Solar World Congress 2025

GRID IMPACT OF ELECTRIC VEHICLE AND SOLAR INTEGRATION: A CASE STUDY FROM STOCKHOLM COUNTY

Summary

Decarbonization policies have accelerated global adoption of plug-in electric vehicles (PEVs), presenting challenges for power distribution systems (DS). This study assesses the grid impacts of large-scale PEV and distributed photovoltaic (PV) integration using a real-world DS case from Stockholm County, Sweden. A Monte Carlo (MC) simulation framework models the stochastic, uncontrolled charging behavior of PEVs based on real travel patterns, considering both residential and commercial charging, at penetration levels up to 100%. To demonstrate the framework's application, a real case study explores how solar PV can mitigate PEV-induced grid impact and enhance hosting capacity across seasons. Results show limited synergy during winter due to low solar availability, with a 2% voltage improvement during summer peak hours. The methodology provides valuable insights for municipalities, DS operators (DSOs), and policymakers planning the sustainable integration of electric mobility and decentralized renewable energy into existing grids.

Keywords: Plug-in electric vehicles, Solar PV, Monte Carlo simulation, Distribution systems, Grid impact

1. Introduction

Integrating the transport and electricity sectors through plug-in electric vehicles (PEVs) presents a global opportunity to reduce carbon emissions, particularly in countries with clean electricity grids. With approximately 99% of its electricity coming from fossil-free sources (IEA, 2025), Sweden, along with countries such as Brazil, Norway, Costa Rica, and Uruguay, has a low-carbon electricity grid, making PEVs a significant technology to reduce carbon emissions and meet energy transition goals. Accordingly, Sweden aims to achieve a 70% reduction in CO_2 emissions by 2030 compared to 2010 levels, 100% fossil-free power generation by 2040, and carbon neutrality by 2045. The country serves as a strong reference case for other nations on a similar path, and one promising solution to meet climate goals is to enhance the synergy between the electricity and transport sectors.

However, widespread PEV adoption presents challenges for the operation and planning of current distribution systems (DSs), due to the stochastic nature of PEV charging. For instance, charging may coincide with existing peak consumption periods in the DS, exacerbating demand during critical times (Anastasiadis et al., 2019). Furthermore, significant PEV penetration is anticipated in specific DSs, particularly because PEV users tend to share similar sociodemographic characteristics and cluster in certain areas (Liu et al., 2017). Previous studies (Topel and Grundius, 2020; Arnaudo et al., 2020) have assessed the impact of PEVs on DSs in Stockholm, though typically without incorporating public charging infrastructure or stochastic modelling of charging behaviour.

This study addresses existing gaps by applying Monte Carlo (MC) simulations to model the random nature of residential and public PEV charging and assess its impact on the grid. A real case study from Stockholm County is used to evaluate key performance indicators, including voltage levels, line loadings, and transformer utilization. Unlike previous work focused on controlled charging, this study examines uncontrolled charging under a full PEV adoption scenario to capture worst-case conditions. Results are analysed using the 95th percentile of all MC trials to highlight the most severe, yet realistic, operational risks to grid components when no mitigation measures are in place.

2. Models and methods

The methodological framework developed in this study consists of four main steps, as shown in Fig. 1. Step 1 involved collecting all the necessary data for the analysis. This included local population statistics from Region Stockholm's travel habits survey (Region Stockholm, 2020), which were used to create probability density functions (PDFs) for charging start times and daily driving distances. Data on the locations of public and private charging stations (CS), the vehicle market share in the area, and solar PV production were also collected. Real data from the local DS operator (DSO) was gathered as well, including the grid layout (Fig. 2) and electricity demand profiles of customer units (CUs) for the year 2022. Solar photovoltaic (PV) systems were added to residential CUs by assigning typical daily solar production profiles. PV simulation and weather data were managed using PySAM (SAM, 2024). Rooftop area availability was estimated using digital maps from Google Earth™ to determine where PV could be installed.

