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Assessing a regional building applied PV potential – Spatial and dynamic analysis of supply and load matching

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ABSTRACT

Electricity production by PV is growing world-wide, and grid parity of PV-electricity can be found in many countries, even in low sunlight countries, such as Sweden (at latitude 58°). High installation-rate of PV-systems poses a challenge to the grid-operator. Building-integrated PV-supply potential analysis was performed for Linköping municipality in Sweden based on GIS-data for all the buildings in the municipality. The Linköping model provides a high spatial resolution (>180 000 buildings). The data are sorted based on azimuth and tilt, categorized in steps of 10°, and then used to construct hourly power supply data. The supply data are fed into the existing electricity load-profile of Linköping municipality. The strength and novelty of the method is that it provides the possibility of varying the installation-rate in different spatial directions to better match the load-profile.

The results indicate a solar supply-rate of 19, 43 and 88% respectively if using the tilted roofs (>900 kWh/m^2 × yr), the flat-roofs optimized with tilted panels for a winter solar supply and the fully available PV-area on existing buildings (8.1 km^2). Nevertheless, in approximately 70, 1400 and >3000 h/yr, respectively, surplus-power is created, which could be used to match a future load in a wider electro-mobility scenario.

1. Introduction

Over the past 20 years, while fossil-fuel based energy use has increased drastically, the impact of global warming has become more clear [1]. One promising technology for providing a sustainable power supply is local building applied conversion of solar energy using a photovoltaic (PV) system. In Sweden, Linköping, at latitude 58°, it is far from self-evident that PV systems can be a substantial renewable energy supply option. Nationally, 55% of all electricity use is utilized in the building sector, and in the EU, approximately one-third of all energy use is utilized within the built environment [2]. However, studies providing estimates of the potential of PV systems indicate that half of all present electricity use can be supplied via building integrated PV systems, see Ref. [3]. High installation rates of PV systems pose a challenge for operating the electric grid due to the possible situation of a large supply power compared to the load. However, one interesting feature is that most transportation activity is performed during the daytime, and in a future electro-mobility scenario, the energy requirements for transportation could be provided by the excess day-time PV supply.

In Ref. [4], a survey covering 50 km^2 for rooftops in different sectors in Austin, USA, indicates a potential for PV systems to provide 84.2% of the existing AC capacity (module efficiency 185 W/m^2 × yr), which leads to an energy substitution potential of 27.6% of the energy demand in Austin. In Ref. [5], a study of PV installations on residential roof-tops covering a total surface area of 265 km^2 was determined to be able to satisfy 78% of the residential energy demand in Andalusia based on a PV module production of 146 W/m^2 × yr. Neither of these papers focused on the details of when the power is provided and its effect on the power grid. These are important factors when assessing the highly dynamic matching between supply and demand.

The methodology for assessing the potential building PV power supply and its effect on the existing electricity load profile is presented. Because PV systems supply power during the daytime, which represents only approximately half of the hours of the year, the need for analyzing when power is supplied in comparison to the demanded load is important. Varying the tilt and azimuth of PV systems can alter the distribution in time of the PV supply,

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depending on the spatial distribution of the PV installations. A study that investigated the PV potential of Indonesia, see Ref. [6], indicated that PV systems could provide 26% of the consumption in 2010, accounting for restrictions such as the electricity demand during daytime and the minimal base load of conventional power systems. The study presented in Ref. [6] differs from this paper because the degree of electrification of Indonesia is very low compared to that in Sweden and because the focus of that study also concerned the electrification rate. In addition, the above-mentioned paper does not consider the PV supply on an hourly basis, which becomes increasingly important at higher penetration rates of the PV power supply.

It is difficult to compare the various studies on PV systems with each other and with the present paper due to the use of different terminologies, for example, energy demand versus electricity demand. This paper presents a comparison of the electricity load. It is also difficult to compare PV studies due to the different local conditions considered, for example, the different primary energy distribution system or degree of electrification. This paper uses a highly electrified city in an industrialized country (Sweden). The paper considers an initial electricity load and the use of solar electricity to first match the load (load matching). Any excess solar power provided is called surplus power, which can be exported, not used at the time, or stored for use in future loads. The term yield refers to the energy yield [$kWh/kW_p \times yr$] per installed power unit of a solar module and time, (usually presented as a year). The term solar supply rate is used to indicate the percentage of the energy demand supplied by solar PV systems, not taking load matching into account, that is, the annual supply divided by the annual demand.

Our study assesses the PV potential for all buildings within the geographical area of the Linköping municipality. This area includes both the city center and the countryside. The aim is to assess in detail the building integrated potential PV power supply and to investigate the matching of the PV power supply with the load profile for the electric grid in the same geographical area of the Linköping municipality. The electricity load curve has an hourly resolution and is used to calculate the resulting load curve when including the hourly building PV system supply. The main question is how the power supply profile matches the present power consumption under different PV-installation scenarios based on the amount of surface area available on the rooftops of the buildings. Ordóñez et al. [3] indicated that 78% of the energy demand of the residential sector can be provided by rooftop PV systems. The situation is different in Sweden, which is located at latitude 58, compared to Andalusia, which is Europe's most sunny region. Moreover, this paper focuses on all dwellings and all electricity use. There is a need to focus on matching the solar power supply with the present power consumption. In Ref. [7], large-scale solar power was analyzed to reveal the effects of geographic dispersion and the effect of having optimally tilted, 2-axis tracking and building-mounted solar systems; this study was used for comparison with our results.

Ref [8] presents a simple methodology based on a 2-D footprint area of the buildings for assessing favorable areas on roofs in the urban landscape for PV installation. The proposed methodology had three main steps, i.e. building of a digital terrain and surface models, predicting population distribution and using the code Solar Analyst extension in a geographic information system for solar radiation modeling. The major weaknesses of this modelling approach is its inability to taken into account the reflected radiation on neighboring buildings, as well as not assessing the PV potential of the building facades. The main advantage of this modelling approach is to use it as a first and rapid approximation to estimate the PV potential of urban areas.

Ref [9] presents a solar 3-D urban model that has been applied to estimate the PV potential on the Campus of the University of Lisbona in Portugal. The main improvements in the proposed model enable not only to take into account both roofs and facades to assess the PV potential but also to calculate direct and diffuse solar radiation on the considered surfaces with a spatial resolution of about 1 m and a time resolution of 1 h. The main finding from the case study was to highlight that the solar potential of facades was rather important due to their very large areas compared to the roofs which are more favorable surfaces for PV installations.

Ref [10] presents a methodology for the assessment of PV potential using open-source solar radiation tools and a 3-D city model implemented in a geographic information system. However the employed software i.e. solar radiation model r.sun is a 2-D model using a footprint area of the buildings. The proposed method has been successfully implemented on a small city in eastern Slovakia (latitude 49°). The results revealed that the PV potential is able to cover 2/3 of the present annual electricity consumption. The results have also stated that the PV potential has large spatial and temporal variations due to the global and local factors. The authors have also mentioned the importance of 3-D modelling of solar radiation and more detailed 3-D city models as well as power consumption statistics to assess matching and miss-matching of the PV potential in complex urban environments. Our paper takes the PV potential study further by including the load matching of the potential PV supply.

2. Methodology

The methodology presented estimates the total power supply potential in a region and to analyze the matching of the PV power supply with the electricity load pattern. The paper also explores the possibility of altering the spatial and to some degree the temporal distribution of PV supply to match the load. This means that a characterization is required of when, that is, at what time of the day, the power supply is provided. The following software packages and models were used in this study: Google Earth, Autodesk Ecotect, PVsyst and MS Excel based models.

2.1. Ecotect software

The Autodesk Ecotect Analysis software (Ecotect) is a recently developed tool for designing sustainable buildings. The strengths of Ecotect are its visualization capabilities, which can aid the overall assessment of a site's solar potential just as much as the detailed sizing of PV elements on a single roof. It is also possible to extend Ecotect's functionality by writing custom scripts in its native programming language, allowing it to adapt to a variety of tasks. Ecotect was used in Ref. [11] for residential planning. When performing a practical solar potential analysis, Ecotect is best used as visualization software in conjunction with technical simulation software packages, such as PVsyst, to achieve comprehensive results [12].

