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PV park site selection for utility-scale solar guides combining GIS and power flow analysis: A case study on a Swedish municipality

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ABSTRACT

Utility-scale solar photovoltaic (PV) parks have dominated the international market for the past few years. However, in some countries, like Sweden, utility-scale PV is on the verge to economic viability. Using existing infrastructure in a resource-efficient manner could be a crucial strategy for a successful implementation at scale. In this study, a new methodology for a utility-scale solar guide is developed by studying the hosting capacity in the local grid and identifying land appropriate for PV parks. The method is applied on a rural municipality in Sweden (512 km^2) with a local distribution grid (5,000 customers). The impact on the grid, if connecting a PV park to a substation, was analyzed through power flow simulations and the geographical assessment was done using multi-criteria analysis with a Boolean approach. Three different sizes of PV parks, 1, 3, and 5 MW$_p$, were analyzed. Results showed that 3.7% of the studied area is qualified for locating 1 MW$_p$ PV parks. However, if introducing a maximum distance threshold to the nearest substation that can host the PV generation from the park, the potential is further reduced (e.g., to 1% for a 750 m threshold). Furthermore, parts of the grid can host PV parks of 3 and 5 MW$_p$, but only near urban areas, where qualified land is lacking. The results highlight that the proposed methodology can function as a tool in the dialog between utility companies, municipalities, PV companies, land-owners and other stakeholders in order to find resource- and system-efficient locations for PV parks.

1. Introduction

One of the major challenges that the electricity grid is facing is how a 100% renewable electricity system should be designed and controlled, especially in cases of high shares of variable power generation [1–3]. Today, political goals exist on different levels, both locally and internationally, for a completely renewable energy system [1,4]. Globally, the share of photovoltaic (PV) power is still marginal, around 2.7% (in 2019) of the annual electricity demand, but significantly higher in several countries and regions (e.g., Germany and Japan) [5]. PV parks accounted for 62% of the cumulative installed PV power capacity globally by 2019 [6].

For a resource- and system-efficient expansion, it is important to find the best locations for PV parks considering a range of different aspects. Several studies have proposed methods for the site selection for mainly wind and PV, but sometimes also for other renewable energy resources (RES), such as biomass [7], geothermal [8] and concentrated solar power (CSP) [9,10]. In some studies locations for several RES are identified in parallel [11–13]. While the following literature review focuses on academic publications, there are some examples of PV site selection guidelines from local governments worth mentioning [14–18]. For instance, IRENA [14] gives a comprehensive guide all the way from the site selection to the decommissioning of a utility-scale PV park.

Since the site selection problem to a large extent is spatial, geographical information systems (GIS) are in most cases used in the analysis. In the site selection process, one first needs to identify what criteria are important. The selection of criteria is often done by asking a group of experts, through interviews or indirectly extracted from the literature. Since there are more than one criteria used, the process is often referred to as a Multi-Criteria Decision Analysis (MCDA). In the simplest form, the criteria are used in a *Boolean overlay*, meaning that GIS layers representing different properties of the studied geographical area are overlaid and certain sites or patches of land that meet all or a sufficient number of criteria are labeled as interesting [19], e.g., if it is within a nature reserve or not [20]. Due to its simplicity the method is fairly common in site selection studies [21–23]. However, a land area may also be more or less suitable for the purpose in mind, i.e., different criteria can be assigned weights by a panel of experts and a final score of each site can be given as the weighted sum.

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The most commonly used MCDA of this kind, used in RES site selection, is the Analytical Hierarchy Process (AHP) [19], first introduced by Saaty [24], where criteria are compared pairwise by experts in order to come up with a ranking of all criteria. Other commonly used MCDA techniques are the Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), ELimination et Choice Translating Reality (ELECTRE) [25] and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) [26].

ANP was introduced by Saaty [27] and is a general form of AHP, with the main difference that inter-dependency between criteria is considered (used for RES site selection in, e.g., Yazdani et al. [28], Ebrahimi et al. [29]). TOPSIS, first introduced by Hwang and Yoon [30], identifies the site which lies closest to the ideal position and furthest from the least ideal position, used, e.g., in Sánchez-Lozano et al. [31], Sánchez-Lozano et al. [32], Sindhu et al. [33]. ELECTRE is a family of MCDA methods, first introduced by Roy [34], which is used for choosing, ranking and sorting among a set of alternatives. For PV site selection, the ELECTRE TRI method was used by Sánchez-Lozano et al. [35]. The method is designed to sort among the alternatives into predefined categories (e.g., excellent, good, bad, insufficient). ELECTRE II was used by Jun et al. [36] to choose the best locations for PV/wind hybrid parks in China. PROMETHEE can help decision makers from different disciplines to find a proper solution among several alternatives based on their specific preferences [26]. The method is often used in combination with another MCDA methodology, such as AHP [37–39].

Sometimes fuzzy set theory (e.g., FAHP) is introduced [40] in order to take into consideration the non-sharp boundaries between criteria in the ranking [41–43], which may be the result of differences in the judgments of the experts or the challenge of interpreting the statements of the experts.

Several review papers list the most common criteria in RES site selection [25,44,45]. For instance, Rediske et al. [45] ranks the top six criteria from literature as (1) solar radiation, (2) proximity to power lines, (3) slope (of ground), (4) proximity to main roads, (5) proximity to residential areas and (6) land use. Similar rankings are found in the other review papers mentioned above.

While solar radiation is the most common criterion in the literature, it is not always key. For instance, across a regional area (i.e., municipality or county), with the exception of dramatic topography causing shading [46,47], the spatial variability of the solar irradiance is low. On the national scale, however, the spatial variability may be significant. Also, in a local context, in which the specific placement of the panels is considered, shading from surrounding objects, predominantly trees (or buildings in urban areas) becomes important [48–50].

In many regional studies, therefore, other criteria than the solar resource are considered more important. For instance, Díaz-Cuevas et al. [13] and Solangi et al. [43] both identified proximity to the grid as the most important criterion. Even though several studies on MCDA for PV parks include more or less sophisticated methods for assessing the solar resource (e.g., Merrouni et al. [22], Suh and Brownson [46], Sabo et al. [51]), the same is not the case for the power grid. To the best of the author's knowledge, only the proximity to power lines or substations has been studied, neglecting the technical prerequisites of connecting a PV park to the grid, in particular the impact that a PV park would have on the existing grid.

The amount of distributed electricity generation that an electricity grid can handle without compromising its performance during operation, is usually referred to as the *hosting capacity* [52]. Several studies have shown that the hosting capacity of the distribution grid as a whole exceeds even the most ambitious goals on the penetration of variable power generation in the system [53–56]. However, most studies also identify weaker and stronger parts of the grid [57]. A previous study conducted on the same medium voltage (MV) grid as in the case study here, showed that connecting distributed PV systems to the parts of the electricity grid that have the highest capacity can increase the hosting capacity from 22% to 74% on an annual basis [53], i.e., avoiding the weaker parts of the grid. It is thus valuable for the Distribution System Operator (DSO) and the contractor to be aware of these limitations in order to avoid costly grid reinforcements.

Furthermore, it has been shown that the grid is stronger in the proximity of urban areas (with some exceptions, e.g., Watson et al. [57]) than in more rural parts of the grid [53,58,59]. This poses a dilemma when searching for a suitable site for PV, since available land near densely populated areas most often is limited. Hence, it motivates the development of a method that finds locations with high grid capacity that are also suitable from a land use perspective.

This study advances the field of utility-scale solar guides in a number of respects. Previous studies have solely focused on either geographical mapping [21,44,60] or the grid capacity of RES [59,61,62]. Here, a more detailed analysis is included, combining power flow analysis (in which currents, voltages and losses are calculated for the whole distribution grid) with a geographical analysis where suitable areas for PV parks are identified. Furthermore, we argue that criteria for the site assessment can be identified from existing literature, without intervention of experts. Since input data are insufficient or often of poor quality (which is rarely discussed in the literature), expert intervention is anyway needed in the last step of the site selection, irrespective of used MCDA method, which makes it more reasonable to wait involving experts at all until the last step. Therefore, we propose a simple Boolean overlay approach, which is easy to communicate to and between affected stakeholders and which can be used to identify constraints and opportunities (unsuitable and suitable areas) for PV parks in combination with the grid analysis. Also, in agreement with the previous reasoning for regional solar variability, the spatial variability of the solar resource is not considered here (the same hourly irradiance profile is used across the study area), since it is negligible for the typical scale of a local power distribution system. The techno-economics are to some extent indirectly included in the proposed methodology, such as proximity to the existing grid that do not need to be upgraded and the identification of open (non-arable) land for a PV park, while other economic aspects are not captured in available data sets, e.g., the land owner's willingness to make the land available and to what price. The outcome of the proposed methodology will, however, support the DSO, regional planner and other stakeholders in their discussion of potential sites for utility-scale PV parks, where other criteria can be considered that are not captured in available GIS layers.

The paper is structured as follows; In Section 2 the methodology of the combined land use and grid analysis is presented including a case study. Section 3 presents the results from the case study, which are discussed in Section 4 including ideas for future studies. Finally, in Section 5, the main conclusions are put forward.