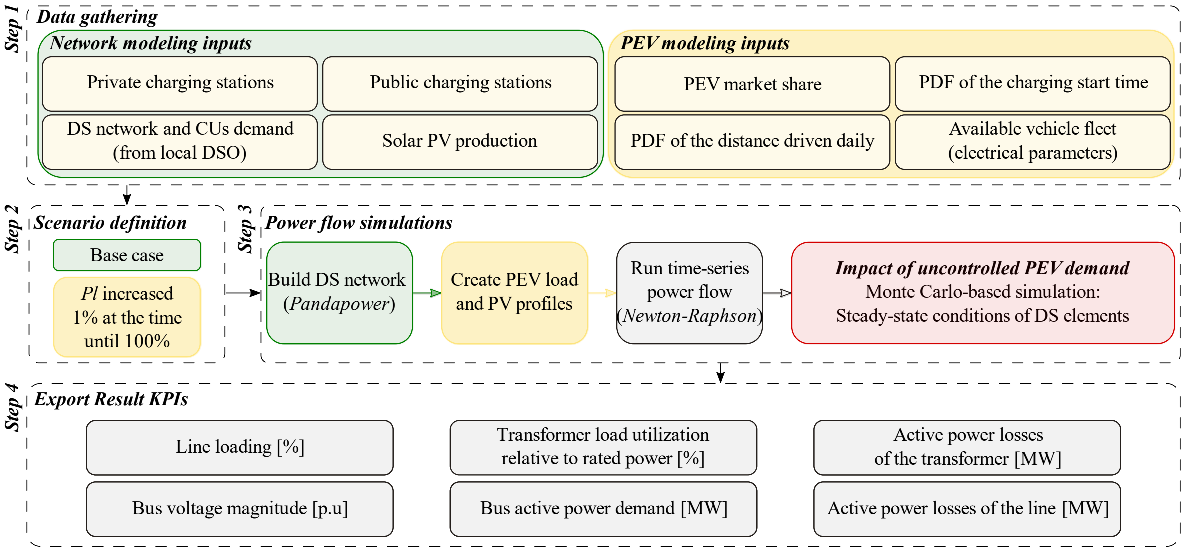

Fig. 1: Method framework.

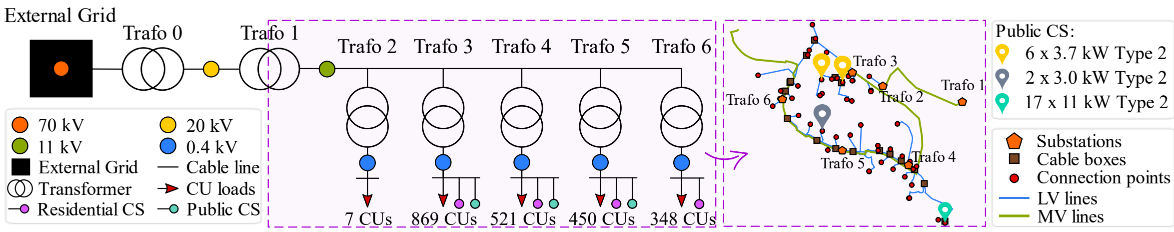

Fig. 2: Schematic diagram and topology of the offline digital twin of the DS.

Step 2 defined the scenarios based on different levels of PEV penetration. Step 3 used Monte Carlo (MC) simulations to model the random behaviour of uncontrolled PEV charging. Step 4 involved analysing the results of all simulation trials. The 95th percentile of the results was used to capture the most extreme, yet still realistic, impacts on key grid components such as buses, lines, and transformers. For more detailed information on the MC model used, refer to the authors' previous work (Nascimento and Topel, 2023).

3. Probabilistic results

Fig. 3 shows the PV power output profiles for each residential building (RB), assuming rooftop panels fully covering the available roof area. During summer (Fig. 3a), PV generation starts as early as 3:00 and continues until 21:00, reaching up to 0.03 MW per building. In contrast, winter output is approximately four times lower, peaking at around 0.008 MW and limited to the hours between 9:00 and 14:00 due to reduced solar irradiance (Fig. 3b).

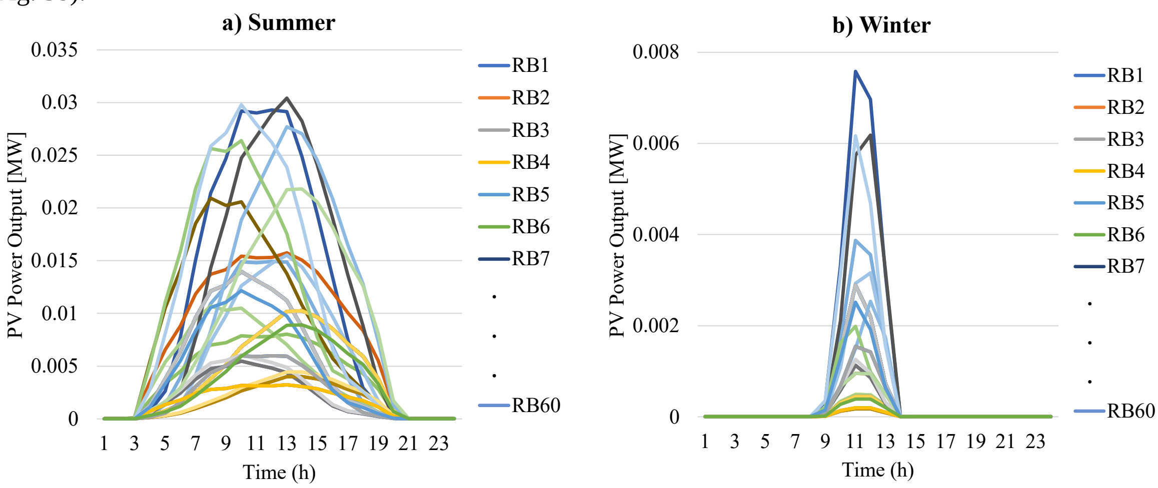

Fig. 3: PV power output profiles for individual buildings, showing variation over time due to irradiance and panel orientation.