2.2. STRÅNG model

The STRÅNG model is a mesoscale model of solar irradiation. This model system produces the instantaneous fields of global radiation, photosynthetically active radiation, UV radiation (CIE-(International light standardization committee)weighted) and the direct normal radiation together with the sunshine duration at a horizontal resolution of approximately 11 km $\times$ 11 km and a temporal resolution of one hour. The model covers the geographic area of Scandinavia and the run-off region of the Baltic sea with a grid of size 268 $\times$ 246. Information regarding direct solar radiation and global radiation from the radiation network of Swedish Meteorological and Hydrological Institute (SMHI) was used for tuning and validation [13,14].

2.3. PVsyst software

PVsyst software is a PV system tool capable of accurate system yield calculations using detailed hourly resolution. PVsyst can adopt irradiation data for the site, various orientations, horizon shading, shade scenes, PV module characteristics (such as I–V (Current–Voltage)-curves), and inverter characteristics (such as efficiency curves) to calculate the system yield. The strength of PVsyst is its technical detail and the possibility to analyze all parameters in the study by exporting to spreadsheet such as MS Excel [15 and16].

PVsyst has been shown to underestimate the energy yield [kWh/kW$_p$ × yr], but at the same time it overestimates the irradiation if using preset data [16]. This issue of under/over-estimation is handled by inserting our own average monthly irradiation data from the STRÅNG model for the years 1999–2012. The average temperature data were obtained from the NASA-SEE database. The monthly irradiation and temperature data were used to synthetically construct hourly values in PVsyst that are renormalized to the monthly sum. The STRÅNG model provides direct irradiation data normal to the beam. In PVsyst, the global horizontal data and the diffuse horizontal data are used to construct the amount direct irradiation data normal to the beam. To provide the correct amount of direct beam irradiation data, an iterative process of four iterations is used to optimize the resemblance.

PVsyst is used to provide the detailed solar potential on an hourly basis. To tune PVsyst, the energy yield from a pilot plant was measured and compared with measured data on an example installation in Linköping University building; the DC-side losses that are overestimated are the primary factors that require tuning. The PVsyst model was evaluated and compared with measured values in Ref. [15]. Deviations were found due to the snow-covering of PV modules and the albedo effects due to snow, which can be handled only as a monthly average in PVsyst. The whole solar-potential methodology was compared to [7].

3. Case study of Linköping, Sweden

Linköping is a city in southern Sweden, with approximately 140 000 inhabitants; Linköping belongs to Linköping Municipality and is the capital of Östergötland County. Currently, Linköping is known for its university and its high-technology industry. The characteristics of Linköping are listed in Table 1. Linköping is actively working to implement sustainable development; one of the more recent targets is to become a CO_2 neutral region by 2025.

Table 1
Linköping presentation.

Coordinates:	58°24′57″N 15°37′31″
Country	Sweden
Province	Östergötland
Municipality	Linköping Municipality
City area	42.16 km^2 (16.28 sq mi)
Elevation above sea level	45 m (148 ft)
Population (31st December 2010) [1]	
• City	104 232
• Density	2500/km^2 (6400/sq mi)
• Municipacilty	140 367
Time zone	CET (UTC+1)
• Summer (DST)	CEST (UTC+2)
Website	www.linkoping.se

The electricity load profile for the city of Linköping is more affected by the demands of students than by the demands of industry, and the peak hours are approximately 19.00, see Fig. 1.

3.1. The built environment in Linköping

To estimate the power supply characteristics, the area, tilt and azimuth of each building surface is required. In this study, GIS-data were used for all dwellings in the city of Linköping, based on a 3D radar-scan. In Fig. 2, the methodology of this paper is presented. To the right in Fig. 2, a top-view of Linköping city is shown. Autodesk Ecotect software was used to determine the surfaces suitable for solar PV installations in the city of Linköping. In the countryside, the building area was measured one-by-one using a web-based aerial view tool provided by Linköping municipality and the azimuth was determined using the aerial view of the software Google Earth.

Regarding the countryside, the municipal office provided a map of all of the properties with buildings and a map with all of the properties with a total built area of more than 2000 m^2. The latter was analyzed via aerial view for categorization in steps of 10° tilt and 15° azimuth. The remaining buildings were assumed to have similar categorization. The building surfaces are sorted based on the azimuth and tilt and categorized in steps of 10° tilt and 15° azimuth. The categorization is used to construct the hourly power supply data in the software PVsyst.

The load matching of the PV supply was analyzed compared to an electricity load profile for all loads in Linköping Municipality, provided by the Linköping municipality owned grid-operator Tekniska Verken AB electric network. The grid-operator owns some smaller loads outside the municipality border and misses some loads due to other grid-operators being active inside the municipality border; these factors are assumed to cancel each other out. The electricity load data for Linköping from the years 2011–2013 were used for the evaluation is shown in Figs. 1 and 10.

3.2. PV-scenarios

The PVsyst software was used to calculate the power supply from the PV systems in the categorized tilts and azimuths. From the PVsyst software, it is possible to provide output files with hourly resolution. A complementary code was subsequently developed in Excel to perform simulations between 5° and 85° tilts at 10° intervals. Twenty-four azimuths/tilt were also collected. The Excel code is configured to easily vary the spatial amount of area, which is of certain interest when load matching the PV supply of the flat roof top areas.

The PV power supply was estimated in PVsyst based on a crystalline PV module with an efficiency of 15.5%, a temperature coefficient of −0.42%/°C and a 98% inverter efficiency. These assumptions are reasonable, given that the current market conditions are that approximately 90% of the market is crystalline solar panels, with efficiencies in the range of 14–21%, and that the majority of the sales are for solar modules at 15–16% efficiency. The thermal loss factor was calculated using a cooling heat transfer coefficient of 20 W/m^{2}K. IAM (Incidence Angel Modifier) losses were calculated using the PVsyst-standard model called “ASHRAE” (as it has become a standard in this American norm) using a value of $b_o = 0.05$. Other losses were set as follows: Ohmic wiring losses of 1.5%, module quality loss of 0.8%, and mismatch loss of 2.0%. For each step of azimuth and tilt, the hourly resolution power supply profiles are simulated.

In Table 2, an overview of the scenarios used is presented. Primarily, in the Full Roof Potential (FRP) scenario, the total potential for installing PV systems on all identified roof areas, regardless of

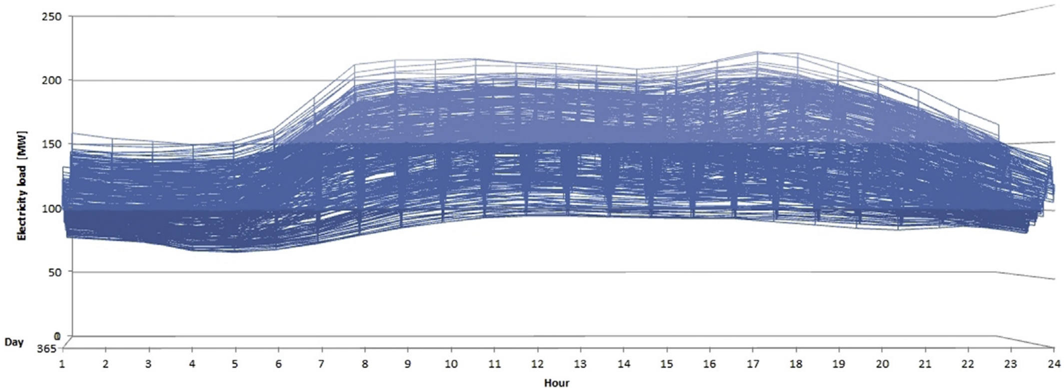

Fig. 1. Electricity load profile used in the case study. The load profile is taken from the electricity load data of Linköping, 2013.

