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Accelererande av elfordonsintegrationen i en smart och robust elinfrastruktur	
Energimyndighetens titel på projektet – engelska	
Accelerating the Integration of Electric Vehicles in a Smart and Robust Electricity Infrastructure	
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Nyckelord: 5-7 st Elnät, Sammanlagring av effekt, Elektrifiering, Elbilsladdning, Elkvalitet	

Förord

Projektet "Accelererande av elfordonsintegrationen i en smart och robust elinfrastruktur" strävar efter att utveckla en ny standard för dimensionering och drift av elnät med avseende på elbilsladdning. Projektet började i December 2021. Energimyndigheten har finansierat projektet och Ellevio AB och Lidingö stad har samtfinansierat genom deras input, data och tid.

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Sammanfattning

Att integrera plug-in elfordon (PEV) i Sveriges transport- och elsektorer utgör en stor möjlighet att uppfylla landets mål för energiomställning, inklusive att minska koldioxidutsläppen med 70 % till 2030 och uppnå koldioxidneutralitet till 2045. År 2020 stod Sveriges transportsektor för 76 % av fossila bränslen, medan elsektorn endast stod för 1 %. PEV har potential att kraftigt minska användningen av fossila bränslen. Deras utbredda införande innebär dock utmaningar för distributionssystemen (DS), särskilt med den ökade efterfrågan på toppeffekt. Sveriges transmissionsnät står redan inför kapacitetsbrister, vilket påverkar prestandan på distributionsnivån. Detta projekt adresserar dessa utmaningar genom att fokusera på integrationen av PEV i befintliga DS. Viktiga åtgärder inkluderade: identifiering av tre studieområden med olika sekundära transformatorstationer; beräkning av aggregerade effektförhållanden för PEV-laddning i olika nätdistrikt och kundtyper; analys av dessa förhållanden med lasthanteringsstrategier för att optimera förluster och kostnader; samt fastställande av fem kritiska investeringsprioriteringar för Stockholmsregionen under de kommande åren. Projektet har dessutom resulterat i tre akademiska publikationer och en doktorsavhandling. Resultaten ger viktiga insikter om lokala flaskhalsar och värdkapacitet för PEV-integration, vilket ger värdefull vägledning för nätoperatörer. Dessa insikter är tillämpliga på olika nät och platser, och även om effekterna av PEV-laddning kan variera beroende på lokala nätegenskaper, kommer regioner med liknande förhållanden sannolikt att uppleva liknande trender. Den utvecklade metoden är anpassningsbar till andra nät och utgör ett användbart verktyg för både kort- och långsiktig DS-planering. Strategisk planering är avgörande för att säkerställa att övergången till eldriven mobilitet inte äventyrar framtida leveranskvalitet för kunderna.

Summary

Integrating plug-in electric vehicles (PEVs) into Sweden's transport and electricity sectors offers a major opportunity to meet the country's energy transition goals, including a 70% reduction in carbon emissions by 2030 and achieving carbon neutrality by 2045. In 2020, Sweden's transport sector was responsible for 76% of fossil fuel consumption, while the electricity sector accounted for just 1%. PEVs have the potential to significantly cut fossil fuel use. However, their widespread adoption introduces challenges for distribution systems (DSs), particularly with increased peak power demand. Sweden's transmission grid is already facing power capacity shortages, which impacts distribution-level performance. This project tackles these challenges by focusing on the integration of PEVs into existing DSs. Key actions included: identifying three study areas with diverse secondary substations; calculating aggregated power ratios for PEV charging across various network districts and customer types; analyzing these ratios with load management strategies to optimize losses and costs; and pinpointing five critical investment priorities for the Stockholm region over the next years. Additionally, the project produced three academic publications and a PhD thesis. The results provide crucial insights into local bottlenecks and hosting capacity for PEV integration, offering valuable guidance for grid operators. These findings are applicable to various grids and locations, and while the impact of PEV charging may differ based on local grid characteristics, regions with similar conditions are likely to experience comparable trends. The developed methodology is adaptable to other networks, making it a useful tool for both short- and long-term DS planning. Strategic planning is essential to ensure that the transition to electric mobility does not compromise future customer supply quality.