2. Method

This section describes the methodology proposed in the study. Fig. 1 presents an overview of the methodological steps and the input data needed. The colored part of Fig. 1 describes the steps related to the spatial analysis, where blue ellipses are input data, yellow boxes are spatial tools and green ellipses are intermediate and final outputs. Section 2.1 presents further details about the spatial analysis in order to identify *qualified areas* for PV parks. The uncolored part of Fig. 1 relates to the grid analysis of the proposed methodology. Parallelograms at the top are input data, round-edged boxes are methodological steps, rhombuses are important query points and rectangles intermediate and final outputs. Section 2.2 gives further details of how the grid capacity was analyzed and Section 2.3 presents a case study for which the methods were evaluated. Finally, data used in the case study are presented in Section 2.4.

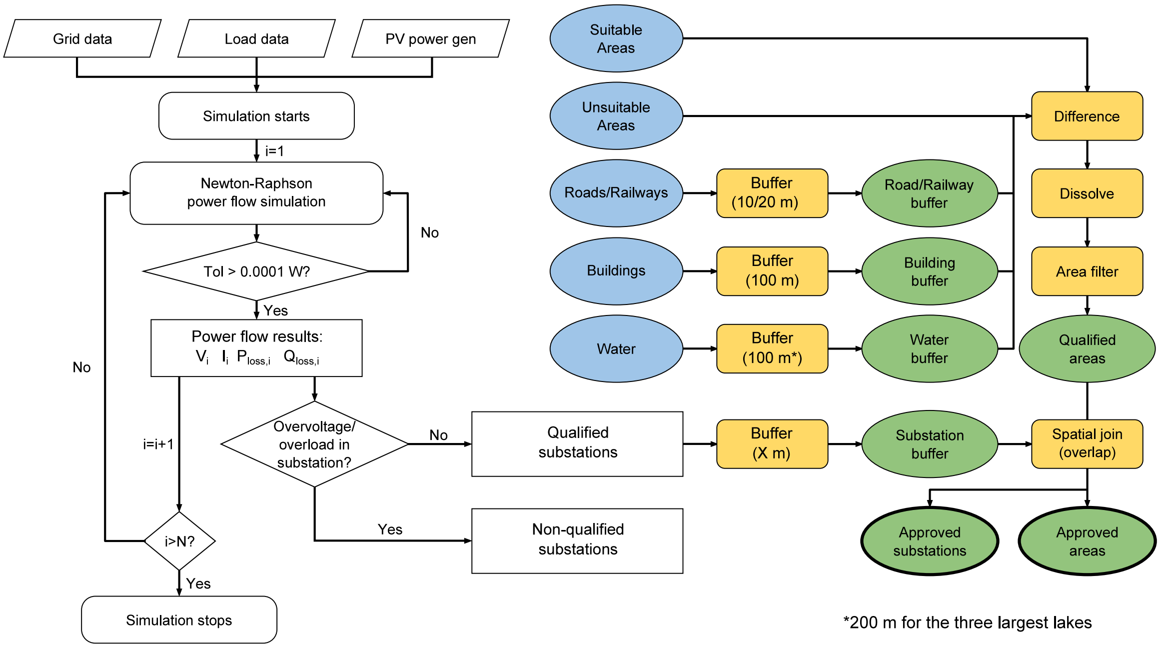


Fig. 1. Flowchart of the proposed method for deriving a utility-scale solar guide. Colored boxes represent the geographical analysis and non-colored boxes the power flow analysis (of the i:th substation out of N total). The thick-lined ellipses at the bottom right indicate the final output of the process, i.e., the approved areas and substations for PV parks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1. Identification of qualified areas

The selection of suitable land for PV parks was based on MCDA with a Boolean overlay approach, where areas were classified as either ‘suitable’ or ‘unsuitable’, due to conflicting interests as shown in Table 1. All GIS layers in Table 1 are part of the Municipal Comprehensive Plan (MCP) of Herrljunga (see Ref. [63] in Swedish). An MCP is a common requirement in many countries according to law, including Sweden [64]. Most of the layers are produced by national authorities, while some are produced by the municipality. Some layers have open access (see footnotes in Table 1), while others do not. However, since it is natural to produce a solar guide in close cooperation with the municipality, the layers in the MCP can be provided by the municipality upon request. Unfortunately, only the Swedish Land Survey provide detailed metadata in English about their layers [65,66].

‘Pasture Land’ was considered suitable, because there are several examples of coexisting livestock and PV parks (see e.g., [16]). ‘Other Open Land’ is defined as open land of vegetation less than 1.5 m high, most commonly former agricultural land often of low or non-productive value, but also open land for special, non-agricultural use (for a full definition, see p. 87 of [65]). However, just as studies of the roof-top PV potential cannot give a definite answer on what buildings may be used for PV (due to economy, construction, obstacles such as chimneys that are difficult to survey, etc.) [48,67], a solar guide for land-based PV systems can merely indicate what lands that are most likely to be used.

Furthermore, several types of land were considered unsuitable. According to the Swedish Environmental code [68], a land or water area is considered a natural reserve if it is important for preserving biodiversity and valuable habitats or to meet the needs of human outdoor activities. *Natura 2000* is a network of protected areas, in the EU, with the purpose to protect biodiversity. Both natural reserves and Natura 2000 are also considered national interests according to Swedish law [68]. Hence, these areas were considered unsuitable for PV parks. According to the same law [68], a general shore protection within 100 m from water bodies prohibit new constructions or modifications to the landscape, but exemption can be granted if applied for. For the three largest lakes in the municipality, there is, according to the MCP, an extended shore protection within 200 m (see Fig. 3). Therefore a new layer was produced based on the water layer in the Topographic map [65]. It represents the shore protection around the three largest lakes (200 m) and water bodies exceeding 30,000 m^2. The layer also includes the two larger streams in the northwest and east of Herrljunga (see Fig. 3), as they may be subject to flooding, but also have high recreational value.

Other national interests that were considered unsuitable included cultural heritage sites and areas claimed by the Swedish Armed Forces. Densely populated urban and rural areas were considered unsuitable for PV parks due to the proximity to buildings; a minimal distance of 100 meters was set as a threshold between a PV park and buildings, in order to limit the visible impact it may have on the occupants, rather than making room for urban growth. Some general guidelines on visibility assessment of solar farms have been proposed [69–72], in which expert-based landscape character and visible impact assessment are the most widely used methods (see e.g., Amalgam Landscape [73], Eco Logical Australia [74]). However, while these methods are time-demanding, automatic tools for quantitative visibility assessment have been proposed, but these have so far mostly focused on roof-applied PV systems in an urban context [75,76].

Areas reserved for rural development at the waterfronts, if included in the MCP, were also considered unsuitable. In Sweden, multiple municipalities have developed corresponding wind guides, where suitable areas are identified. Because these areas are already reserved for wind power they are considered unsuitable for PV parks. However, this is a conservative assumption since, due to the negative correlation between wind- and solar power generation [77], it may be beneficial to co-locate these and thereby utilise the connection to the transformer more efficiently. Finally, between a PV park and roads, a minimal distance of 10 m was set. Since a connection between the PV park and an existing substation may be a substantial part of the project cost, different distances (hence marked with X in Fig. 1) were considered.

Since suitable and unsuitable areas sometimes overlap, e.g., a suitable open area may be part of a ‘Natura 2000’ area, these over-lapping areas were filtered out (using *difference* according to Fig. 1) in a Geographical Information System (GIS), in this case QGIS [78]. Furthermore, since a 1 MW_p solar park was considered the smallest size

Table 1
Layer (and name of map, if the map consists of multiple layers) of each land, classed as either suitable or unsuitable and including its source (responsible institution) and download link as footnote, if available.

Layer (Map)	Source
Suitable	
Other open land (Topographic Map[a])	Swedish Land Survey [65]
Pasture land (Agricultural block[b])	Swedish Board of Agriculture
Unsuitable	
Agricultural land (Agricultural land[b])	Swedish Board of Agriculture
Built environment (MCP)	Herrljunga Municipality
Buildings (Property Map)	Swedish Land Survey [66]
Forest (Topographic Map[a])	Swedish Land Survey [65]
Nationally designated areas — Cultural heritage[c]	County Administration Board
Nationally designated areas — Military areas[d]	Swedish Armed Forces
Nationally designated areas — Nature conservation[e]	Swedish Environmental Protection Agency
Natura 2000 — Habitat directive[f]	Swedish Environmental Protection Agency
Natural reserves (Topographic Map[a])	Swedish Land Survey [65]
Other designated areas (MCP)	Herrljunga Municipality
Roads & Railways (Topographic map[a])	Swedish Land Survey [65]
Water (Topographic map[a])	Swedish Land Survey [65]
Wind power (MCP)	Herrljunga Municipality

[a] https://www.lantmateriet.se/en/maps-and-geographic-information/open-geodata/.
[b] https://jordbruksverket.se/download/18.17cef05d170e1ff7ea95b8d7/1584439006661/JORDBRUKSBLOCK2020.zip.
[c] http://ext-dokument.lansstyrelsen.se/Gemensamt/Geodata/ShapeExport/RAA.RAA_RI_kulturmiljovard_MB3kap6.zip.
[d] http://www.forsvarsmakten.se/siteassets/4-om-myndigheten/samhallsplanering/shapefiler/riksintresseomrade_av_betydelse.zip.
[e] http://gpt.vic-metria.nu/data/land/RI_Naturvard.zip.
[f] http://gpt.vic-metria.nu/data/land/SCI_Rikstackande.zip.

for a park, a constraint of 20,000 m^2 was used to define a ‘qualified area’, which is the final layer of the land use analysis (see Fig. 1). The corresponding areas for the 3 and 5 MW_p parks were set to 60,000 and 100,000 m^2, respectively. Fig. 2 gives an example of how a qualified area can be identified from the layers; suitable, unsuitable, roads, buildings and water.