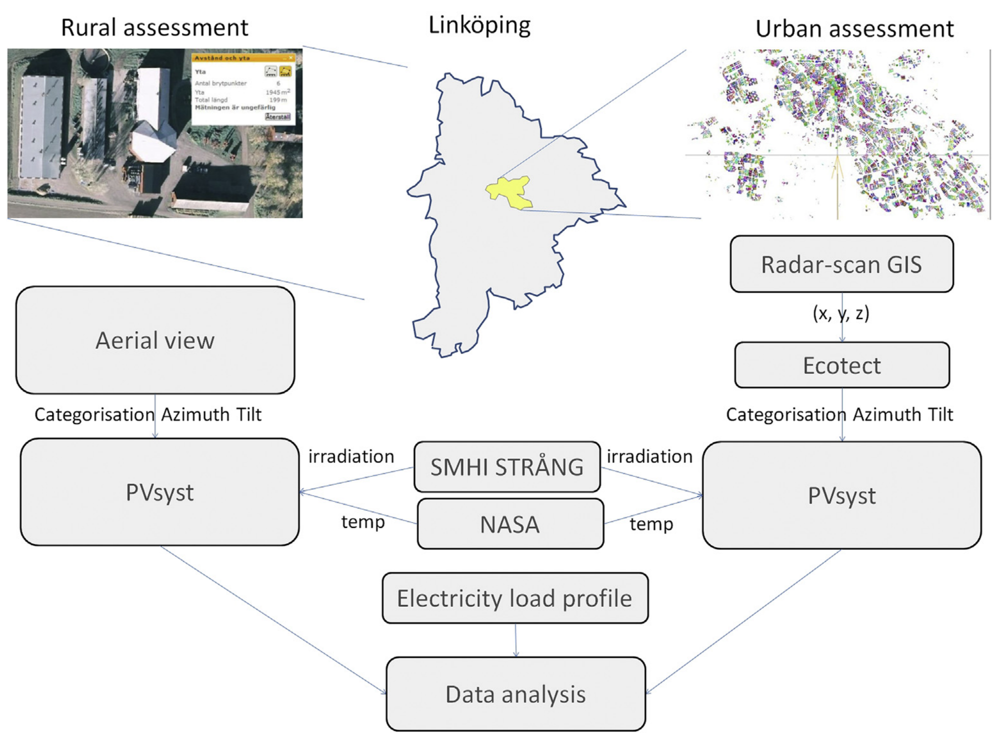

Fig. 2. Schematic of the methodological procedure used in this study.

yield, is calculated. Because the yield per installed kW PV system varies depending on the azimuth and the tilt, a second scenario, High incl. Flat (HF), where the yield is over 800 kWh/kW$_p$ × yr, and a third scenario, Low (L), where the yield is over 900 kWh/kW $_p$ × yr, are calculated. Three additional scenarios are also considered. Medium, using a yield over 900 kWh/kW $_p$ × yr where the flat surfaces (0–10° tilt) are used for tilting the PV systems to an appropriate tilt to fit in the present load and to reach yield over 900 kWh/kW $_p$ × yr. The Medium-Seasonal Distribution scenario (MSD) uses the flat surfaces for 75° tilt −15°–15° azimuth. The Medium Daily Distribution (MD) scenario uses flat surfaces for 45° tilt and is evenly distributed for azimuth values in the range between −60° and 60°. The Medium Supply Peak Shaving (MSPS) uses flat surfaces with half deployment in 45° tilt and −60° azimuth and other half in 45° tilt and 60° azimuth.

Because the full potential deployment of a PV system provides a high output, especially during the summer months, in comparison to the electricity load, a scenario that presents a more appropriate yield to the season and day and still has an acceptable yield per kW$_p$ and year can be found. By varying the characteristics of installing solar panels onto the flat surfaces of rooftops, an optimum can be found using this method. The data analysis also considers the possibility of having electric storage, which could be provided by future electric vehicles. In this paper, electric storage is considered using a 255 h average supply (approximately 10 days).

3.3. Assessment of the urban available building surface area

The Linköping city model contains over 180,000 objects (buildings), see Fig. 2, which enables high resolution potential power supply data for approximately 5.7 km^2 of the Linköping city model. A presentation of this interface is shown in Fig. 6. In Ecotect, it is not feasible to calculate all of the objects simultaneously due to the high complexity of the model. The computational requirements

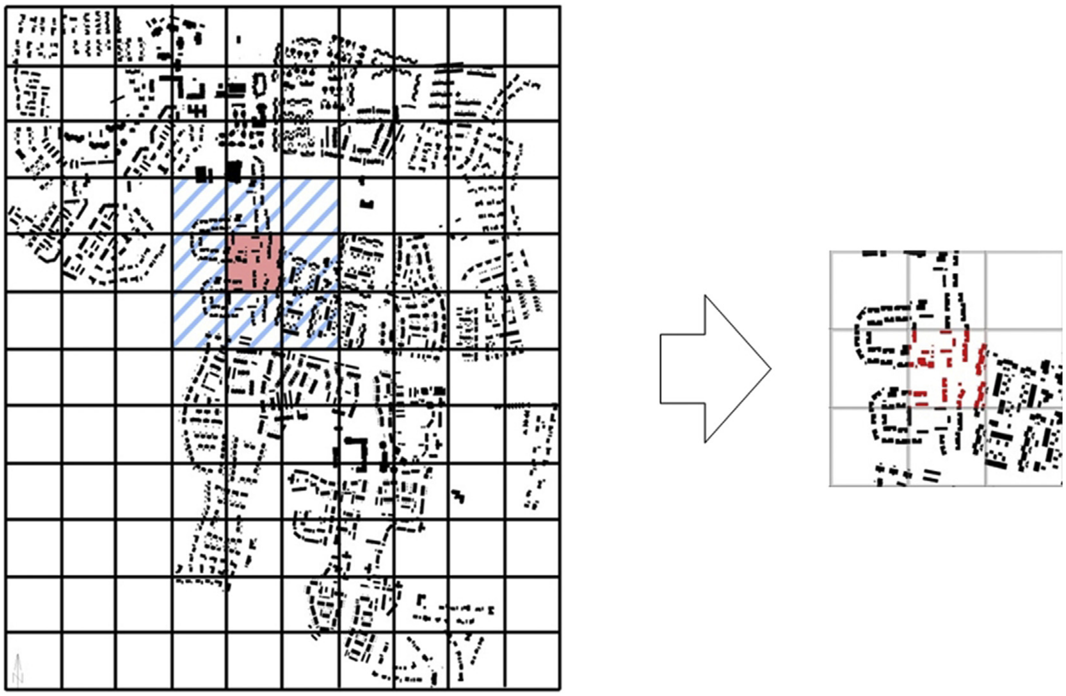

Fig. 3. Illustration of the shadow calculation algorithm. Each tile is simulated only with the surrounding tiles present.

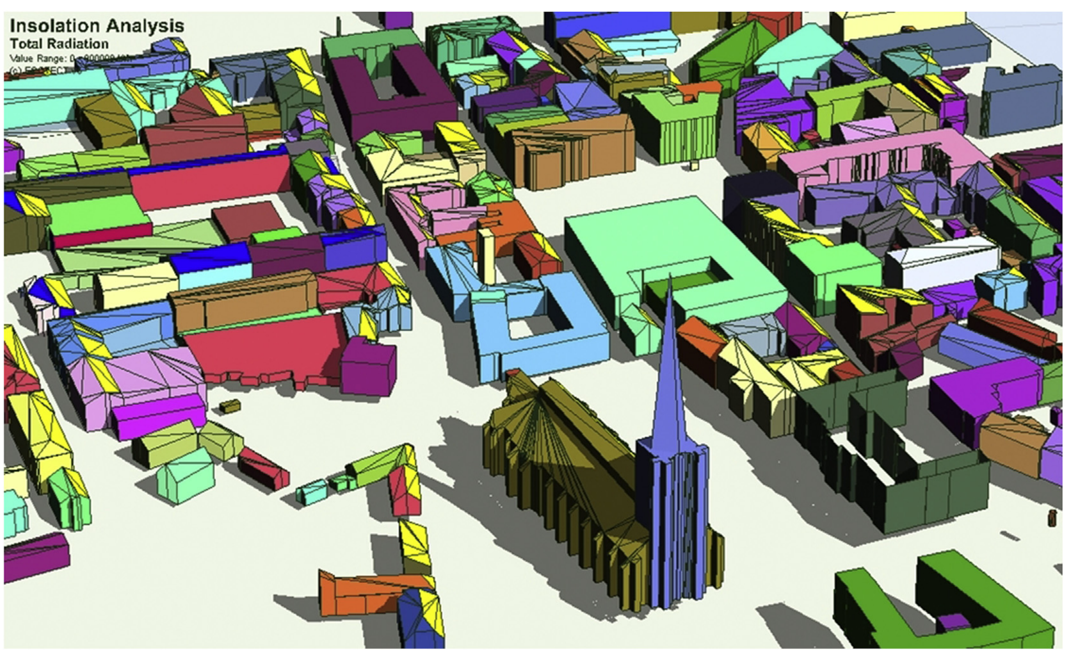

Fig. 4. Sample of the radar scanned 3D GIS-data for Linköping City.