Motivation/Background

Sweden's transport sector is the largest consumer of fossil fuels, accounting for 76% of total fossil fuel consumption in 2020, while the electricity sector relies on just 1% [1]. This creates a significant opportunity for sector coupling, particularly through the integration of plug-in electric vehicles (PEVs). PEVs have the potential to significantly reduce fossil fuel dependence, especially in the passenger car segment, which is responsible for 66% of the transport sector's emissions [2]. While PEVs support Sweden’s electrification and decarbonization goals, their widespread adoption presents challenges for distribution systems (DSs). One of the key challenges lies in residential PEV charging. Since PEV owners often share similar sociodemographic characteristics and tend to live near one another, the demand for charging is highly concentrated. Uncoordinated charging can overload distribution transformers, increase technical losses, and cause power quality issues, all of which may require costly upgrades or reconfiguration of the DS. Furthermore, Sweden faces a shortage of transmission grid capacity, particularly at the regional level, affecting major cities like Stockholm. In this growing region with specific additional electricity needs [3], the situation is already strained. The transmission system operator (TSO) has indicated that these shortages cannot be fully addressed before 2030.

To effectively manage a high share of PEVs at the district level, it is essential to assess the impact of collective PEV charging loads on the DS, especially given the existing regional capacity limitations. This project aims to investigate these effects and develop robust, practical PEV integration allowance factors for distribution networks. These factors will be standardized and applicable across various networks. A key parameter in this investigation is the ratio between aggregated peak power (sammanlagrad effekt) from lower-voltage partial loads and the actual peak power at higher voltage levels. This ratio is directly influenced by PEV charging behaviors. The project will analyze variations in this ratio caused by different customer charging patterns and load management strategies across voltage levels. By mapping these variations, we can quickly identify whether PEV integration in a given area may lead to bottlenecks and, more importantly, whether these bottlenecks result from local infrastructure constraints or regional capacity shortages. This approach allows for a more accurate understanding of how PEV charging behavior at the local, low-voltage level affects the regional network, where capacity limitations are expected to remain for the next 5-7 years.

Currently, distribution system operators (DSOs), such as Ellevio, have limited information about how charging infrastructure at lower voltage levels impacts the overall grid. This project will calculate and map load aggregation factors due to PEV charging and generalize them based on customer types and demographics, making them applicable to any secondary station in the network. These aggregation factors will be derived from the aggregated peak power ratios (sammanlagringseffekt) calculated for various scenarios, considering behavioral differences at lower voltage levels. To date, no study has systematically observed and compared the effects of PEV charging on these ratios.

This project builds on the extensive expertise of KTH’s Energy Department, which has led numerous research initiatives on integrated energy infrastructure, in collaboration with Ellevio AB and Lidingö’s municipality. The findings from this study are expected to follow similar trends in other regions and be applicable both within and outside Sweden. The project was conducted at the Department of Energy Technology at KTH from 2021 to 2024.

Implementation

The project was divided into five work packages (WPs), each targeting specific goals. Most of the work was conducted at the KTH Energy Technology Department, with Ellevio AB and Lidingö's municipality co-financing through their contributions of data, input, and time. This section outlines the content and methods developed within each WP and their alignment with the corresponding goals (G).

WP1 End-user demographics and critical area selection: A demographic study was performed, including an analysis of connected customer types. GIS-based information, such as property type maps (to distinguish schools, hospitals, apartments, detached houses) and traffic maps, was studied. Locations where private or public charging infrastructure had been or would be installed were also considered. This was done in connection with G1 to define specific areas critical for PEV integration, ensuring enough variation between them to secure differences in result analyses and allow for generalization in later WPs.

> **G1:** Identification and selection of three areas of study based on demographics and connected customer information, focusing on encompassing a diverse mix of secondary substations within the selection.

WP2 Low voltage (local) load flow analyses: The project developed PEV charging load profiles based on customer behavior and the available charging infrastructure in the area. A power flow analysis was performed on individual secondary stations to determine the maximum allowable level of PEV penetration. In relation to G2, the aggregated charging power ratios were calculated, and the impact of PEV integration on these ratios was analyzed. Additionally, the effect of load management strategies on EV charging was considered by comparing the aggregated power ratios with the business-as-usual charging scenario, as outlined in G3.