2.2. Simulation of grid impact from PV parks

This section describes how the grid impact of PV parks was determined. In Section 2.2.1 the power flow simulation method is presented, in Section 2.2.2 the PV power generation model and finally in Section 2.2.3 how qualified substations for the connection of PV parks were identified.

2.2.1. Power flow simulations

Power flow simulations are used to calculate bus voltages, line currents and power losses, both active and reactive, in a power grid. The power flow equations derive from Kirchoff’s law and can be expressed as [79]:

$$P_i = \sum_{n=1}^{N} |Y_{in} V_i V_n| cos(\delta_{in} + \theta_n - \theta_i), \qquad (1)$$

and

$$Q_i = -\sum_{n=1}^{N} |Y_{in} V_i V_n| sin(\delta_{in} + \theta_n - \theta_i). \qquad (2)$$

Here, the active and reactive power P_i and Q_i, respectively are known for each hour and bus i. Also the admittances $Y_{in} = |Y_{in}|\angle\delta_{in}$ between bus i and all other N nodes are known (from the cable impedances), while the voltages (V) and phase angles (θ) are unknown. One of the buses needs to be assigned as *slack bus*, which means that it remains at a constant voltage due to unlimited power flow to or from the grid. It is natural to assign the feeding substation as slack bus, which is normally equipped with an on-load tap changer (OLTC) to keep the voltage constant. The known voltage at the slack bus results in 2(N-1) unknowns and equally many non-linear equations that need to be solved.

Since the distribution grid is meshed, the power flow equations was solved using the Newton–Raphson method, which is a standard iterative method for solving the power flow equations, implemented in a Matlab script used in previous studies [80]. The simulations were run until a set fault tolerance was reached (i.e., the difference between the left- and right hand sides of Eqs. (1) and (2)), in this case 0.0001 W (see Fig. 1).

2.2.2. PV power generation model

A simple PV system model [80] was used to generate the electrical power produced by a PV park. Included parameters are the PV panel tilt (40°), azimuth (0° or due south), albedo (constant at 0.3) and geographic location (58.08N, 13.02E used for all sites), which are used to calculate the hourly solar irradiance on the tilted (G_T) plane of the PV arrays based on the Hay & Davies model [81]. It should be noted that internal shading depends on the shape of the park, but it was neglected, since it would not affect the over-voltages and -currents. The size of 20,000 m^2/MW_p is a conservative estimate based on existing Swedish parks, which in reality also will depend on the shape of the park. The power output from the PV park is:

$$P_{PV} = G_T A \eta_{mod} \eta_{sys}. \qquad (3)$$

where G_T is the incident solar irradiance, A is the total PV array area of the park, $\eta_{mod} = 17\%$ is the PV module efficiency at Standard Test Conditions (STC) and $\eta_{sys} = 80\%$ is the total system efficiency, in which losses in the inverter, cables and soiling of the PV modules are included.

2.2.3. Identification of qualified substations

In the process of identifying ‘qualified substations’ for the connection of PV parks (see Fig. 1), a ’worst-case’ week (nr 27 of 2018) of low load, due to Swedish holidays, but at the same time high solar irradiance, was chosen for the power flow simulations. Simulated PV

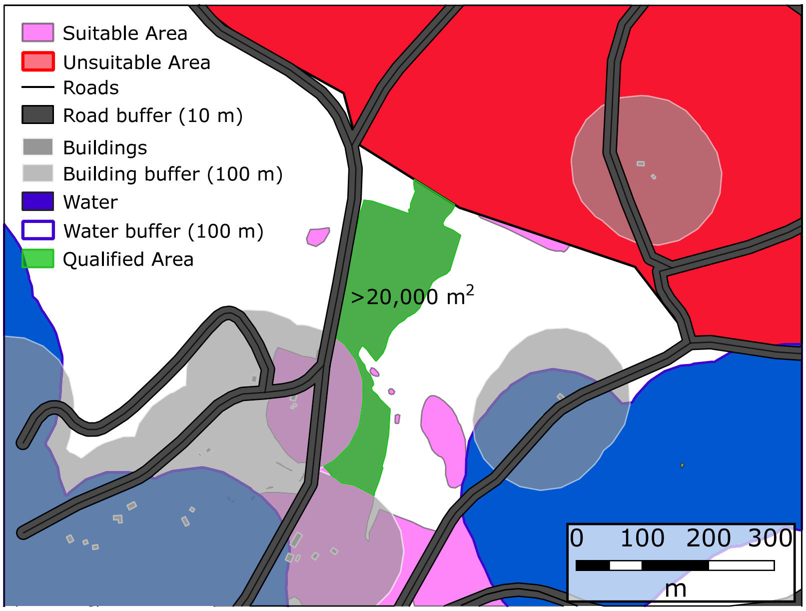


Fig. 2. Illustration of how a qualified area is identified from the layers suitable, unsuitable, roads, buildings and water.

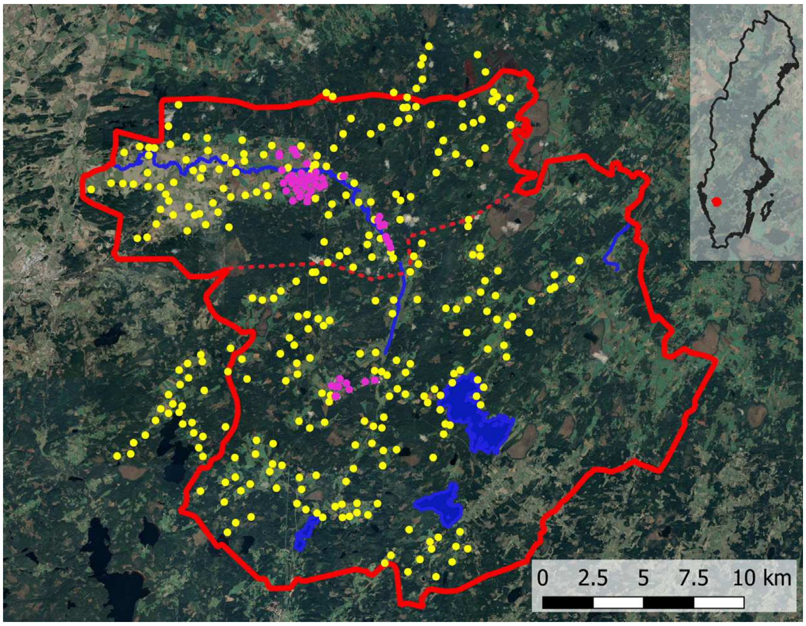


Fig. 3. The municipality of Herrljunga (red solid line) including urban (purple) and rural (yellow) MV/LV substations and the separation between the two subgrids (red dashed line). The three largest lakes and two largest streams with a shore protection of 200 and 100 m, respectively, are marked with blue [65]. The in-folded map illustrates the location of the municipality in Sweden. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
© 2020 Google Map data.

power generation corresponding to a 1, 3 or 5 MW_p park was added to a substation and a power flow simulation was performed for the whole distribution grid. The PV power generation was then successively moved from one substation to the next and the power flow simulation was repeated in each step, as illustrated in Fig. 1, until all substations had been analyzed. In each power flow analysis, not only the substation itself but also the neighboring substations were evaluated with respect to a set of power quality criteria, and the number of neighboring substations not meeting the criteria was determined. Previous studies have shown that the most important criteria are the voltage rise and to some extent the load on the transformer and cables (i.e., over-currents) [57,59]. These were also the two criteria examined in this study. In addition, it was examined if a park of a certain size connected to a certain substation gave rise to *lower losses* in the grid as a whole.

The results from the power flow simulation were then linked to the geographical positions of the substations. Those substations for which a PV park did not violate the power quality criteria of the grid as a whole were deemed ‘qualified substations’. Combining the qualified areas (see Section 2.1) and substations will result in ‘approved areas’, which are linked to ‘approved substations’ for PV parks. In order to find these locations, a maximum threshold has to be set for the distance between the land area and closest qualified substation, which to a large extent depends on the local context, not least economics. As mentioned previously, proximity to the grid is identified as one of the key criteria in PV site selection studies [25,44,45]. For instance, thresholds could be set based on the recommendations of pricing for new grid connections. In this study, a definite threshold is not set, but it is varied over a wide range of distances to determine the sensitivity of the number of approved substations to the threshold.

