ASSESSING THE ECONOMIC VALUE FOR GRID OPERATORS OF QUANTIFIED SMOOTHING EFFECTS FROM PV SYSTEMS WITH VARYING ORIENTATIONS

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ABSTRACT: As the number of solar photovoltaic (PV) installations grows rapidly, accurate registry data and efficient use of existing grid capacity are increasingly critical for stable and cost-effective distribution grid operation, as well as for enabling further PV deployment without unnecessary physical grid reinforcement. This study employs an innovative remote sensing method that combines aerial imagery, machine learning, and Light Detection and Ranging (LiDAR) data to identify, validate, and simulate PV power generation. The method can detect discrepancies between grid operator registries and actual PV installations and quantify the orientation-based smoothing effects that arise when distributed PV systems have varying azimuths and tilt angles. By accounting for these effects, it can free up significant existing capacity in low-voltage distribution grids, reducing the need for costly reinforcements. Application of the method in three Swedish low-voltage grids demonstrated tangible economic benefits, with planned investments of 400,000 (~€36k) and 1.5 million SEK (~€136k) avoided. The study evaluates the value creation of inventory-based PV mapping and PV orientation smoothing effect analysis from the perspective of grid operators, highlighting the method's potential as a cost-effective, data-driven tool for grid planning, investment prioritization, and integration of distributed PV power generation.

Keywords: Photovoltaics, Grid capacity, Economic value assessment, Remote sensing, Orientation smoothing effect

1 INTRODUCTION

Solar power is expanding at a rapid pace both globally and in Sweden. In 2024, photovoltaics (PV) accounted for 75% of all newly installed power generation capacity worldwide, with a preliminary addition of 600 GW [1]. In the European Union, solar now represents 14% of electricity generation [1], of which about half is distributed PV systems connected to a grid connection point where also consumption takes place. This fast and decentralized growth is fundamentally challenging electricity distribution grids [2] which in northern Europe have traditionally been designed to handle peak demand occurring during cold winter days. In areas with high PV penetration, the most critical loading hours for distribution grids now occur during sunny summer days rather than during winter peaks, marking a paradigm shift in grid planning.

A key challenge for grid operators lies in the lack of detailed information about the grid connected PV systems. Typically, Distributed System Operators (DSOs) only have access to basic data such as the property address and the installed capacity of modules and/or inverters. Missing information includes the azimuth and tilt of the PV systems [3], whether installations consist of multiple orientations, and the total actual PV generation profiles as DSOs only measure the power injected to the grid. In the absence of more detailed information, DSOs face challenges in accurately estimating PV power injected into the grid [4], [5], and it is therefore praxis among DSOs in Sweden (and many more European countries) to assume that all PV systems can produce their maximum power — usually the rated power of the inverters — simultaneously and that no electricity is self-consumed. These assumptions tend to overestimate grid stress, leading to unnecessary and costly reinforcements.

In practice, this scenario cannot occur, since distributed PV systems are typically rooftop-mounted and therefore follow the underlying roof geometry [3]. As a result, their orientations and tilt angles vary considerably [6], producing asynchronous generation patterns and giving rise to a natural 'smoothing effect,' here defined as the PV Orientation Smoothing Effect (POSE).

To address this information gap, an AI-based remote sensing and PV power simulation model package, called *Alfrödull*, has been developed. By combining aerial imagery with Light Detection and Ranging (LiDAR) data, this method can identify more than 95% of all PV systems in a given area [7], [8] and estimate their azimuth and tilt with an accuracy of ±3° in 95% of cases [6]. These parameters are then used to simulate the hourly electricity generation of individual PV systems with high spatial and temporal resolution. Validation against measured data from 40 reference systems shows strong agreement, with coefficients of determination (R^2) in the range 0.83–0.96 [9].

A crucial outcome of this approach is the ability to quantify the POSE, i.e., the reduction in aggregated PV power peaks due to differences in PV system orientations. By simulating the generated power from all PV systems connected to a distribution grid over several years of historical weather data (2017–2024), this smoothing effect has been systematically quantified and analyzed in three Swedish grids, down at the level of individual substations, in a parallel technical study [10].

Building on these results, the present study investigates the value creation of the remote sensing generated data and the economic implications of the quantified POSE analysis from a DSO perspective.