> **G2:** Calculation of the aggregated power ratios due to PEV charging for four low voltage network districts and three intermediate network areas considering differences in charging behavior between residential and commercial customer types.

> **G3:** Calculation of the aggregated power ratios subject to charging load management strategies for one of the areas, considering loss and costs optimization strategies.

WP3 Intermediate voltage (district) load flow analyses: The aggregated power ratios obtained in WP2 were characterized in terms of substation size, customer type shares, and EV load management type. This was done to generalize and replicate the results for application at additional secondary substations. In relation to G2, power flow analysis was performed on a group of secondary substations connected to the same primary station. The aggregated charging power ratios were calculated from each case, and the impact of PEV charging was evaluated by comparing these ratios to those present on the network prior to PEV integration.

WP4 Regional Capacity Analyses: Using the generalized aggregated power ratios identified in the previous WPs, the project compared how different primary stations were loaded under normal conditions and under maximum PEV charging shares. This was done with the aim of mapping capacity shortages across the entire region for the coming years and prioritizing investments in the network in connection with G4.

> **G4:** List of three key investment priority areas in the Stockholm region for the next years subject to critical limitations from PEV penetration.

WP5: Final Reporting of the project as comprised within this report.

> G5: Three academic publications and one licentiate thesis defense as part of PhD studies.

Energimyndigheten

Results and discussion

This section presents the results and conclusions derived from the project. The following subsections are organized according to the work packages structure outlined in the Implementation section.

WP1: End-user demographics and critical area selection

The project was implemented using a bottom-up approach, and all the data necessary for modeling the plug-in electric vehicle (PEV) charging loads, including end-user demographics and the selected study area, are detailed in this subsection. This data is crucial for the development of the remaining work packages of the project.

Area selection The island of Lidingö was identified and selected as the pilot in this study due to its rapid electrification scenario. Figure 1 shows Lidingö categorized by primary substations (fördelningsstation – FS), represented in different colors, and their respective secondary substations (nätstation – NS) belonging to each different electrical area. Three areas (Gångsätra (GNG), Torsvik (TOR), and Kyrkviken (KYR)) have been selected for analysis in the project, both with regards to the low voltage (WP2) and intermediate voltage network (WP3). The three areas together represent approximately 60% of all NSs and 70% of the island's population. Data regarding the medium voltage (MV) and low voltage (LV) networks, including FS transformers, NS transformers, connection points, cable boxes, MV and LV lines, geolocation of network elements, and customer type classification, were provided by Ellevio. In summary, this included all the data needed for realistic modeling of the electrical grid in the chosen areas.

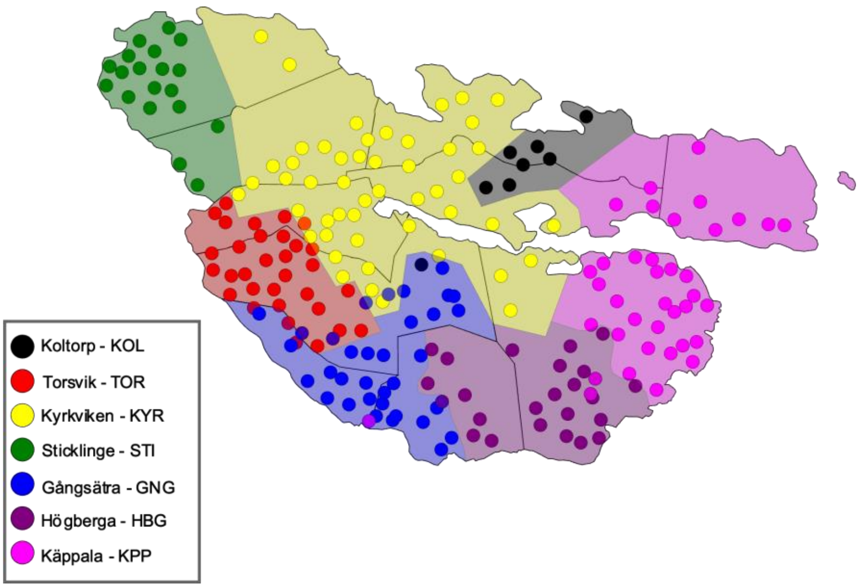

Figure 1 – Lidingö categorized by electrical substations.