2.3. Case study

The methods described in Sections 2.1 and 2.2 were applied to a local distribution grid, which roughly follows the extent of the municipality of Herrljunga, Sweden (N58.0, E13.0) and is maintained by the DSO Herrljunga Elektriska AB. It is a 10.8 kV three-phase medium-voltage (MV) distribution grid, separated into a north and south part (see Fig. 3). There are connections between the north and south parts of the grid, but these are kept open by disconnectors and the two grids are operated (and thus simulated) separately. The grid has approximately 5000 end-users in 337 low-voltage (LV) grids connected to MV/LV substations. An illustration of the substations in relation to the geographical extent of the municipality is shown in Fig. 3. To compare the impact that PV parks have on the grid in rural and urban areas separately, substations within land areas defined as 'built environment' or 'other designated areas' (see Table 1) were classified as urban (purple in Fig. 3). Both the north and south MV grids consist of rural areas as well as a smaller urban area.

The distribution grid is connected to the regional high-voltage (HV) grid via two HV/MV substations (i.e., the northern and southern subgrids, respectively, according to Fig. 3). Unlike the MV/LV substations, the HV/MV substations are equipped with OLTCs for voltage control. The OLTCs are kept at fixed voltage on the MV side of the distribution substations, meaning that these stations serve as slack buses in the power flow analysis.

While land use data are fairly easy to get access to for any Swedish region, it is more challenging to come across detailed grid data. However, since data for the power consumption in every MV/LV substation as well as the impedances of every cable were available, it was possible to calculate the voltages and currents in the whole MV grid on hourly basis. The power-quality standard EN 50160 states that the 10-min average voltage magnitude deviation at end-users in the public European distribution grids must be within ± 10% of the rated voltage [82]. Since this study focuses on the MV grid, a lower acceptance threshold must be set in order to give slack to deviations in the LV grid and the lower time resolution of the load data (hourly). This threshold is not defined in the EN-50160 standard, but national recommendations exist (e.g., 2.5% in Sweden [83]). After discussions with the DSO, the voltage magnitude deviation threshold at the substation was set to 3% in this study.

Three different sizes of PV parks (1, 3 and 5 MW_p) were simulated following the procedure outlined in Section 2.2 and Fig. 1. These were chosen as they represent typical sizes of PV parks currently deployed in Sweden. Since most cables in the grid could not carry electrical power above 5 MW_p, larger PV parks were ruled out.

2.4. Data

The MV grid data consist of interconnections between buses and lines, per-km cable impedances, and cable lengths. The load data consist of hourly end-user loads from 2018, aggregated on MV/LV substation level. Data of higher resolution could not be used to avoid conflicts concerning personal data defined by the General Data Protection Regulation (GDPR). Since only the active power is reported, a static power factor of 0.95 was assumed for an estimation of the reactive power (cf. [59]).

Hourly data for solar irradiance were retrieved from the STRÅNG model, developed by the Swedish Meteorological and Hydrological Institute, the Swedish Environmental Protection Agency and the Swedish Radiation Safety Authority [84].

Geographical data were retrieved from the property map from the Swedish Land Survey [66] and Herrljunga municipality's MCP. The geographical data consist of current land use along with local strategies and future goals for the municipality. The quality of the geographical data is usually high for large areas such as forests, open water, plowed fields and settlements. However, the quality might be lower for areas hard to distinguish due to gradual transitions such as thinning tree lines [66]. Awareness of the data limitations is important when evaluating the results, e.g., land use data classification may be too coarse, not up-to-date or poorly defined. Hence, a manual assessment of the areas of interest is needed and common data limitations may be reported back to the data provider. Geographical coordinates for each substation were provided by the DSO Herrljunga Elektriska AB.

Table 2
Comparative statistics in percentage with regards to over-voltages, over-currents and lower losses between urban and rural areas and scenarios of PV parks of 1, 3 and 5 MW_p. Total numbers of urban and rural substations are presented in brackets.

% Substations	Urban (51)			Rural (286)		
	1	3	5	1	3	5
	[MW_p]			[MW_p]		
Over-voltages	0	12	16	10	74	90
Over-currents	0	10	31	0	46	82
Lower losses	100	45	10	21	1	0

Table 3
Unsuitable, suitable, qualified and approved area (km^2) and substations, respectively, for PV parks of 1, 3 and 5 MW_p.

MW_p	Area (km^2)			Substations (№)		
	1	3	5	1	3	5
Unsuitable	— 115 —			—		
Suitable	— 71 —			—		
Qualified	17	11	8	309	119	73
Approved[a]	4.6	1.2	0.6	98	9	2
Total	— 512 —			— 337 —		

[a] For the case of 750 m.

3. Results

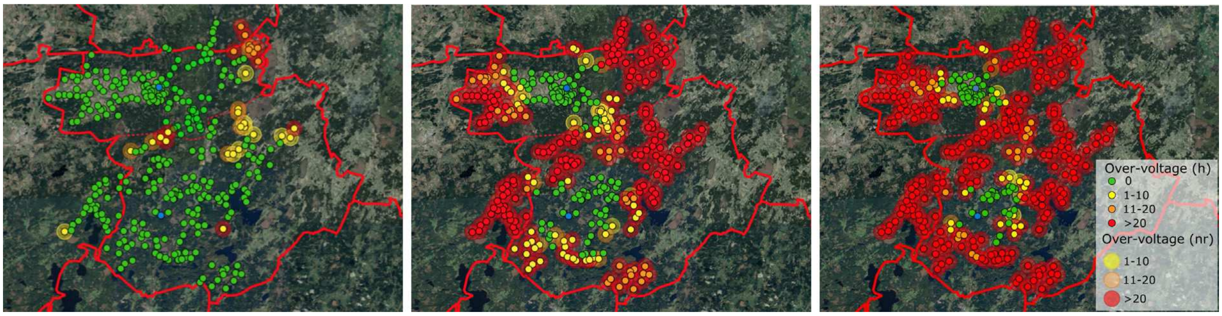
Here results from the case study are presented. Qualified substations from the power simulations are presented in Section 3.1 and qualified areas in Section 3.2. Approved areas and substations are presented in Section 3.3 and finally, an example of how the results may be used in a utility-scale solar guide 3.4, is presented.

3.1. Qualified substations

Three scenarios, representing PV parks of 1, 3 and 5 MW_p, respectively, were studied for the local distribution grid. As outlined in Section 2.2, for each scenario, PV parks of a certain size were sequentially moved from one substation to the next and in each step a power flow simulation was performed for the worst-case week in order to evaluate in which substations (if any) that the PV park would cause over-voltages and/or over-currents and for how many hours (see Fig. 1). If the overall power losses in the grid would decrease or not, due to the PV park, was also determined for the same week. This procedure was repeated until all 337 substations had been evaluated (see Fig. 1). Results from the three scenarios are summarised in Table 2.

Over-voltages are also represented geographically in Fig. 4, color-coded according to number of hours of over-voltage for the substation itself (smaller circle) or number of neighbors affected (enclosing circle). Thus, green circles not within an enclosing circle represent substations that are qualified for PV parks.

For the first scenario (1 MW_p), results show that over-voltages within the urban areas never surpass the nominal voltage by more than



(a) (b) (c)

Fig. 4. Maps of substations in the distribution grid color-coded according to the number of hours of over-voltage (small circles) and, if in question, the number of affected neighboring substations (enclosing circles) when introducing PV parks of (a) 1 $\mathrm{MW_p}$, (b) 3 $\mathrm{MW_p}$ and (c) 5 $\mathrm{MW_p}$, respectively. Blue markers represent the HV/MV substations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
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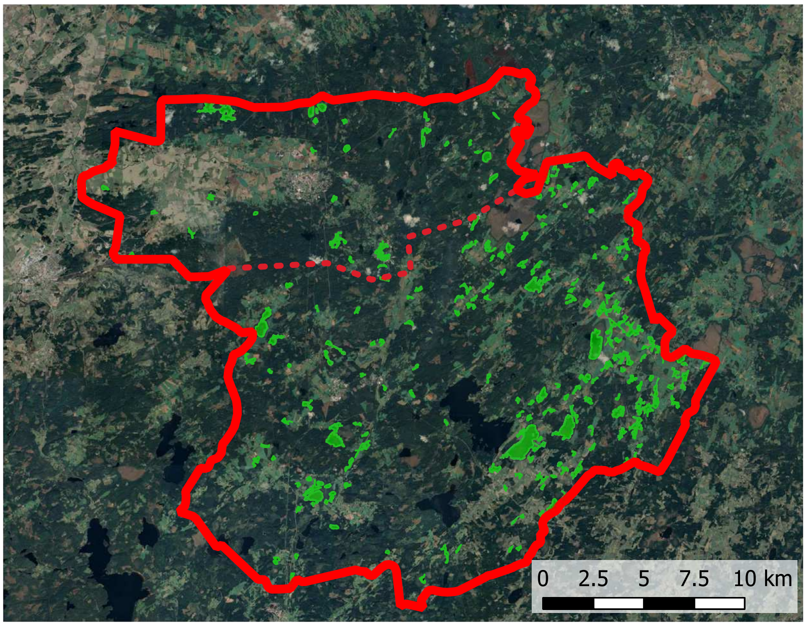

Fig. 5. Map of Herrljunga municipality where green areas represent qualified areas for a 1 $\mathrm{MW_p}$ PV park.
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3%, i.e., all urban substations are classed as 'qualified'. Table 2 also shows that a PV park of 1 $\mathrm{MW_p}$ would also lead to lower power losses in the grid as a whole, if applied in any urban substation. However, over-voltages in the rural areas occur in 10% of the substations. Also, a 1 $\mathrm{MW_p}$ PV park only leads to lower losses when applied at 21% of the rural substations.