increase nearly quadratically with the number of objects in the model. However, the computational burden is reduced if the surface (land) is rather flat and the buildings have similar heights, which is reasonable in Linköping city. Another important aspect in reducing the computational burden involves the assumption regarding shading effects in the model that only the neighboring squares are affected by shading. For a suburban area with typical buildings of similar height, the algorithm for shading does not interfere with the results. However, if skyscrapers exist in an area, the algorithm must consider buildings that are sufficiently high to also include shading from high-rise buildings. By using an algorithm that limits the shadowing scene for the actual object down to just the neighboring area (Fig. 3), the calculation time can be decreased dramatically. This means that the shading taken into consideration is merely a square of 300 $\times$ 300 m instead of the whole city. To simulate the entire Linköping city model, single point resolution per surface was used. Single-point resolution per surface is a simplification that makes each surface calculated be affected by

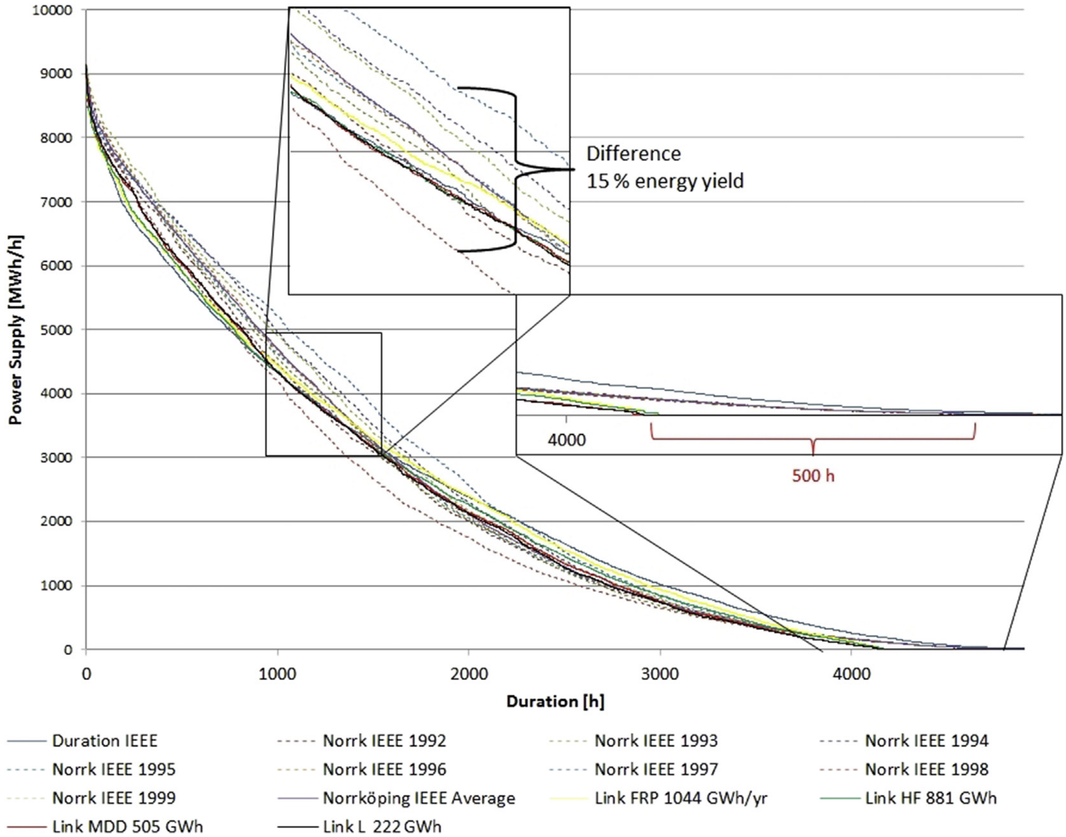

Fig. 5. Power supply profile comparison of the IEEE (Sweden), Norrköping (Norrk) IEEE and our PVsyst generated profile (Linköping (Link)) for the scenarios FRP, HF, MD and L.

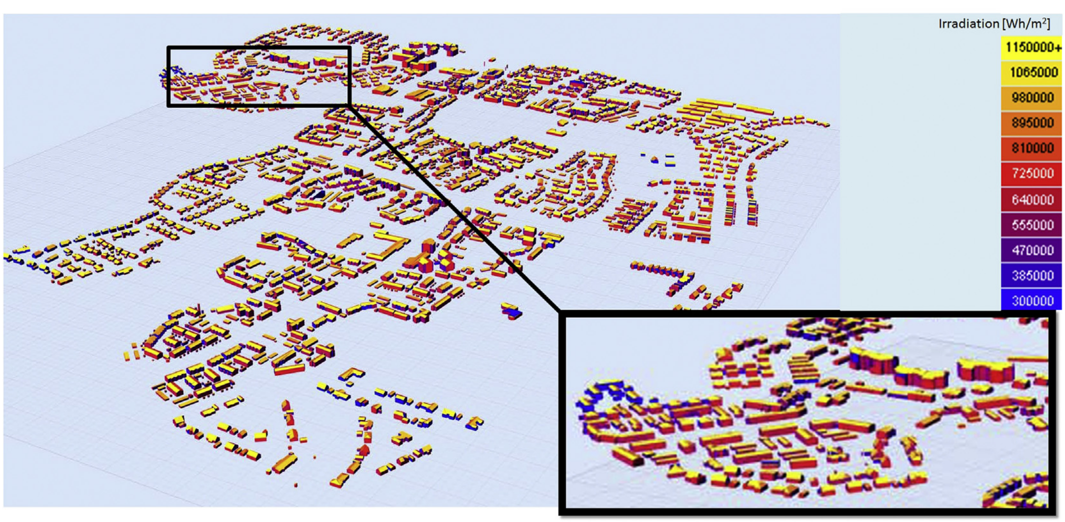

Fig. 6. Total irradiation false color 3D map for the district of Lambohov, a part of Linköping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shadowing in the same manner as the whole surface. A more detailed resolution, such as sub-dividing surfaces into 1 m × 1 m, would indicate where individual PV-modules should not be installed due to shadowing.

However, because of shadowing, there are few facades that are useful in the city model. The facades are commonly shadowed by surrounding buildings. Still, it is possible to find suitable spots for PV-installation in the upper part of a facade. The radar-scanned GIS-data for the city, see Fig. 4, contains imperfections that produce unrealistic triangles at some surfaces. These imperfections result in sometimes very small surfaces with only a marginally shifting tilt or azimuth. As a result, the output of the Ecotect simulation is the sum of areas within the categorization in steps of 10° tilt and 15° azimuth. More details, such as sky-dome resolution, which has negligible effects, can be found in Ref. [9].