End-user demographics During the initial stages of the project, a collaboration with Lidingö's municipality was developed, and an active dialogue concerning the municipality's activities was established. GIS-based information about land and energy-intensive buildings owned by the municipality was shared, including public parking spots and public charging infrastructure that currently exist on the island, as well as ongoing or future projects belonging to the municipality's short-term development plans (see Figure 2).

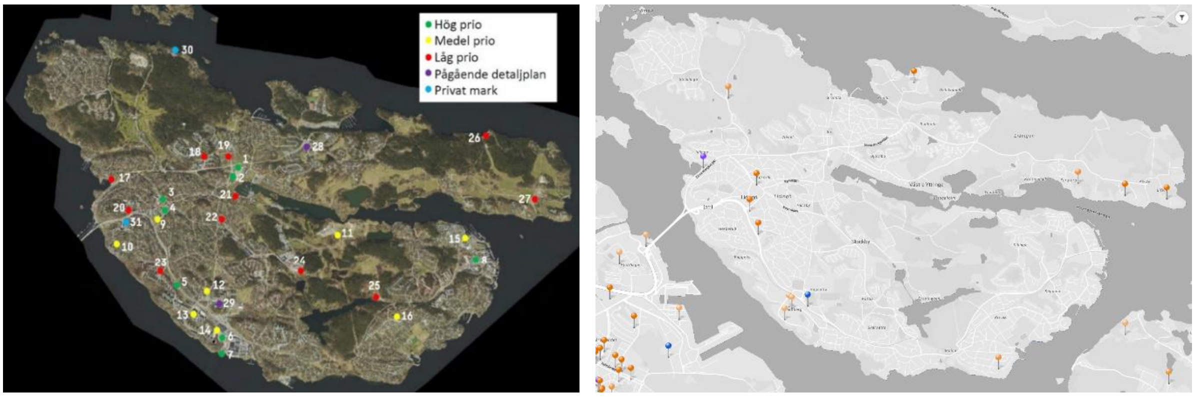

Figure 2 – On the right, existing public charging infrastructure within Lidingö [4]; on the left, priority locations for charging infrastructure designated by Lidingö’s municipality.

GIS-based information, such as property type maps (to differentiate between schools, hospitals, apartments, and detached houses) and traffic maps, was also examined. This analysis, conducted in connection with G1, aimed at identifying specific critical areas for PEV integration. Figure 3 shows a polygon layer depicting properties owned by the City of Lidingö, which owns most of the island.