Fig. 4 shows that while for 1 $\mathrm{MW_p}$ PV parks there are plenty of possible locations, it is less so for 3 $\mathrm{MW_p}$ and 5 $\mathrm{MW_p}$ parks. For most cases, the power losses in the grid will actually increase (i.e., lower losses for less than 50% of the substations in Table 2). The likelihood of over-voltages in the urban areas is still relatively low for 3 $\mathrm{MW_p}$ (12%) but much higher in the rural areas (74%). Over-currents in cables between substations occur in 10% of the power flow simulations when PV power generation is added to urban substations. The corresponding number for rural substations is 46%. For the 5 $\mathrm{MW_p}$ case, the number of qualified substations is further restricted to locations around the urban areas, as Fig. 4(c) shows.

3.2. *Qualified areas*

Table 3 presents a summary of the total area and number of substations after certain steps of the methodology were applied on the case study object. The total area of Herrljunga municipality is about 512 $\mathrm{km^2}$. Suitable land area is 71 $\mathrm{km^2}$ (or 14%), but the qualified area is limited due to overlapping unsuitable areas and the minimum size needed for a 1, 3 and 5 $\mathrm{MW_p}$ PV park (20,000, 60,000 and 100,000 $\mathrm{m^2}$, respectively). The resulting qualified area is, thus, 17, 11 and 8 $\mathrm{km^2}$ for the respective park sizes. As an example, in Fig. 5, the area that is qualified for a 1 $\mathrm{MW_p}$ PV park is shown, which corresponds to 3.2% of the municipality area. For 3 and 5 $\mathrm{MW_p}$ PV parks, the corresponding shares are 2.1% and 1.6%, respectively.

3.3. *Approved areas for PV parks*

In this section we present results regarding *approved* areas for PV parks, i.e., qualified areas that are located within reach from at least one qualified substation, in line with the proposed methodology (illustrated in Fig. 1).

Going back to Table 3, we see that if a maximum Euclidean distance of 750 m between the edge of a qualified area and a qualified substation is introduced, *approved* areas and substations are further reduced compared to the qualified. For a 1 $\mathrm{MW_p}$ PV park, the approved land area is 4.6 $\mathrm{km^2}$ and the number of approved substations is 98. Just as can be

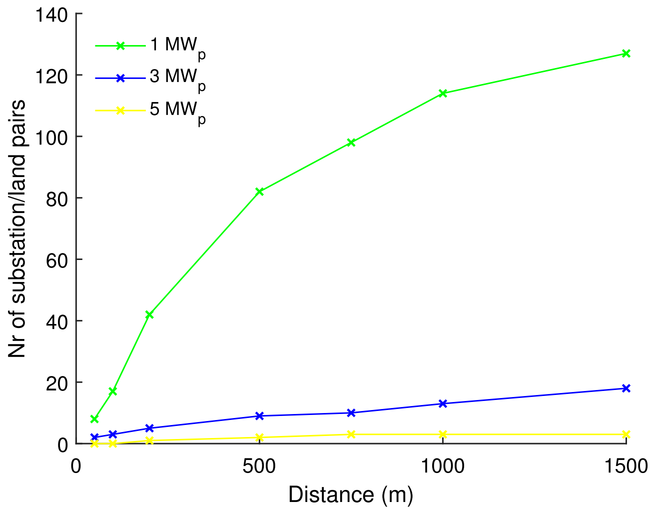


Fig. 6. The number of substation/land pairs as a function of the internal distance for 1, 3 and 5 MW$_p$ PV parks.

seen in Fig. 6, the approved land area and number of substations for larger PV parks is dramatically smaller, which to a large extent can be explained by the concentration of qualified substations near the urban areas (see Fig. 4(c)), where there is a lack of sufficiently large qualified areas within reach.

3.4. Utility-scale solar guide examples

Fig. 7 illustrates an example of how a utility-scale solar guide could be used based on the combined results from the grid simulation and the geographical mapping. Fig. 7(a) gives an overview of the substation/land pairs that could be used for 1, 3 and 5 MW$_p$ with respective color codes, if a maximum of 750 m between the *approved* land and substation is allowed. This threshold limit is related to the cost for the project, which is context specific and may vary between and within countries. Fig. 6 illustrates the number of substation/land pairs available as a function of their internal distance. For the larger park sizes, the number of substation/land pairs does not increase significantly with the distance. This is especially true for the 5 MW$_p$ park, which reaches the maximum of 2 parks already at 500 m. One likely explanation could be that the grid is stronger closer to the urban areas, hence it is only here that larger parks are possible. At the same time the substations are closer to each other here, which means that there is always a qualified substation relatively close to a qualified land area. In the rural areas, on the other hand, the distance between a qualified land area and its nearest substation is often longer than 500 m.

Fig. 7(b) represents the white box in Fig. 7(a). The green color of both the land area and substation indicates that a 1 MW$_p$ park in theory could fit here. The first apparent limitation one may think of is the irregular shape of the land area, which may make it impractical to install a solar park in whole area. However, there are several examples of PV parks using narrow strips of land (e.g., [49]). Other likely reasons why the land cannot be fully utilised are obstacles such as uneven, rocky or wet terrain, groups of trees acting as obstacles or causing shading, or shading from an adjacent forest.

4. Discussion

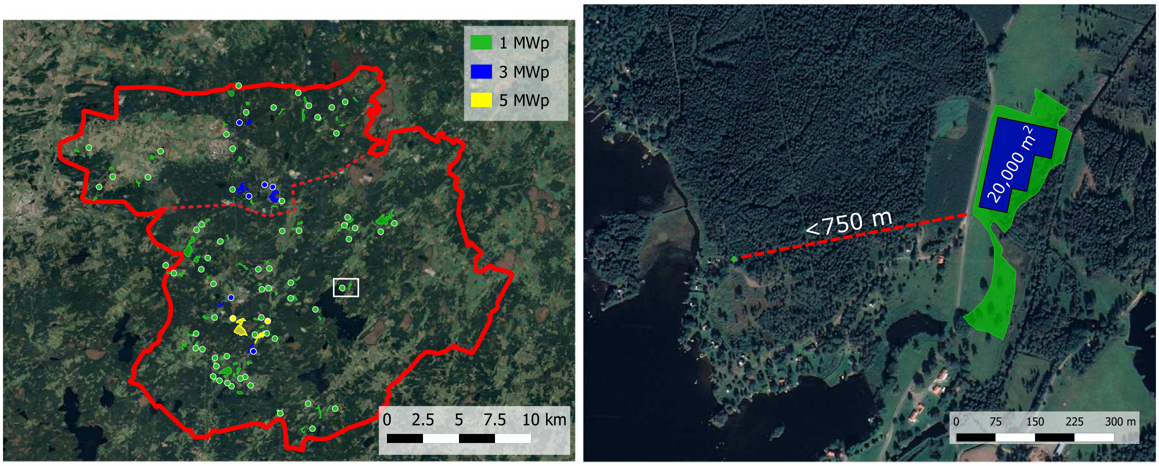
As outlined in the introduction of this paper, the main novelty of the methodology proposed here is the combination of traditional land use analysis in RES site selection methods and power flow analysis of the local grid. In recent review papers [25,44,45], the proximity to power lines or substations are identified as one of the most influential criteria in RES site selection problems, yet only the distance to the grid infrastructure is evaluated. Several studies also put weight on the proximity to urban areas, defining a large distance as beneficial [45]. This conclusion is made for good reasons, as land near urban areas are more valuable and a PV park may interfere with the recreational values, i.e., people cannot move as freely due to the barrier that a PV park may give rise to. On the other hand, as this study has shown, it is only near urban areas that the grid is strong enough to host a larger PV park (>1 MW$_p$) if connected to a 10 kV substation, i.e., this contradiction may result in suboptimal recommendations of PV park sites.

Even though Sweden has a relatively low PV penetration level from an international perspective (0.3% in 2018 [85]), DSOs are already experiencing some issues, not least because new PV systems are often reported to the DSO after the installation is done. This makes it tricky for the DSO to take counter-measures in case the grid cannot host the new generation. The other problem is that Sweden has 170 local DSOs, of which a majority is small, i.e., of similar size as Herrljunga Elektriska AB, who provided the data for the current case study. Many of these DSOs do not have the knowledge or tools to estimate the impact of distributed generation in their grid, and are therefore acting conservatively, not promoting PV (nor charging of electric vehicles). Of course these small DSOs could get help externally, but the recently introduced GDPR makes them anxious and therefore restrictive on handing out any data with the risk of violating the new EU law. This last point, we think is a major factor why there are so few (if any) RES site selection studies that integrate detailed analysis of the local grid. It should be noted that in many grid integration studies, unidentified grids, such as the IEEE test grids, are used to test new methods, partly for benchmarking reasons, but also due to the lack of access to real grid data [86].