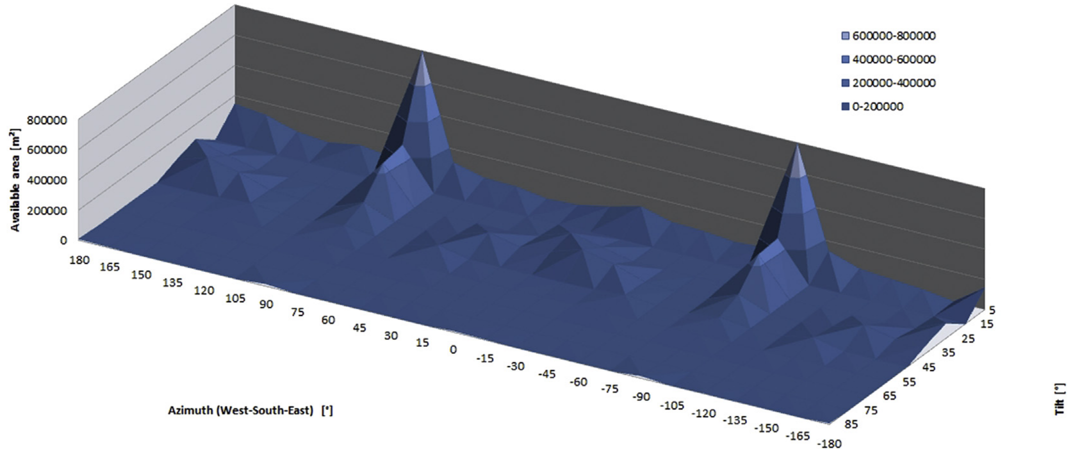

Fig. 7. Available surface area as a function of tilt and azimuth in the urban solar potential assessment.

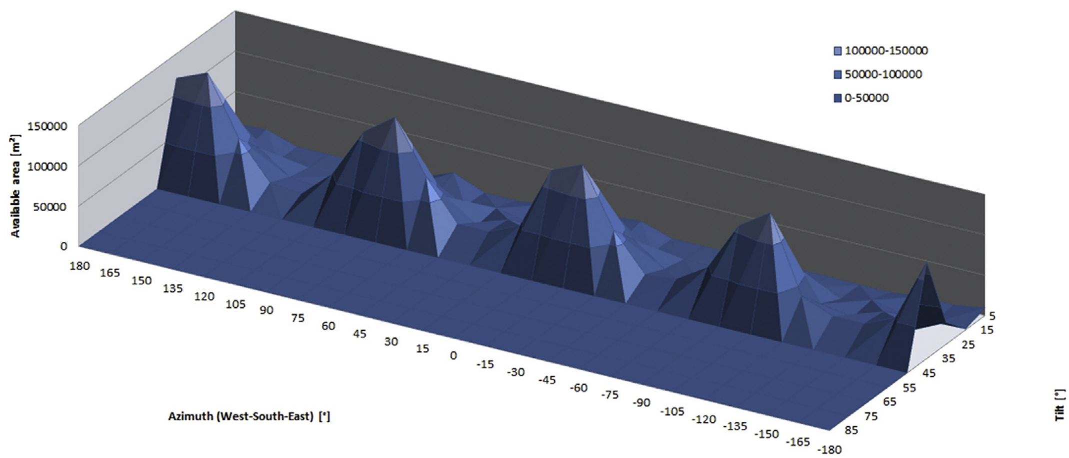

Fig. 8. Available surface area as a function of tilt and azimuth for the rural solar potential assessment.

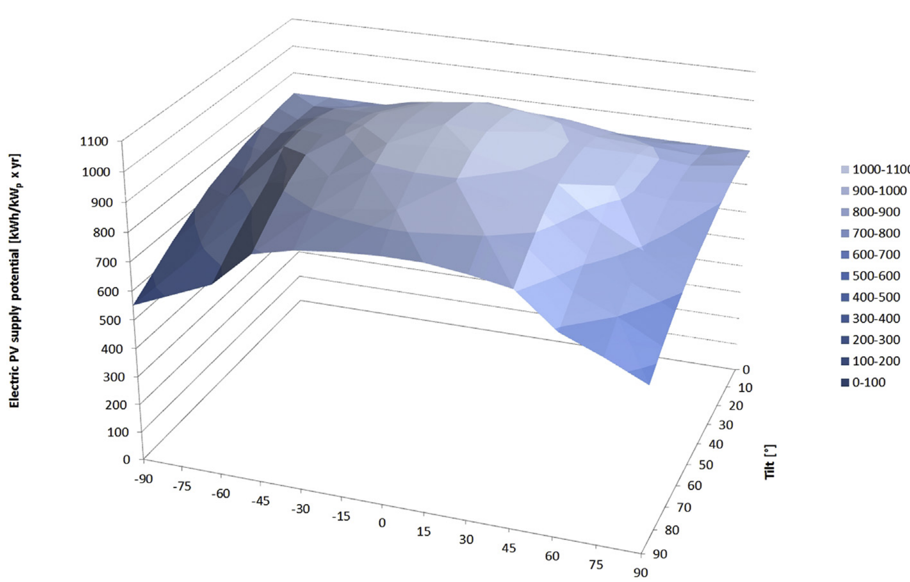

Fig. 9. Solar yield assessment as a function of tilt and azimuth.

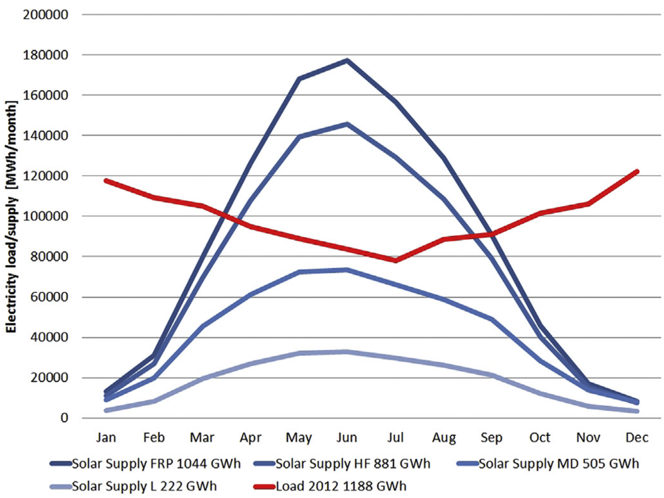

Fig. 10. Total Electric load for the Linköping grid area of 2012 and the solar supply L, MD, HF and FRP-scenarios.

3.4. Assessment of the rural available building surface area

All of the properties in the municipality were characterized first according to the built area. Two-hundred seventy-seven buildings, each with a built area above 2000 m^2, were analyzed to assess the categorization of the azimuth and tilt for the solar potential of the countryside. The area of the rural built environment was measured one-by-one using a web-based aerial view tool provided by the Linköping municipality (Fig. 2), and the azimuth was determined using the aerial view of the software Google Earth. Roof surfaces of less than 20 m^2 were not included in the categorization. In total, 3332 buildings were analyzed, having a total area of 1.269 km^2. Out of the area of these buildings, 1.164 km^2 was included in the categorization in steps of 10° tilt and 15° azimuth. The tilt was analyzed using aerial view when measuring the building based on the age and appearance on the aerial view. The categorization of tilt is as follows: old farm building = 30–40°, new farm building = 20–30°, industrial building = 10–20° and horizontal roof = 0–10°. Because a large proportion of the buildings have a tilt greater than 10°, it is necessary to include an area increase because the aerial view measures the horizontal surface. The tilted area is calculated according to Equation (1). The total roof surface area including this area increase due to tilt sums up to 1.365 km^2.

$$tilted\ surface = \frac{aerial\ view\ measured}{\cos(tilt^{\circ})} \quad (1)$$

Shading was also noted; however, most of the shadowing stemmed from trees. Shadows from trees were neglected in the categorization.

Once all of the buildings in the group of the 277 properties with an area greater than 2000 m^2 was categorized in steps of 10° tilt and 15° azimuth, the other 1291 properties with areas of 0.964 km^2 were categorized proportionally, meaning that a total of 1.037 km^2 was taken into account. The aerial view method has an estimated error related to the aerial view measurements of approximately 0–5%. This error was confirmed by investigating approximately 100 roof surfaces in more detail.

Table 3
Distribution of the areas in the study.