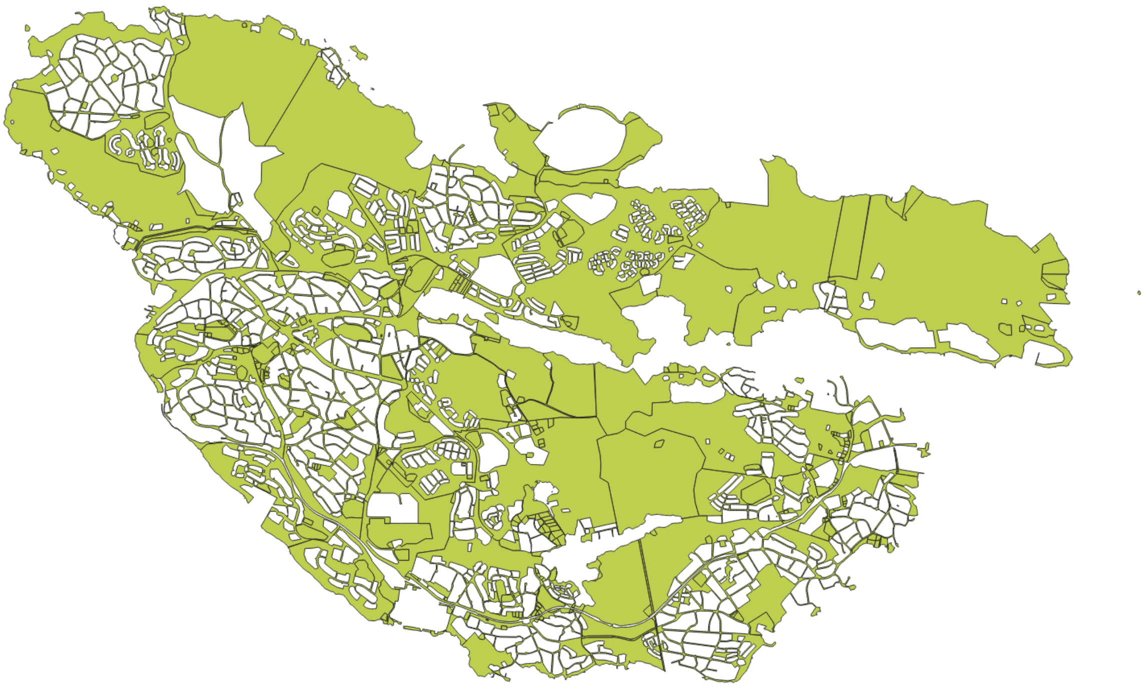

Figure 3 – Polygon layer containing properties owned by the City of Lidingö.

Figures 4 and 5 show parking spaces and regulations. Figure 4 includes information on current traffic regulations for stopping and parking on municipal land. Figure 5 presents a polygon layer depicting parking areas regulated by the municipality, and it also includes information on 16 parking garages and spaces outside municipal responsibility.

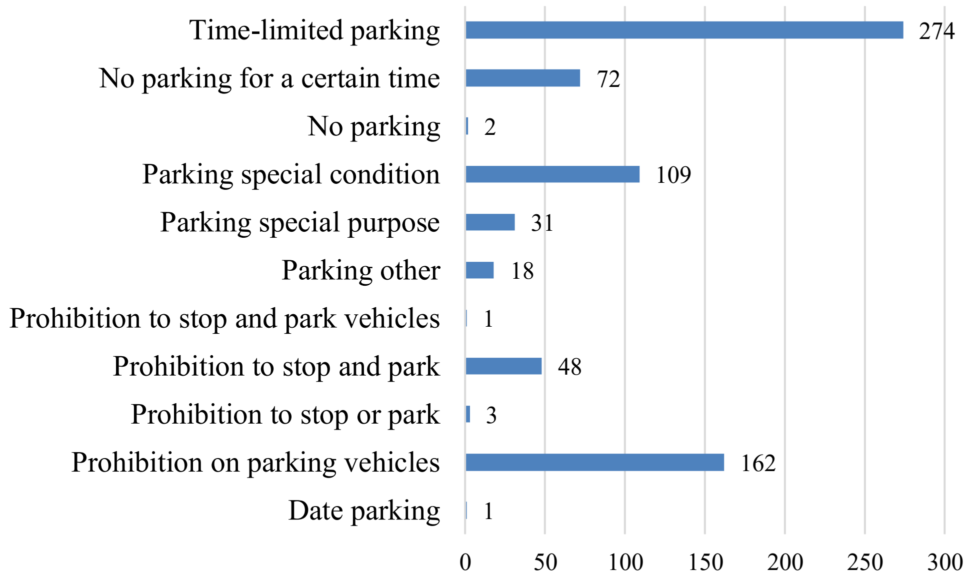

Figure 4 – Parking regulations classification in Lidingö.

Figure 5 – Parking spaces in Lidingö.

The island has 209 energy-intensive buildings that belong to the municipality and serve community functions on municipal land. Figure 6 shows a map of the island, highlighting in green the land owned by the municipality. A pink point on the map indicates the location of an energy-intensive building or part of such a building.