While Sweden already is seeing some issues when introducing PV in weaker parts of the local grid, EU countries with an extensive PV penetration are already placing restrictions on the feed-in to the grid, not at least to comply with the new Network Code Requirements for Generators (NC RfG) [87]. The most obvious example of national grid code requirements for PV are those from Germany, where frequency disconnection settings of the inverter have been diversified (to avoid a domino effect of disconnections in case of a frequency disturbance) and PV systems below 30 kW$_p$ should be able to limit their power production to 70% of rated power [88]. Therefore, the proposed methodology should be valuable in an international perspective. Furthermore, the case study may be used as a proof-of-concept in the dialog with other DSOs that want to know their grid better but are worried about GDPR or other security aspects. A natural next step would be to ask affected stakeholders, such as the municipality, to make a more detailed assessment of one or a few identified sites and then follow the process and their dialog with other stakeholders. Such assessment would include economic and potentially other aspects that were foreseen or could not be captured by the quantitative approach that the proposed methodology provides.

Furthermore, a utility-scale solar guide would not only benefit the DSO, but would also allow other stakeholders, such as regional planners, landowners and contractors to discuss the best locations for PV parks in the area. For instance, landowners who do not have the ambition or the resources to build a PV park can lease the land to someone that does.

Regarding the technical aspects of the methodology, a number of possible improvements and extensions can be imagined. In this study, the impact of adding a PV park to just one substation, and not to several at the same time, was investigated in each power flow simulation, in order to evaluate the impact on the grid in its current state. While this was not the main focus of this study, it is of course possible and of interest to study the impact from multiple parks (or roof-mounted systems), which has been done extensively in the past. For instance, higher PV penetration can be studied by randomly placing PV parks in the grid



(a)

(b)

Fig. 7. In (a), approved substation/land pairs with an internal distance of max 750 m illustrated for PV park sizes of 1 MW_p (green), 3 MW_p (blue) and 5 MW_p (yellow), respectively. The white box in (a) represents the zoomed-in usage example of the utility-scale solar guide in (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
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one by one and running power flow simulations before adding every new one. The process can be repeated as a Monte-Carlo simulation to determine the probability that a PV park in a certain location will cause future problems in the grid given different deployment scenarios.

Furthermore, it is also important to study how the proposed methodology may be integrated with the DSO's and physical planner's current tools for grid and spatial planning (i.e., the MCP). Not at least, due to grid modifications and extensions, new loads or generators, and changes or re-classifications of the land use, there is probably a need to re-run the analysis on regular basis.

In the introduction, it is argued that the solar resource does not necessarily have to be mapped in high detail for a regional study, since the spatial variability on hourly basis would be negligible. This is true if shading is not considered. However, sites that are declared *approved* following the methodology proposed here should be further examined before choosing them as actual PV park sites. In some cases, sites will be ruled out because of circumstances not captured by the geographical data, such as misclassification or that other intentions exist for the area. Since pasture land is considered a viable option due to its multipurpose nature [16], it is likely that there are trees populating the area of interest. These trees could then either be cut down (if economically viable) or treeless parts of the pasture land could be reserved for the PV park. While a digital surface model (DSM) can be derived with high resolution in urban areas due to the access of LiDAR data, in rural areas the resolution is lower and often limited to a digital elevation model (DEM) [41,57], which in contrast to a DSM does not consider trees and buildings and other objects that may shade a PV system. For a meaningful solar resource assessment when surveying a potential PV park in a rural setting in detail, it is therefore suggested for future studies to develop methods that could be used to estimate the impact from shading in the absence of LiDAR data, e.g., land use data or satellite images.

5. Conclusions

In this study the impact that utility-scale PV parks have on the distribution grid are incorporated into a traditional Boolean overlay-based PV site selection methodology. Results show that while patches of land representing 3.2% of the total area in a rural Swedish municipality are qualified for a 1 MW_p PV park, only patches representing 1% can be used without grid reinforcement and assuming a maximum distance of 750 m to the nearest substation that could host the PV power generation from the park. However, if multiple parks are planned, this percentage will likely decrease. For larger parks (3 and 5 MW_p), the corresponding available land is even less (0.2% and 0.1%, respectively). This can be explained by the lack of appropriate land near urban areas where the grid is strong enough to host the PV power generation. As the proximity to the grid infrastructure has been identified as key in several previous PV site selection studies, utility-scale solar guides produced using the methodology proposed here may be useful when different stakeholders consider the establishments of PV parks, e.g., landowners, regional planners, grid operators and contractors. A solar guide may also be integrated in the comprehensive municipality plan just as wind guides have been previously.

CRediT authorship contribution statement

O. Lindberg: Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **A. Birging:** Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **J. Widén:** Conceptualization, Validation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **D. Lingfors:** Conceptualization, Software, Validation, Writing - review & editing, Visualization, Supervision.

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.

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References

[1] Swedish Energy Agency. 100 procent förnybar el - Delrapport 2: Scenarier, vägval och utmaningar [100% renewable electricity - part 2: Scenarios, roadmaps and challenges]. Technical report, Eskilstuna: Swedish Energy Agency; 2019, p. 134.

[2] Olauson Jon, Ayob Nasir Mohd, Bergkvist Mikael, Carpman Nicole, Castellucci Valeria, Goude Anders, et al. Net load variability in Nordic countries with a highly or fully renewable power system. Nat Energy 2016;1(12):1–8. http://dx.doi.org/10.1038/nenergy.2016.175, URL http://rdcu.be/msJT, http://www.nature.com/articles/nenergy2016175.

[3] Kroposki Benjamin, Johnson Brian, Zhang Yingchen, Gevorgian Vahan, Denholm Paul, Hodge Bri Mathias, et al. Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy. IEEE Power Energy Mag 2017;15(2):61–73. http://dx.doi.org/10.1109/MPE.2016.2637122.

[4] European Commission. Fourth report on the state of the energy union. Technical report, Brussels: Eropean Comission; 2019, URL https://ec.europa.eu/commission/publications/4th-state-energy-union_en.

[5] BP. Statistical review of World Energy 2020. 2020, URL https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[6] Masson Gaëtan, Kaizuka Izumi. Trends in photovoltaic applications 2019. In: Task 1: Strategic PV analysis and outreach. Technical report, IEA-PVPS; 2019, URL http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:TRENDS+IN+PHOTOVOLTAIC+APPLICATIONS#0.

[7] Delivand Mitra Kami, Cammerino Anna Rita B, Garofalo Pasquale, Monteleone Massimo. Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: A case study on electricity productions in South Italy. J Cleaner Prod 2015;99:129–39. http://dx.doi.org/10.1016/j.jclepro.2015.03.018.

[8] Rumbayan Meita, Nagasaka Ken. Prioritization decision for renewable energy development using analytic hierarchy process and geographic information system. In: 2012 International conference onadvanced mechatronic systems. IEEE; 2012, p. 36–41.

[9] Sánchez-Lozano JM, García-Cascales MS, Lamata MT. Evaluation of suitable locations for the installation of solar thermoelectric power plants. Comput Ind Eng 2015;87(2015):343–55. http://dx.doi.org/10.1016/j.cie.2015.05.028.

[10] Kengpol Athakorn, Rontlaong Piya, Tuominen Markku. Design of a decision support system for site selection using fuzzy AHP: A case study of solar power plant in north eastern parts of thailand. In: 2012 Proceedings of PICMET '12: technology management for emerging technologies. IEEE; 2012, p. 734–43.

[11] Janke Jason R. Multicriteria GIS modeling of wind and solar farms in colorado. Renew Energy 2010;35(10):2228–34. http://dx.doi.org/10.1016/j.renene.2010.03.014.

[12] Watson Joss JW, Hudson Malcolm D. Regional scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landsc Urban Plan 2015;138:20–31. http://dx.doi.org/10.1016/j.landurbplan.2015.02.001, URL https://linkinghub.elsevier.com/retrieve/pii/S0169204615000249.

[13] Díaz-Cuevas Pilar, Domínguez-Bravo Javier, Prieto-Campos Antonio. Integrating MCDM and GIS for renewable energy spatial models: assessing the individual and combined potential for wind, solar and biomass energy in Southern Spain. Clean Technol Environ Policy 2019;21(9):1855–69. http://dx.doi.org/10.1007/s10098-019-01754-5.

[14] IRENA. Technical concept guidelines utility scale solar PV. Technical report, IRENA; 2016, URL www.irena.org.

[15] New South Wales Government. Large-scale solar energy guideline. Technical report, NSW Government; 2018, p. 15.

[16] BRE National Solar Centre. In: Scurlock Jonathan, editor. Agricultural good practice guidance for solar farms. Technical report, BRE National Solar Centre; 2014.

[17] US EPA, NREL. Screening sites for solar PV potential. In: RE-Powering america's land initiative: solar decision tree. Technical report, US EPA; 2013, p. 1–18, URL https://www.epa.gov/re-powering.

[18] State of Queensland. Queensland solar farm guidelines. Technical report, State of Queensland; 2018.

[19] Choi Yosoon, Suh Jangwon, Kim Sung Min. GIS-Based solar radiation mapping, site evaluation, and potential assessment: A review. Appl Sci (Switzerland) 2019;9(9). http://dx.doi.org/10.3390/app9091960.