Although winter PV generation offers limited savings through self-consumption, it still helps the grid. The biggest benefit is a improvement in voltage profiles. The full electrification scenario assumes that all 1,585 residents with regular access to a car switch from internal combustion engine (ICE) vehicles to PEVs. This follows the local market share of PEV types. Charging is assumed to happen either at home or at one of the 25 public charging stations in the area. This scenario puts significant stress on the DS. Fig. 4 shows the 95th percentile of the minimum voltage at all buses, and the 95th percentile of the maximum transformer loadings throughout the day. These are compared across four cases: the base case (no extra PEV load), uncontrolled 100% PEV charging, and the same with PV added in both winter and summer. Line loading results are similar to transformer loading, but are not shown due to space limits. PV does not help much during evening peaks. It only improves voltage magnitude by about 2%. However, it reduces grid stress during the day, especially in summer. Overall, daytime PV generation lowers peak demand, which helps reduce voltage drops and transformer overload.

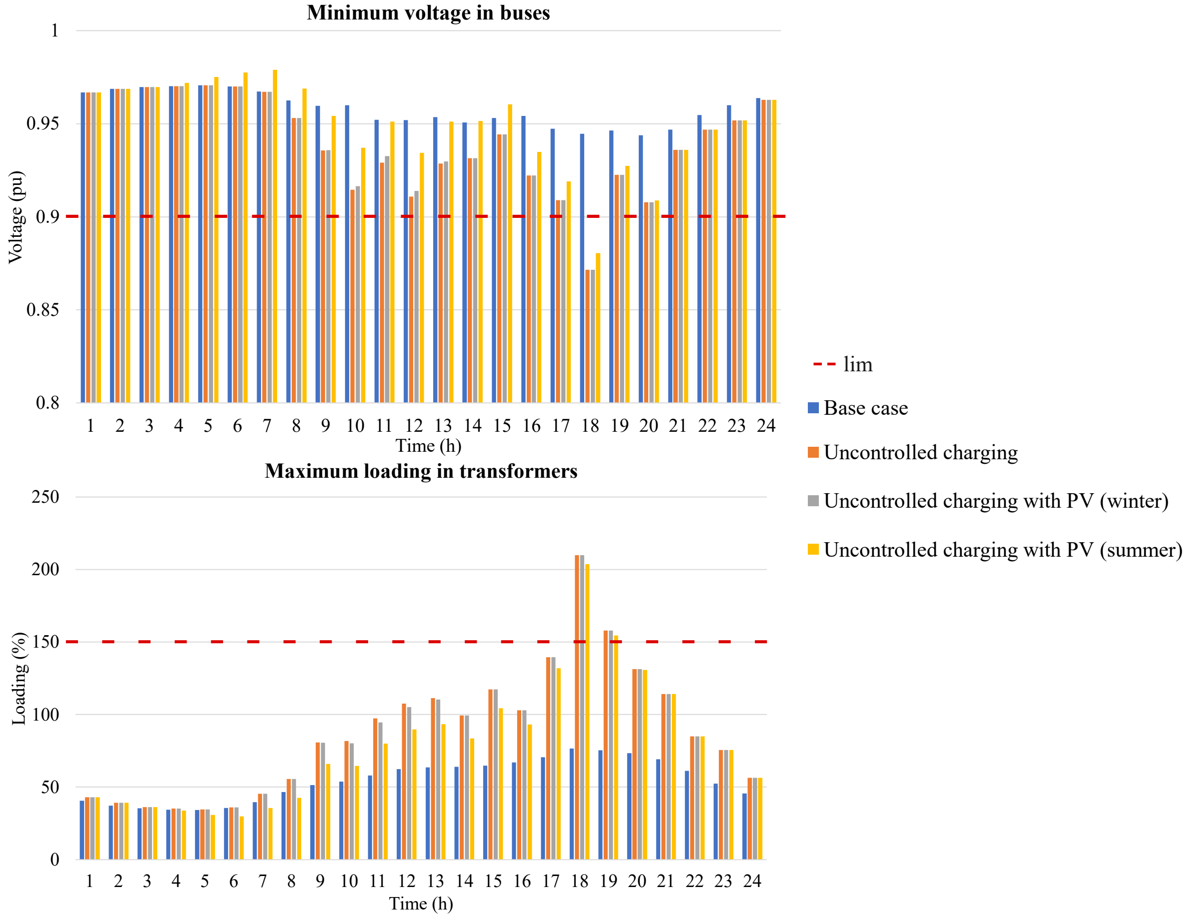

Fig. 4: 95th percentile of minimum bus voltages and maximum transformer loadings for 100% PEV penetration level.

4. References

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