Tilt	Rural	Average	Urban
80–90°	<0.1%	1.0%	1.5%
70–80°	<0.1%	<0.1%	<0.1%
60–70°	<0.1%	<0.1%	<0.1%
50–60°	<0.1%	0.1%	0.2%
40–50°	<0.1%	2.3%	3.3%
30–40°	67.4%	32.2%	17.4%
20–30°	26.6%	18.5%	15.1%
10–20°	2.5%	7.0%	8.9%
0–10°	3.5%	38.8%	53.7%

3.5. Comparison of the solar supply data

In Fig. 5, a comparison to [7] is shown. The comparison contains a duration graph determined under the Swedish IEEE scenario, the Norrköping IEEE scenario average, the Norrköping IEEE [7] scenario for individual years 1992–1999, and the Linköping scenarios FRP, HF, MD, L, renormalized to the IEEE scenario for buildings 11.2 GW_p. The maximum output power is therefore always renormalized to 9.2 GW electric AC power. The area of interest for this study is the area beneath the line forming the energy yield per year at a maximum output power of 9.2 GW AC power. The deviation is not significant; nevertheless, this comparison indicates that a high variety among the years is found. Furthermore, the deviation between the 2 methods is a result of the low power region and is due to differences in how the threshold and IAM are treated. In practice, this means that the method takes into account the nonlinearity of the efficiency graphs for inverters and modules. This nonlinearity occurs because there is a certain threshold power before the system starts output. The IEEE scenarios have power being supplied 500 h longer than this study using the PVsyst-methodology. This difference represents up to a 5% difference in the energy output difference between the methods, where the FRP, 1044 GWh/yr Linköping scenario deviates 1% from the Norrköping IEEE average, and the Linköping, L, 222 GWh/yr deviates 5% in the energy output. The maximum difference among the years in Norrköping IEEE scenarios is 15% on an energy basis. Note that the IEEE scenario uses a proportionally higher rate of façade installations and that the Swedish IEEE scenario uses irradiation data from 12 different irradiation sites, which better distributes the power and therefore yields a higher rate of energy per peak supply.

4. Results

4.1. Urban available surface

In Autodesk Ecotect, a false color map is used to visualize the

Table 2
Presentation of the scenarios used, the installation rate, conditions and type of surfaces used.

Abbreviation	Installation rate	Condition	Used roof-tops
FRP	Maximum (Full Roof Potential)	Full roof potential	All roofs used, also north facing
HF	High-incl. flat	yield >800 kWh/kWp·yr	All flat roofs used
MSD	Medium-Seasonal Distribution	yield >900 kWh/kWp·yr	Flat roofs tilted 75°
MSPS	Medium-Supply Peak Shaving	yield >900 kWh/kWp·yr	Flat roofs tilted 45°, to SW & SE
MD	Medium Daily Distribution	yield >900 kWh/kWp·yr	Flat roofs tilted 45°, evenly distributed
L	Low	yield >900 kWh/kWp·yr	No flat roof used

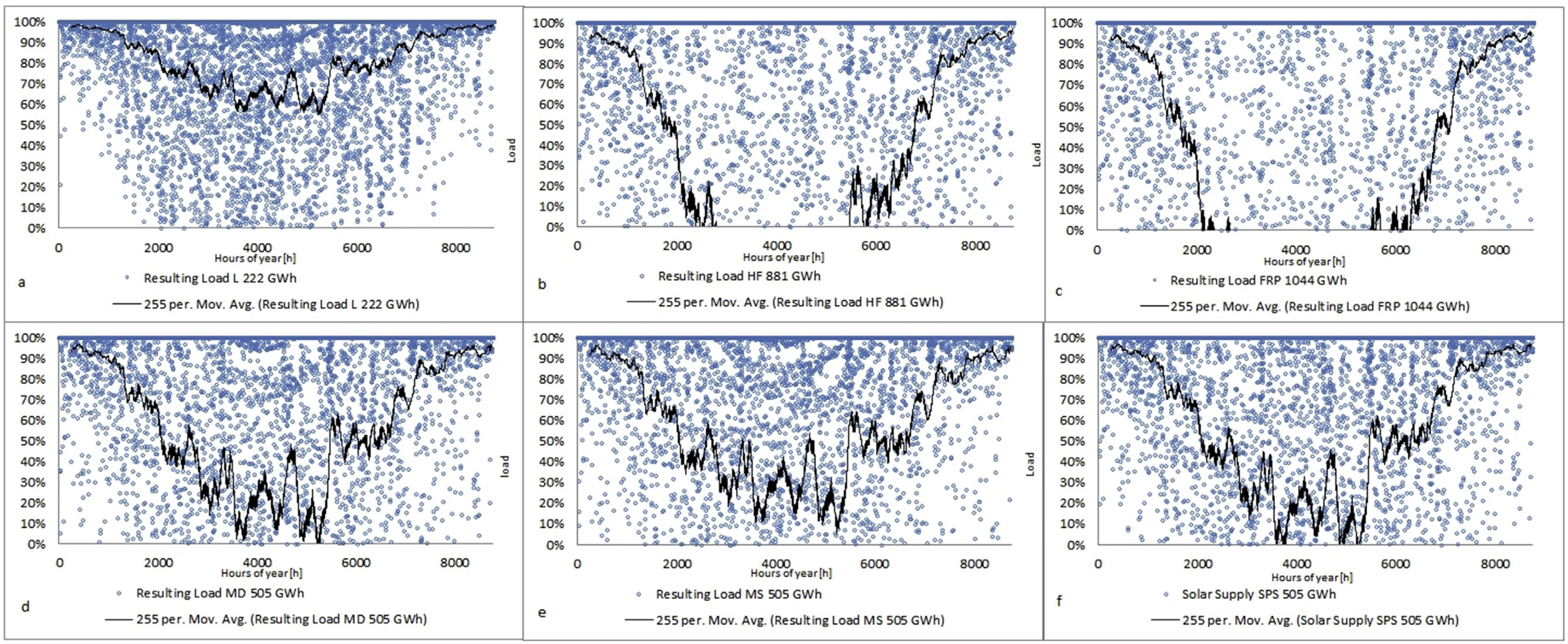

Fig. 11. **a**–**f**: Resulting Electric load for the Linköping grid area, including the total power supply potentials of 1044 GWh (FRP), 880 GWh (HF), 505 GWh (MD, MS, MSPS) and 222 GWh/year (L).