Traditionally, increasing the acceptance limit [11] for PV systems in distribution grids requires physical grid reinforcement, with associated costs determined by the scope and capacity of the grid. If the power lines cannot handle the increased load, they may need to be replaced or upgraded, costing between €10k and €100k per kilometer (in Sweden), depending on whether they are overhead lines or underground cables. Additionally, transformers may require upgrades, which can range from €10k to €500k.

2 DATA

Alfrödull scans were applied to the most recent aerial imagery of three Swedish low voltage grids — June 2024 for Falun (FLN), and May 2024 for Karlshamn (KHN) and

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Fagersta (FGA) — covering their respective grid areas. The scans identified 2015 PV systems within FLN, 327 within KHN and 256 within FGA. Of those it turned out that 80, 1 and 28, respectively, were off-grid systems not connected to the distribution grid.

For all grid-connected PV systems in these grids, PV power generation was simulated at 30-minute resolution and subsequently aggregated at the substation level. The POSE was then calculated for each substation as the difference between the maximum aggregated PV output observed over the 2017–2024 period and the sum of the rated AC capacities of the connected inverters, following the methodology described in detail in [10].

3 METHODOLOGY

To assess the perceived value of the *Alfrödull* method from a DSO perspective, two semi-structured interviews were conducted. The first took place with the Head of Grid Market, Oscar Willén, at the Swedish DSO Falu Elnät, and the second with the Head of the Grid Business Area, Benjamin Gacanin, together with the Business Developer, Felix Kjellvåg, at Karlshamn Energi. Full interview transcripts (in Swedish) are available in this research project report [12].

The objective of the interviews was to collect qualitative insights regarding the benefits of improved knowledge about existing solar PV capacity, the potential to avoid or postpone costly grid reinforcements, and the requirements and expectations for a method such as *Alfrödull* to be applicable in routine grid planning.

3 RESULTS AND DISCUSSION

3.1 Detection of Discrepancies in PV Registries

An unexpected value of the *Alfrödull* method, first identified in [7] and confirmed in this study, is its ability to detect discrepancies between PV systems identified through remote sensing and those registered by DSOs.

Once applied to a grid area, *Alfrödull* generates a dataset of PV system polygons that can be compared with the DSO's administrative registry, which is based on notifications submitted by installers or property owners. Both PV databases contain errors, but by aligning them — using property identifiers as a linking key — missing or incorrect entries can be identified, thereby improving overall data quality. Figure 1 illustrates this overlap using a Venn diagram of actual PV installations within the scanned grid areas. Such reconciliation is a necessary first step toward constructing a complete and connected database that can be used to simulate PV generation and quantify the PV orientation smoothing effects.

Because *Alfrödull* relies exclusively on remote sensing data sources, such as aerial orthophotos, LiDAR data and geospatial data from the Swedish Land Survey, it can detect PV modules that are absent from the DSO's registry. Discrepancies may occur when systems are installed without formal notification, when registration processes are incomplete, or when installations are off-grid applications. Conversely, *Alfrödull* may also identify systems inconsistencies in reported system size, for example when the observed module area does not match the registered capacity.

Although effective, *Alfrödull* does not capture every system. Certain types, such as vertically mounted PV arrays or building-integrated PV (BIPV) systems, remain undetectable in aerial imagery. Even conventional rooftop installations can be overlooked if, for instance, they are heavily shaded at the time of imaging [7]. Nonetheless, the machine-learning-based recognition method achieves an identification accuracy of about 95% [7]. This is supported by the results shown in Figure 1, where 96.7% of all 2,489 grid-connected PV systems in the three scanned grids were correctly identified.

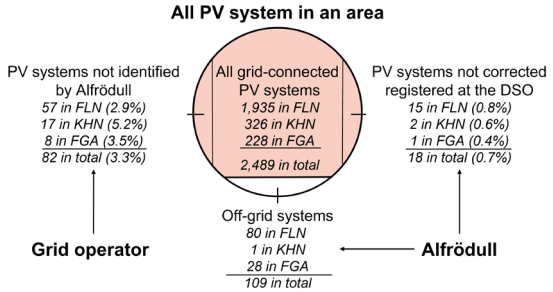

Figure 1. Venn diagram over the results of the inventory scans of three distribution grids.