[20] Quirós-Tortós Jairo, Valverde Gustavo, Argüello Andrés, Ochoa Luis Nando. Geo-information is power: Using geographical information systems to assess rooftop photovoltaics in costa rica. IEEE Power Energy Mag 2017;15(2):48–56. http://dx.doi.org/10.1109/MPE.2016.2637158.

[21] Yousefi Hossein, Hafeznia Hamed, Yousefi-Sahzabi Amin. Spatial site selection for solar power plants using a gis-based boolean-fuzzy logic model: A case study of markazi province, Iran. Energies 2018;11(7). http://dx.doi.org/10.3390/en11071648.

[22] Merrouni Ahmed Alami, Mezrhab Abdelhamid, Mezrhab Ahmed. PV Sites suitability analysis in the eastern region of Morocco. Sustain Energy Technol Assess 2016;18:6–15. http://dx.doi.org/10.1016/j.seta.2016.09.006.

[23] Wang Siheng, Zhang Lifu, Fu Dongjie, Lu Xu, Wu Taixia, Tong Qingxi. Selecting photovoltaic generation sites in Tibet using remote sensing and geographic analysis. Sol Energy 2016;133:85–93. http://dx.doi.org/10.1016/j.solener.2016.03.069.

[24] Saaty Thomas L. A scaling method for priorities in hierarchical structures. J Math Psych 1977;15(3):234–81. http://dx.doi.org/10.1016/0022-2496(77)90033-5.

[25] Ilbahar Esra, Cebi Selcuk, Kahraman Cengiz. A state-of-the-art review on multi-attribute renewable energy decision making. Energy Strategy Rev 2019;25(September 2018):18–33. http://dx.doi.org/10.1016/j.esr.2019.04.014.

[26] Brans JP, Vincke Ph, Mareschal B. How to select and how to rank projects: The Promethee method. European J Oper Res 1986;24(2):228–38. http://dx.doi.org/10.1016/0377-2217(86)90044-5, URL https://linkinghub.elsevier.com/retrieve/pii/0377221786900445.

[27] Saaty TL. Decision making with dependence and feedback: The analytic network process: the organization and prioritization of complexity. Analytic hierarchy process series, Rws Publications; 2001, URL https://books.google.se/books?id=MGpaAAAAYAAJ.

[28] Yazdani Morteza, Chatterjee Prasenjit, Zavadskas Edmundas Kazimieras, Streimikiene Dalia. A novel integrated decision-making approach for the evaluation and selection of renewable energy technologies. Clean Technol Environ Policy 2018;20(2):403–20. http://dx.doi.org/10.1007/s10098-018-1488-4.

[29] Ebrahimi M, Aramesh M, Khanjari Y. Innovative ANP model to prioritization of PV/T systems based on cost and efficiency approaches: With a case study for Asia. Renew Energy 2018;117:434–46. http://dx.doi.org/10.1016/j.renene.2017.10.098.

[30] Hwang CL, Yoon K. Multiple attribute decision making: methods and applications: a state-of-the-art survey. Lecture notes in economics and mathematical systems, Springer-Verlag; 1981, URL https://books.google.se/books?id=X-wYAQAAIAAJ.

[31] Sánchez-Lozano JM, García-Cascales MS, Lamata MT. GIS-Based onshore wind farm site selection using Fuzzy Multi-Criteria Decision Making methods. Evaluating the case of Southeastern Spain. Appl Energy 2016;171(2016):86–102. http://dx.doi.org/10.1016/j.apenergy.2016.03.030.

[32] Sánchez-Lozano Juan M, Teruel-Solano Jerónimo, Soto-Elvira Pedro L, Socorro García-Cascales M. Geographical information systems (GIS) and multi-criteria decision making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain. Renew Sustain Energy Rev 2013;24:544–56. http://dx.doi.org/10.1016/j.rser.2013.03.019.

[33] Sindhu Sonal, Nehra Vijay, Luthra Sunil. Investigation of feasibility study of solar farms deployment using hybrid AHP-TOPSIS analysis: Case study of India. Renew Sustain Energy Rev 2017;73(December 2016):496–511, URL http://dx.doi.org/10.1016/j.rser.2017.01.135.

[34] Roy Bernard. The outranking approach and the foundations of electre methods. Theory and Decision 1991;31(1):49–73. http://dx.doi.org/10.1007/BF00134132.

[35] Sánchez-Lozano Juan M, Henggeler Antunes Carlos, García-Cascales M Socorro, Dias Luis C. GIS-Based photovoltaic solar farms site selection using ELECTRE-TRI: Evaluating the case for Torre Pacheco, Murcia, Southeast of Spain. Renew Energy 2014;66:478–94. http://dx.doi.org/10.1016/j.renene.2013.12.038.

[36] Jun Dong, Tian-Tian Feng, Yi-Sheng Yang, Yu Ma. Macro-site selection of wind/solar hybrid power station based on ELECTRE-II. Renew Sustain Energy Rev 2014;35:194–204. http://dx.doi.org/10.1016/j.rser.2014.04.005.

[37] Marques-Perez Inmaculada, Guaita-Pradas Inmaculada, Gallego Aurea, Segura Baldomero. Territorial planning for photovoltaic power plants using an outranking approach and GIS. J Cleaner Prod 2020;257:120602. http://dx.doi.org/10.1016/j.jclepro.2020.120602.

[38] Aldrin Wiguna Kadek, Sarno Riyanarto, Ariyani Nurul Fajrin. Optimization solar farm site selection using multi-criteria decision making fuzzy AHP and PROMETHEE: Case study in bali. In: Proceedings of 2016 international conference on information and communication technology and systems. IEEE; 2017, p. 237–43. http://dx.doi.org/10.1109/ICTS.2016.7910305.

[39] Samanlioglu Funda, Aya Zeki. A fuzzy AHP-PROMETHEE II approach for evaluation of solar power plant location alternatives in Turkey. J Intell Fuzzy Systems 2017;33(2):859–71. http://dx.doi.org/10.3233/JIFS-162122.

[40] Zadeh LA. Fuzzy sets. Inf Control 1965;8(3):338–53. http://dx.doi.org/10.1016/S0019-9958(65)90241-X, URL http://www.sciencedirect.com/science/article/pii/S001999586590241X.

[41] Charabi Yassine, Gastli Adel. PV Site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation. Renew Energy 2011;36(9):2554–61. http://dx.doi.org/10.1016/j.renene.2010.10.037.

[42] Noorollahi Younes, Yousefi Hossein, Mohammadi Mohammad. Multi-criteria decision support system for wind farm site selection using GIS. Sustain Energy Technol Assess 2016;13:38–50. http://dx.doi.org/10.1016/j.seta.2015.11.007.

[43] Solangi Yasir Ahmed, Shah Syed Ahsan Ali, Zameer Hashim, Ikram Muhammad, Saracoglu Burak Omer. Assessing the solar PV power project site selection in Pakistan: based on AHP-fuzzy VIKOR approach. Environ Sci Pollut Res 2019;26(29):30286–302. http://dx.doi.org/10.1007/s11356-019-06172-0.

[44] Al Garni Hassan Z, Awasthi Anjali. Solar PV power plants site selection: A review. In: Yahyaoui Imene, editor. Advances in renewable energies and power technologies: vol. 1: Solar and wind energies. Elsevier; 2018, p. 57–75. http://dx.doi.org/10.1016/B978-0-12-812959-3.00002-2.

[45] Rediske Graciele, Siluk Julio Cezar Mairesse, Gastaldo Natália Gava, Rigo Paula Donaduzzi, Rosa Carmen Brum. Determinant factors in site selection for photovoltaic projects: A systematic review. Int J Energy Res 2019;43(5):1689–701. http://dx.doi.org/10.1002/er.4321.

[46] Suh Jangwon, Brownson Jeffrey RS. Solar farm suitability using geographic information system fuzzy sets and analytic hierarchy processes: Case study of Ulleung Island, Korea. Energies 2016;9(8). http://dx.doi.org/10.3390/en9080648.

[47] Lukač Niko, Žlaus Danijel, Seme Sebastijan, Žalik Borut, Štumberger Gorazd. Rating of roofs' surfaces regarding their solar potential and suitability for PV systems, based on LiDAR data. Appl Energy 2013;102:803–12. http://dx.doi.org/10.1016/j.apenergy.2012.08.042.

[48] Lingfors David, Bright JM, Engerer NA, Ahlberg J, Killinger Sven, Widén Joakim. Comparing the capability of low- and high-resolution LiDAR data with application to solar resource assessment, roof type classification and shading analysis. Appl Energy 2017;205:1216–30. http://dx.doi.org/10.1016/j.apenergy.2017.08.045, URL http://linkinghub.elsevier.com/retrieve/pii/S0306261917310619.

[49] Kim Byungil, Han SangUk, Heo Jae, Jung Jaehoon. Proof-of-concept of a two-stage approach for selecting suitable slopes on a highway network for solar photovoltaic systems: A case study in South Korea. Renew Energy 2020;151(xxxx):366–77. http://dx.doi.org/10.1016/j.renene.2019.11.021, URL http://www.sciencedirect.com/science/article/pii/S0960148119317021, https://linkinghub.elsevier.com/retrieve/pii/S0960148119317021.