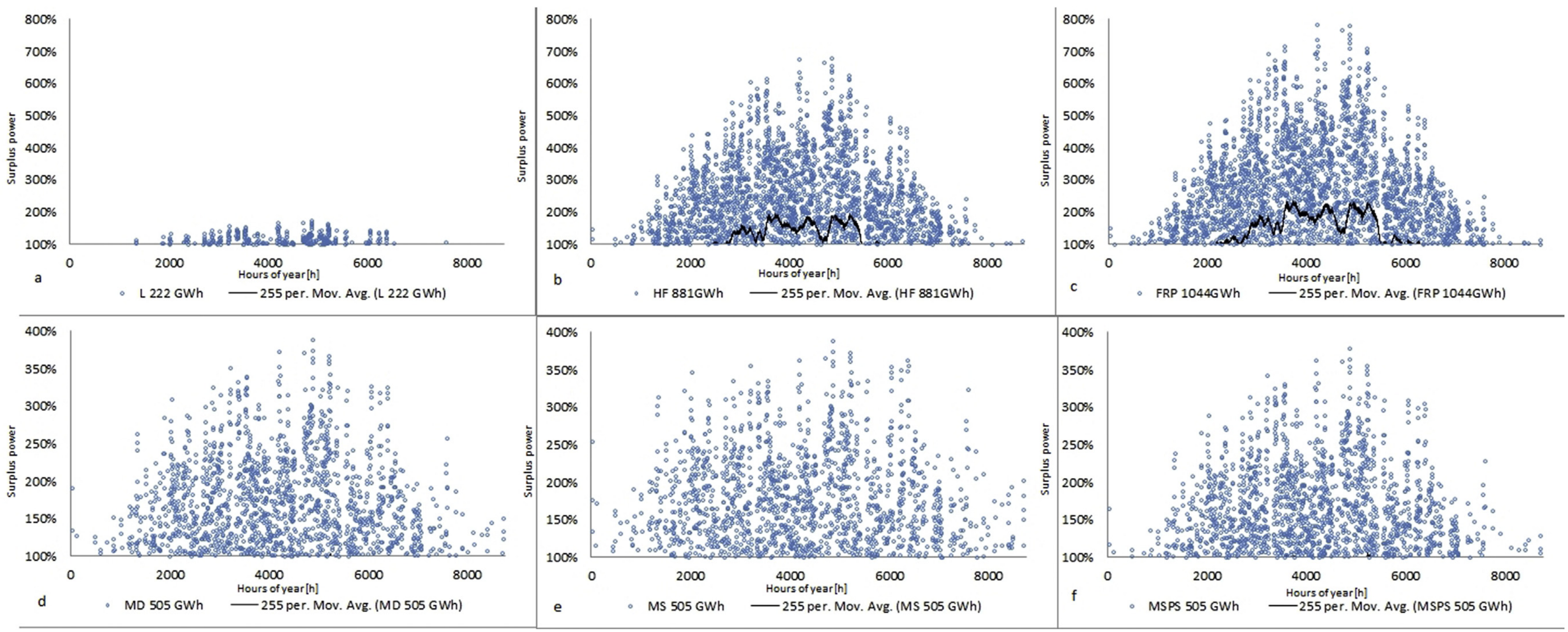

Fig. 12. a–**f**: Surplus power from the solar supply after being matched to the electric load, including the total power supply potential of 1044 GWh (FRP), 880 GWh (HF), 505 GWh (MD, MS, MSPS) and 222 GWh/year (L).

irradiation levels on each roof. A presentation of this map is shown in Fig. 6, where a part of the city is shown.

The available area categorized per azimuth and tilt is presented in Fig. 7. Most areas in the city model are between 0° and 10° tilt, and the majority of these surfaces are oriented to the east and west. Due to high proportion of low tilted areas, it is possible to use tilted panels on these roofs and orient them in any direction to better match the load. Another option to use the low tilted areas is to let them follow the roof tilt at the low tilt angle, which enables the PV systems to supply power over a longer period during a day in summer. The higher tilts at 20°–30°, mainly to the east and to the west, provides a distribution of solar supply over the day.

4.2. Rural available surface

Outside of the city, buildings are more evenly distributed along the north/south azimuth and the east/west azimuth, as shown in Fig. 8. Most buildings are facing to the east-west or north-south at a tilt of 30–40°. The proportions of east-west and of north-south are similar.

In Table 3, the distribution of the areas based on tilt is presented for the rural, urban and total available surfaces in this study. Compared to the references [3] and [7], there is a higher percentage of flat areas and a lower percentage of 90° facades than in this study. This difference can be explained by the fact that:

A. Refs. [3] and [7] used a fixed assumption of tilt 45° for agricultural buildings. The presented method measures the roofs by aerial view
B. Refs. [3] and [7] used a very high proportion of facades that become affected by shadowing in our Ecotect simulation and is not used. Only a small proportion of facades can be used, see Ref. [8].
C. The presented method includes roofs on the northern azimuths (−180 to −90, 90–180), which are not used by Ref. [3]and [7].

4.3. Results of the case-study

In Fig. 9, the solar yield assessment as a function of tilt and azimuth is shown for a shadow-free solar installation in Linköping. A yield of over 800 kWh/kWp•yr can be found for all flat roofs in any direction. Note that this simulation does not include losses due to snow or dirt. In Refs. [15,17,18], the snow losses are studied and were found to be approximately 3% of the annual yield for a snowy winter, while the dirt losses were found to be in the range of 1–8%, mainly depending on the local pollution and also on the tilt. In Linköping, the pollution is low. If tilted more than 10°, the area must be within east (−90°) to west (90°) azimuth to achieve the above-described performance. With a higher tilt than 30°, the direction starts to narrow in a southerly direction, and at 90°, the direction must be within the range of southeast (−45°) to southwest (45°). To reach 900 kWh/kW$_p$, the tilt must be in the range of 10–80° and the direction must be in the range of southeast (−45°) to southwest (45), with the exception that at even higher tilts, the direction must be closer to south.

The time during which the PV power output is aggregated is important. For example, if presented on a monthly basis, a good match is apparent between the PV supply and the electric load. Up to the MD scenario presented in Fig. 10, the PV supply and the electric load appear to be perfectly matched. In Scenario HF and FRP, there is some surplus in the period from April to September. However, note that the resolution in time is not adequate because the solar supply is highly fluctuating, especially for a relatively small spatial distribution of the solar supply. There is thus a strong incentive to examine in detail the description of the solar supply.

If an hourly time step is chosen instead, the matching of the profiles becomes more realistic and a surplus of energy is found in all of the scenarios. In Figs. 11 and 12, the resulting load is presented as a complement to the load charts for the PV supply. The resulting load is the load minus the solar supply on an hourly basis. In Fig. 10, the resulting load is presented as a percentage of the current hourly load in a scatter diagram using the electric load profile. There is also a trend line inserted as a moving average of 255 h Fig. 11 shows the percentage of the surplus supply power of the current hourly load as a scatter diagram of the 6 scenarios (see Table 4). A trend line is also inserted here, where the HF and FRP scenarios clearly exhibit a substantial surplus. Examining the M-scenarios, the trend line is always below surplus for the 75° tilt scenario, meaning that if a 10-day storage capacity is achieved, it would provide a reduced surplus. However, without storage, the M-scenarios result in fewer surpluses when the solar supply is spread over the day in the MD.

However, in all of the scenarios shown in Fig. 11, there are hours with a resulting load below 0%, meaning surplus power in excess of the load. Their characteristics are shown in Fig. 12 a − 12 f, where 100% means a perfect match and 800% means a supply power 8 times higher than the load. The difference among the M-cases is that MSPS that is arranged to perform peak shaving does have a lower winter supply, mainly because the PV systems are tilted to the east and to the west, which spreads the power over the day during summer but still exhibits a concentration of higher power in the summer. Looking at MS reveals an improved spread over the year but very high peaks are also formed during winter time and especially during spring time. MD is a mix between these two cases based on the even distribution of the azimuths of the orientations of the PV systems.

In Fig. 13, the solar supply potential is shown and arranged per day of year and per hour of the day. Fig. 13 d–13 f show the M-scenarios, where it is clearly shown that MD spreads the power over the day and also prioritizes the summer supply over the other 2 scenarios. The seasonal variation is more clearly shown in 13 e, the MS-scenario. The L scenario exhibits a more clear spread over the season in Fig. 13a. The HF and FRP scenarios in Fig. 12 b–c have more spread over the day because they involve a reduced proportion of higher tilted panels.

Table 3 presents a summary of the solar supply energy of 6

Table 4
Summary of the 5 different solar supply scenarios of 1044, 881, 505, 222 and 0 GWh/year analyzed in this paper.

Scenario	Load [GWh/yr]	Solar power supply [GWh/yr]	Export [GWh/yr]	Matched [GWh/yr]	Peak export [MWh/h]	Peak import [MWh/h]
Load	1188	0	0	0	0	226
FRP	1188	1044	603	441	695	226
HF	1188	881	463	418	590	226
L	1188	222	7	215	73	226
MD	1188	505	156	349	290	226
MSPS	1188	505	148	357	280	226
MS	1188	505	165	340	329	226