Cross-checks against DSO registries showed that 79 systems in FLN, one in KHN and 28 in FGA were mounted on buildings without grid connection and were therefore correctly absent from the registries, as Figure 1 shows. The registries, in turn, listed 82 grid-connected systems commissioned before the aerial surveys that *Alfrödull* failed to detect. Conversely, *Alfrödull* identified 18 PV systems across the three grids on grid-connected buildings without corresponding completion reports in the DSO registries, despite the installations being visible in imagery for at least nine months.

In addition, 51 systems in FLN, 35 in KHN and 7 in FGA showed significant discrepancies between observed module area, adjusted using tilt derived from LiDAR data [6], and the registered capacity. Karlshamn Energi followed up on these 35 cases in KHN and confirmed after contact with the system owners that 27 systems indeed had an incorrectly registered size. The causes varied and in some cases included: (1) incorrect information provided at the time of registration by the installer, (2) main fuse capacity had mistakenly been recorded as PV capacity, (3) systems that had been expanded after the initial registration without this being reported, since no change in subscription or fuse rating was required, and (4) in a few instances battery capacity had erroneously been added to PV capacity in the registry.

Both DSOs highlighted in the interviews that the independent inventory added clear value, primarily by identifying missing or incorrectly registered systems. Karlshamn Energi emphasized the benefit of verifying suspected anomalies and proactively contacting customers to correct errors, while Falu Elnät valued the improved overview of actual installed capacity and the reduced uncertainty in grid planning. Although, according to the interviews, the discrepancies in their registry had limited direct economic impact for the DSOs, they noted that errors could lead to missed compensation for customers and pose safety risks for maintenance personnel, as unregistered systems may cause unanticipated reverse power flow.

The findings indicate that remote sensing can serve as a useful tool for improving PV registry quality, which is important for grid planning, load calculations, and future

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investments. The analysis also highlighted deficiencies in existing routines, which the two DSOs reported intending to address.

3.2 Value of Freed Grid Capacity through POSE

The interviews with two Swedish DSOs highlighted how detailed analyses of orientation-based smoothing effects can inform grid planning and investment decisions in areas with high PV penetration. Both Karlshamn Energi and Falu Elnät confirmed that the rapid increase in PV installations has created local capacity challenges, leading in some cases to concrete investments in grid lines or new substations. For example, Karlshamn Energi had planned a new substation at an estimated cost of approximately 1.5 million SEK (~€136k), while Falu Elnät had implemented minor reinforcements but emphasized that most investments are primarily guided by the age of certain parts of their grid and technical condition rather than PV-induced capacity limits.

Across the three studied grids in [13], POSE, i.e., the overestimation of injected PV power relative to rated AC capacity, ranged from 8.7% in KHN to 11.5–11.8% in FLN and FGA. Maximum POSE at individual substations reached up to 20–24% of rated AC power, highlighting that local effects can substantially exceed grid-average values [13].

Representatives from both DSOs acknowledged the value of the remote-sensing-generated data and the POSE analyses, where Figure 2 illustrates the quantified orientation-based smoothing effects in the FGA grid, serving as an example of the analysis conducted and the type of data delivered to the three DSOs.

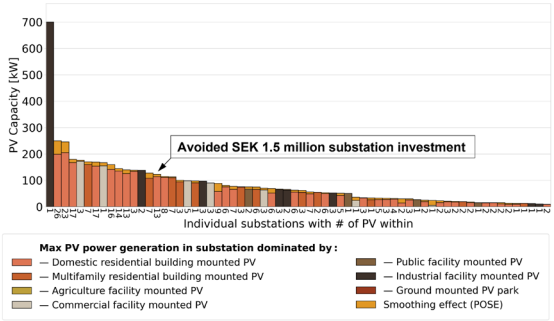

Figure 2. Registered PV capacity at all 91 transformer substations in the FGA grid with at least one PV installation as of May 2024. Each bar represents one substation, with the bar height showing the total rated AC capacity of all connected PV systems—corresponding to the capacity the grid operator assumes could be fed into the grid simultaneously. Bar colors indicate the market segment contributing the largest share of capacity at each substation, while the orange segment denotes the POSE in each substation. Numbers below the bars show the number of PV installations per substation. The arrow points to the substation where Karlshamn Energi had planned a new transformer investment.