[50] Jung Jaehoon, Han Sang Uk, Kim Byungil. Digital numerical map-oriented estimation of solar energy potential for site selection of photovoltaic solar panels on national highway slopes. Appl Energy 2019;242(September 2018):57–68. http://dx.doi.org/10.1016/j.apenergy.2019.03.101.

[51] Sabo Mahmoud Lurwan, Mariun Norman, Hizam Hashim, Mohd Radzi Mohd Amran, Zakaria Azmi. Spatial matching of large-scale grid-connected photovoltaic power generation with utility demand in Peninsular Malaysia. Appl Energy 2017;191:663–88. http://dx.doi.org/10.1016/j.apenergy.2017.01.087.

[52] Bollen Math HJ, Hassan Fainan. Integration of distributed generation in the power system. Hoboken: Wiley; 2011.

[53] Lingfors David, Marklund Jesper, Widén Joakim. Maximizing PV hosting capacity by smart allocation of PV: A case study on a Swedish distribution grid. In: Proceedings of 44th ASES annual conference. State College, PA; 2015.

[54] Thomson M, Infield DG. Impact of widespread photovoltaics generation on distribution systems. Renew Power Gener IET 2007;1(1):10–6. http://dx.doi.org/10.1049/iet-rpg, URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4159950.

[55] Tonkoski Reinaldo, Lopes Luiz AC C. Impact of active power curtailment on overvoltage prevention and energy production of PV inverters connected to low voltage residential feeders. Renew Energy 2011;36(12):3566–74. http://dx.doi.org/10.1016/j.renene.2011.05.031, URL http://linkinghub.elsevier.com/retrieve/pii/S096014811100259X.

[56] Hoke Anderson, Butler Rebecca, Hambrick Joshua, Kroposki Benjamin. Maximum photovoltaic penetration levels on typical distribution feeders. Technical report, NREL; 2012, p. 1–14.

[57] Watson Jeremy D, Watson Neville R, Santos-Martin David, Wood Alan R, Lemon Scott, Miller Allan JV. Impact of solar photovoltaics on the low-voltage distribution network in New Zealand. IET Gener Transm Distrib 2016;10(1):1–9. http://dx.doi.org/10.1049/iet-gtd.2014.1076.

[58] Walla Tobias, Widén Joakim, Johansson J, Bergerland C. Determining and increasing the hosting capacity for photovoltaics in Swedish distribution grids. In: Proc. 27th European photovoltaic solar energy conference and exhibition. 2012, p. 4414–20. http://dx.doi.org/10.4229/27thEUPVSEC2012-6DO.12.3.

[59] Luthander Rasmus, Lingfors David, Widén Joakim. Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage. Sol Energy 2017;155:1319–25. http://dx.doi.org/10.1016/j.solener.2017.07.083.

[60] Majumdar Debaleena, Pasqualetti Martin J. Analysis of land availability for utility-scale power plants and assessment of solar photovoltaic development in the state of Arizona, USA. Renew Energy 2019;134:1213–31. http://dx.doi.org/10.1016/j.renene.2018.08.064.

[61] Mondol Jayanta Deb, Jacob Gibu. Commercial scale solar power generation (5MW to 50 MW) and its connection to distribution power network in the United Kingdom. J Solar Energy Res Updates 2018;44:25–38.

[62] Rakhshani Elyas, Rouzbehi Kumars, Adolfo J S, Tobar Ana Cabrera. Integration of large scale PV-based generation into. Energies 2019;12(1425).

[63] Herrljunga municipality. Översiktsplan 2017 – 2035. Technical report, Herrljunga: Herrljunga municipality; 2017, [in Swedish]. URL http://herrljunga.se/download/18.912baa315ca4b6ed9d56da7/1534145249977/%C3%96versiktsplan%20Herrljunga%20kommun%202017-2035.pdf.

[64] The Swedish National Board of Housing Building and Planning. SFS 2010:900 Planning and buildng act §3. 2010, URL https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2018/legislation-planning-and-building-act/.

[65] Swedish Land Survey. Product description: GSD-topographic map, vector format. Technical report, Swedish Land Survey; 2016, URL https://www.lantmateriet.se/globalassets/kartor-och-geografisk-information/kartor/e_terrshmi.pdf.

[66] Swedish Land Survey. Product description: GSD-property map, vector. Technical report, Gävle: Swedish Land Survey; 2018, URL https://www.lantmateriet.se/globalassets/kartor-och-geografisk-information/kartor/e_fastshmi.pdf.

[67] Lukač Niko, Žalik Borut. GPU-Based roofs' solar potential estimation using LiDAR data. Comput Geosci 2013;52:34–41. http://dx.doi.org/10.1016/j.cageo.2012.10.010.

[68] The Swedish government. Ds 2000:61 the Swedish Environmental code. 2000.

[69] BRE. Planning guidance for the development of large scale ground mounted solar PV systems. Technical report, 2017, p. 28, URL www.bre.co.uk/.

[70] New South Wales Government. Guideline for landscape character and visual impact assessment, no. December. Technical report, Government of New South Wales; 2013.

[71] Sullivan Robert, Abplanalp Jennifer. Utility-scale solar energy facility visual impact. Technical report, 2013, URL https://blmwyomingvisual.anl.gov/docs/SolarVisualCharacteristicsMitigation_Final.pdf.

[72] Sullivan Robert, Meyer Mark. Guide to evaluating visual impact assessments for renewable energy projects, no. August. Technical report, 2014.

[73] Amalgam Landscape. Proposed solar farm at Pines tip, indian queens, cornwall. Technical report, 2019, URL https://cleanearthenergy.com/wp-content/uploads/2020/03/Pines-Tip-LVIA.pdf.

[74] Eco Logical Australia. Sapphire solar farm visual impact assessment, vol. 3. Technical report, 2018, URL https://www.sapphirewindfarm.com.au/wp-content/uploads/2020/01/E_Visual-Amenity-Assessment_SSF_v1a.pdf.

[75] Munari Probst Maria Cristina, Roecker Christian. Criteria and policies to master the visual impact of solar systems in urban environments: The LESO-QSV method. Sol Energy 2019. http://dx.doi.org/10.1016/j.solener.2019.03.031.

[76] Lingfors David, Johansson Tim, Widén Joakim, Broström Tor. Target-based visibility assessment on building envelopes: Applications to PV and cultural-heritage values. Energy Build 2019;204(109483):1–8. http://dx.doi.org/10.1016/j.enbuild.2019.109483, URL https://www.sciencedirect.com/science/article/abs/pii/S0378778819316433?via, https://linkinghub.elsevier.com/retrieve/pii/S0378778819316433.

[77] Widén Joakim. Correlations between large-scale solar and wind power in a future scenario for Sweden. IEEE Trans Sustain Energy 2011;2(2):177–84. http://dx.doi.org/10.1109/TSTE.2010.2101620, URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5685581.

[78] QGIS. A free and open source geographic information system. 2020, URL https://www.qgis.org/en/site/.

[79] Grainger JJ, Stevenson WD. Power system analysis. Electrical engineering series, McGraw-Hill; 1994, URL https://books.google.se/books?id=a1OzQgAACAAJ.

[80] Widén Joakim. System studies and simulations of distributed photovoltaics in Sweden. [PhD thesis], Uppsala University; 2010, URL http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-132907.

[81] Duffie John A, Beckman William A. Solar engineering of thermal processes. 4th ed.. Hoboken, NJ, USA: John Wiley and Sons, Inc.; 2013, p. 910. http://dx.doi.org/10.1002/9781118671603, URL http://doi.wiley.com/10.1002/9781118671603.

[82] Markiewicz Henryk, Klajn Antoni. EN 50160 – voltage characteristics in public distribution systems. In: Power quality application guide. Technical report, Copper Development Association; 2004, URL http://www.cdtechnics.be/542-standard-en-50160-voltage-characteristics-in.pdf.

[83] Energiföretagen. Anslutning av produktionsanläggningar till mellanspänningsnätet - AMP [Connection of production to the medium voltage grid], vol. 5. Technical report, Energiföretagen; 2020, p. 1–80.

[84] Swedish Meteorological and Hydrological Institute (SMHI). Strång - a mesoscale model for solar radiation. 2015, http://strang.smhi.se/.

[85] Lindahl Johan, Stoltz Cristina, Oller-Westerberg Amelia. National survey report of PV power applications in Sweden 2018. Technical report, IEA-PVPS; 2019.

[86] Schneider KP, Mather BA, Pal BC, Ten C-W, Shirek GJ, Zhu H, et al. Analytic considerations and design basis for the IEEE distribution test feeders. IEEE Trans Power Syst 2018;33(3):3181–8. http://dx.doi.org/10.1109/TPWRS.2017.2760011, URL https://ieeexplore.ieee.org/document/8063903/.

[87] European Commission. No. 2016/631 of April 14 regarding establishing a network code on requirements for grid connection of generators. 2016, URL https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32016R0631&from=EN.

[88] Masson Gaëtan, Kaizuka Izumi. Trends 2018 in photovoltaic applications. Technical report, IEA-PVPS; 2018, p. 88.