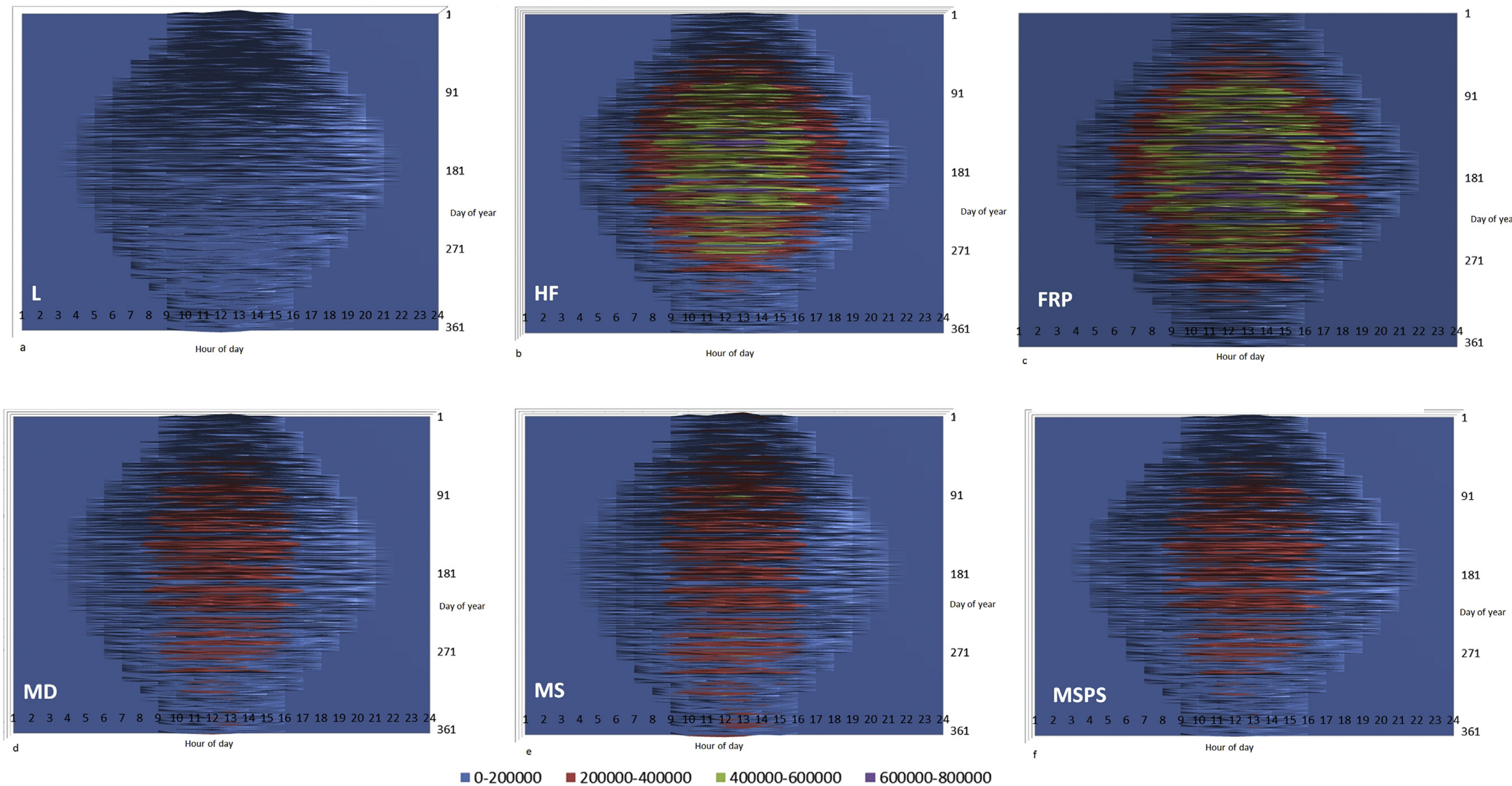

Fig. 13. **a–f**: Solar power supply for the total power supply potential of, L, HF, FRP, MD, MS & MSPS-scenarios.

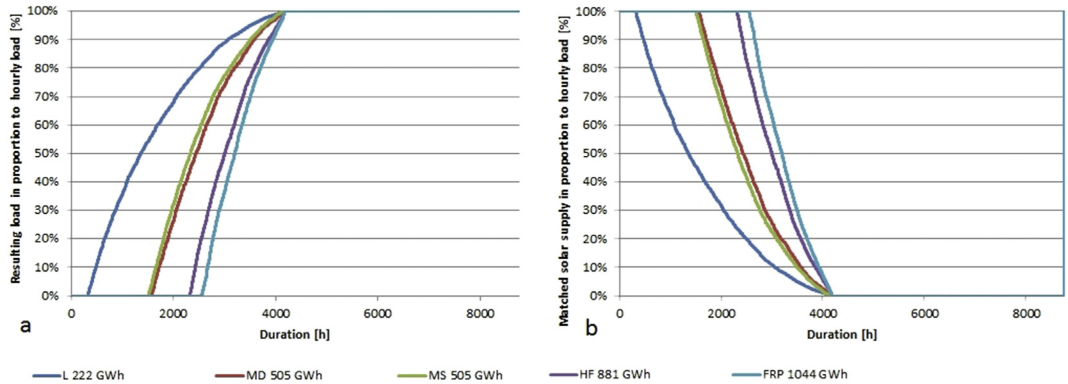

Fig. 14. a, b: Duration diagram of the total resulting load percentage and surplus power percentage for the Linköping grid area L, HF, FRP, MD, MS-scenarios.

different scenarios, matched solar electricity with end-use, energy export to other grid and peak import/export power. In the L-scenario, 19% of the electricity demand is supplied by the PVs and 3% of the solar power supply is exported to other grid. When including the flat surfaces tilted 45° in the MD-scenario, the solar supply rate increases to 43% and 31% of the solar supply is exported. If tilted 75° at azimuth −15° to 15°, in the MS-scenario, more solar supply would be exported, and if tilted only −60° and 60° azimuth at 45° tilt (MSPS), less would be exported. At a yield of 800 kWh/kWp•yr (HF), the solar supply rate is 74%; however, 52% of the solar supply is exported. At full potential, the solar supply rate is 88%, and 58% of the solar supply is for export. Interestingly, the solar supply always occurs during daytime, when the load is higher, and from April to September, a guaranteed decrease maximum load by at least 10% of the total installed solar peak power occurs.

When varying the tilt and azimuth for the flat roofs, many options of tilt and azimuth can be tested in the presented model. Using the 900 kWh/kWp•yr base, then adding evenly distributed azimuths −60° to +60° tilted 45°, both a yield above 900 kWh/kWp•yr was found with high matched solar direct electricity consumption. The panels could only use −60° and 60°, which would spread the power supply throughout the day and produce a lower yield kWh/kWp.

Fig. 14 shows a duration graph of the matched solar supply to the load profile. The solar supply can only contribute half of the hours of a year (e.g., during day-light). The more the potential is realized, the greater the amount of surplus, as shown in Fig. 14 b. In the FRP-scenario, the solar supply power is up to 8 times the demand (Fig. 12 c). Interestingly, the method of installing the PV systems on the flat roofs is found to affect how it matches the load. A higher tilt to the south provides a better seasonal spread, but with higher day-time peaks in the spring or autumn of power supply and in fact a lower match than spreading them in a lower tilt between the east and west.

5. Discussion and conclusions

This paper presented a method using different well-known software packages, i.e. Google Earth, Autodesk Ecotect, PVsyst and MS Excel, to investigate in detail the total power supply potential in a region and to analyze the matching of the PV power supply with the electricity load pattern. The method highlighted both the spatial and temporal analysis in order to assess the potential for the building PV power supply and its effect on the electricity load profile as well as on the estimation of electric battery storage capacity. This means that a characterization is required of when, that is, at what time of the day, the power supply is provided.

The proposed method was found to be a powerful and robust tool to evaluate possible future scenarios and the solar installation rate. The methodology has been applied to predict PV power supply for one region. However it is worth to mention that there is no specific limitations to use the proposed integrated software packages for other applications.

The main short-coming of this method is the tilt assessment, with the range of tilts that observed in aerial view being ±5°. A high tilted solar panel towards the south provides the best seasonal distribution of solar supply for the studied location and produces high peaks of solar supply on an hourly time-scale. If the PV supply is connected to the grid with electric storage, then the high tilted panel to the south is the better choice. To optimize the solar supply without storage, the efficient choice is to distribute the panels half to the south east and half to the south west in a 45° tilt.

Based on the presented study, one can conclude that for the given location and city:

- A 19% solar supply rate on tilted high yield roof-tops is possible.
- A higher solar supply rate would imply export or other ways to store or offset the solar supply.
- A solar supply rate of up to 43% is possible if using flat roofs with tilted solar systems.
- The full identified roof potential, regardless of yield, is found to be 88% of the present consumption, but this results in a high export to the connecting grid during peak hours.
- The tilt and azimuth of tilted solar panels can be altered to spread the production over the hours of the day or the season.

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