The detailed capacity assessments generated by *Alfrödull* were in the interviews described as an important, evidence-based complement to previous methods. Karlshamn Energi reported that the POSE analysis allowed several pending PV customers to be connected without constructing the planned substation, yielding a savings of 1.5 million SEK (~€136k). Similarly, Falu Elnät postponed a planned cable reinforcement costing 400,000 SEK (~€36k) after the POSE analyses indicated more available capacity than previously assumed [10]. Beyond these specific cases, the analyses provide a valuable tool for evaluating other substations as additional PV installations will be installed.

The remote-sensing generated PV power generation data and POSE analysis were particularly appreciated by the two DSOs in early stages of the connection process, enabling faster and more accurate responses to customers while improving the prioritization of grid interventions. For example, Karlshamn Energi used the detailed analyses of interconnected substations to adjust low-voltage grid breakpoints, optimizing capacity utilization without new investments. Falu Elnät emphasized the importance of considering alternative costs, including preserving residual value in existing components, avoiding displacement effects, and limiting increased grid losses.

3.3 Knowledge Gain among the DSOs

Both DSOs also reported a knowledge gain from the analyses. Karlshamn Energi highlighted that some planned investments could have been avoided and that certain customer connections had previously been rejected unnecessarily. This prompted follow-up with customers and internal process improvements, particularly regarding their pre-notifications and post-connection verification. Both interviewees concluded that existing calculation models did not always reflect actual PV power generation, emphasizing the need for data-driven, installation-specific approaches.

3.4 Regulation, Incentives and Governance

The interviewees further noted that current Swedish and EU regulation and incentive structures largely favor traditional physical grid expansion rather than digitalization or innovative, flexible solutions, which complicates the adoption of methods that could optimize existing infrastructure and delay or avoid costly investments. Karlshamn Energi emphasized that economic incentives for data-driven decision-making, increased digitalization, and smarter grid use are currently limited, although these solutions are crucial for handling electrification and future capacity needs cost-effectively. Falu Elnät shared similar views, noting that their historical financial margins allowed testing new technologies despite regulatory uncertainties and unclear guidance on evaluating alternative technologies.

Both DSOs agreed that upcoming EU requirements for greater flexibility and efficient use of existing infrastructure will drive future development. Strategic use of already collected data, particularly at the substation level, was identified as critical. Forecasts for local power generation, such as PV, were highlighted as an important tool for integrating flexibility solutions in operational management, with remote sensing data generated by *Alfrödull* serving as a concrete example of how such data can be leveraged effectively.

Municipal ownership was described as a strength in promoting innovation, sustainability, and long-term capacity planning. Karlshamn Energi noted that their municipal board provides clear strategic goals related to sustainable development and proactive capacity planning, supporting initiatives such as digitalization and flexible grid agreements. Falu Elnät similarly reported that municipal ownership encourages innovation and a broader, long-term perspective, fostering investments that benefit the municipality. Even when objectives such as

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capacity utilization or innovation are not formally stated in ownership directives, they are actively discussed and prioritized in strategic planning.

4 CONCLUSIONS

This study demonstrates the potential of combining remote sensing and high-resolution PV simulation to optimize grid capacity, guide investment decisions, and facilitate the integration of distributed PV generation, offering a cost-effective and scalable tool for modern distribution grid management.

The *Alfrödull* method enables accurate identification of installed PV systems, detection of discrepancies in DSO registries, and quantification of orientation-based smoothing effects. By accounting for smoothing effects, substantial existing grid capacity can be unlocked, reducing the need for costly physical grid reinforcements, as evidenced by avoided investments of 400,000 SEK (~€36k) and 1.5 million SEK (~€136k) in the participating grids.

Interviews with two Swedish DSOs revealed that the method provides both tangible economic benefits and valuable operational insights, supporting data-driven grid planning, prioritization of grid interventions, and faster customer connections. Moreover, the analyses contribute to improved registry accuracy, reducing risks associated with unregistered or incorrectly registered PV systems.

The study also highlights institutional and regulatory factors affecting the adoption of data-driven solutions. While current incentives and frameworks often favor traditional physical grid expansions, municipal ownership and emerging EU requirements for greater flexibility present opportunities for innovative approaches.

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