellsson E. Study of the potential for building integrated PV in Sweden: report 1: building surfaces. Lund Dep Struct Phys 1999. https://books.google.se/books/about/Potentialstudie_för_byggnadsintegrerade.html?id=krH9jgEACAAJ&redir_esc=y (accessed April 17, 2020).
[49] International Energy Agency (IEA). Potential for Building Integrated Photovoltaics. vol. 2002. 2002.
[50] Ghosh S, Vale R, Vale B. Domestic energy sustainability of different urban residential patterns: a New Zealand approach. Int J Sustain Dev 2006;9:16–37.
[51] Pillai IR, Banerjee R. Methodology for estimation of potential for solar water heating in a target area. Sol Energy 2007;81:162–72. https://doi.org/10.1016/j.solener.2006.04.009.
[52] Izquierdo S, Rodrigues M, Fueyo N. A method for estimating the geographical distribution of the available roof surface area for large-scale photovoltaic energy-potential evaluations. Sol Energy 2008;82:929–39. https://doi.org/10.1016/j.solener.2008.03.007.
[53] Yue C, Huang G. An evaluation of domestic solar energy potential in Taiwan incorporating land use analysis. Energy Policy 2011;39:7988–8002. https://doi.org/10.1016/j.enpol.2011.09.054.
[54] Karteris M, Slini T, Papadopoulos AM. Urban solar energy potential in Greece: A statistical calculation model of suitable built roof areas for photovoltaics. Energy Build 2013;62:459–68. https://doi.org/10.1016/j.enbuild.2013.03.033.
[55] Singh R, Banerjee R. Estimation of rooftop solar photovoltaic potential of a city. Sol Energy 2015;115:589–602. https://doi.org/10.1016/j.solener.2015.03.016.
[56] Campana PE, Landelius T, Andersson S, Lundström L, Nordlander E, He T, et al. A gridded optimization model for photovoltaic applications. Sol Energy 2020;202:465–84. https://doi.org/10.1016/j.solener.2020.03.076.
[57] Swedish Meteorological and Hydrological Institute (SMHI). STRÅNG - a mesoscale model for solar radiation 2017. http://strang.smhi.se/ (accessed June 22, 2020).
[58] Martín-chivelet N. Photovoltaic potential and land-use estimation methodology. Energy 2016;94:233–42. https://doi.org/10.1016/j.energy.2015.10.108.
[59] Campana PE, Wästhage L, Nookuea W, Tan Y, Yan J. Optimization and assessment of floating and floating-tracking PV systems integrated in on- and off-grid hybrid energy systems. Sol Energy 2019;177:782–95. https://doi.org/10.1016/j.solener.2018.11.045.
[60] Asgharzadeh A, Deline C, Stein J, Toor F. A Comparison Study of the Performance of South/North-facing vs East/West-facing Bifacial Modules under Shading Conditi. In: 2018 IEEE 7th World Conf Photovolt Energy Conversion, WCPEC 2018 - A Jt Conf 45th IEEE PVSC, 28th PVSEC 34th EU PVSEC 2018:1730–4. https://doi.org/10.1109/PVSC.2018.8548185.
[61] Hartner M, Ortner A, Hiesl A, Haas R. East to west - The optimal tilt angle and orientation of photovoltaic panels from an electricity system perspective. Appl Energy 2015;160:94–107. https://doi.org/10.1016/j.apenergy.2015.08.097.
[62] Galtieri J, Krein PT. Designing solar arrays to account for reduced performance from self-shading. In: 2015 IEEE Power Energy Conf. Illinois, 2015, p. 1–8. https://doi.org/10.1109/PECI.2015.7064935.
[63] Awad H, Gül M, Ritter C, Verma P, Chen Y, Salim KME, et al. IEEE Conf. Technol. Sustain. 2016;2016:39–46. https://doi.org/10.1109/SusTech.2016.7897140.
[64] Pawluk RE, Chen Y, She Y. Photovoltaic electricity generation loss due to snow – A literature review on influence factors, estimation, and mitigation. Renew Sustain Energy Rev 2019;107:171–82. https://doi.org/10.1016/j.rser.2018.12.031.
[65] IBC Solar. Installation Instructions. Bad Staffelstein, Germany: 2019. https://doi.org/10.1017/cbo9781316529881.002.
[66] Malmsten J. Solar cells on roof: opportunities and pitfalls. Sweden: Stockholm; 2015.
[67] Statistics Sweden (SCB). End use (MWh), by county and municipality, consumer category and fuel type. Year 2009 - 2017. 2019. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START_EN_EN0203/SlutAnvSektor/# (accessed April 17, 2020).
[68] Swedish Energy Agency (Energimyndigheten). Grid-connected solar cell installations, number and installed power 2020. https://pxexternal.energimyndigheten.se/pxweb/sv/Nätanslutna solcellsanläggningar/-/EN0123_1.px/?rxid=5e71cfb4-134c-4f1d-8fc5-15e530dd975c (accessed May 19, 2020).
[69] Jurasz JK, Dąbek PB, Campana PE. Can a city reach energy self-sufficiency by means of rooftop photovoltaics? Case study from Poland. J Clean Prod 2020. https://doi.org/10.1016/j.jclepro.2019.118813.
[70] Palm J, Eidenskog M, Luthander R. Sufficiency, change, and flexibility: Critically examining the energy consumption profiles of solar PV prosumers in Sweden. Energy Res Soc Sci 2018. https://doi.org/10.1016/j.erss.2017.10.006.
[71] Fan JL, Wang JX, Hu JW, Wang Y, Zhang X. Optimization of China's provincial renewable energy installation plan for the 13th five-year plan based on renewable portfolio standards. Appl Energy 2019;254:113757. https://doi.org/10.1016/j.apenergy.2019.113757.