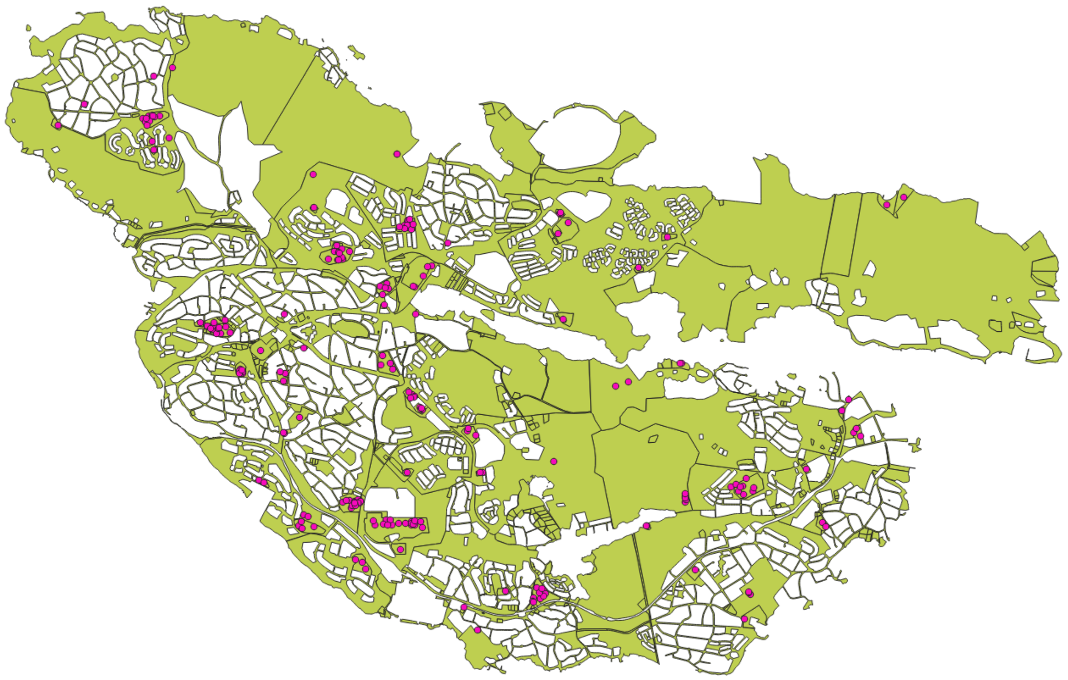

Figure 6 – Energy-intensive buildings owned by Lidingö's municipality.

On Lidingö, apartment buildings are the most common type of home, followed by detached houses, which are often owned. Figure 7 illustrates this distribution [5]. Figure 8 shows the number and type of households on Lidingö: 46.7% are households with or without children, 46% are single-person households (with or without children), and 38% are single-person households without children [6]. Additionally, 82% of the population were born in Sweden, and their average income is 47,467 SEK, which is 38% higher than the average income in Stockholm County (34,458 SEK) and 61% higher than the national average (29,492 SEK) [7].

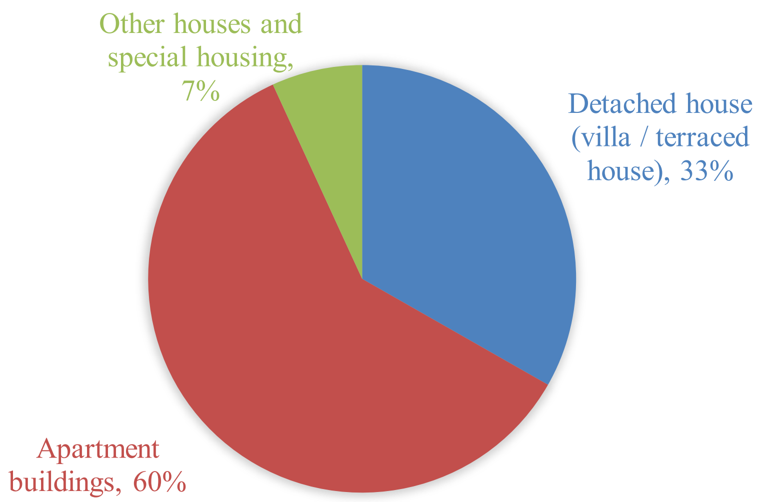

Figure 7 – Lidingö's housing 2017 [5].

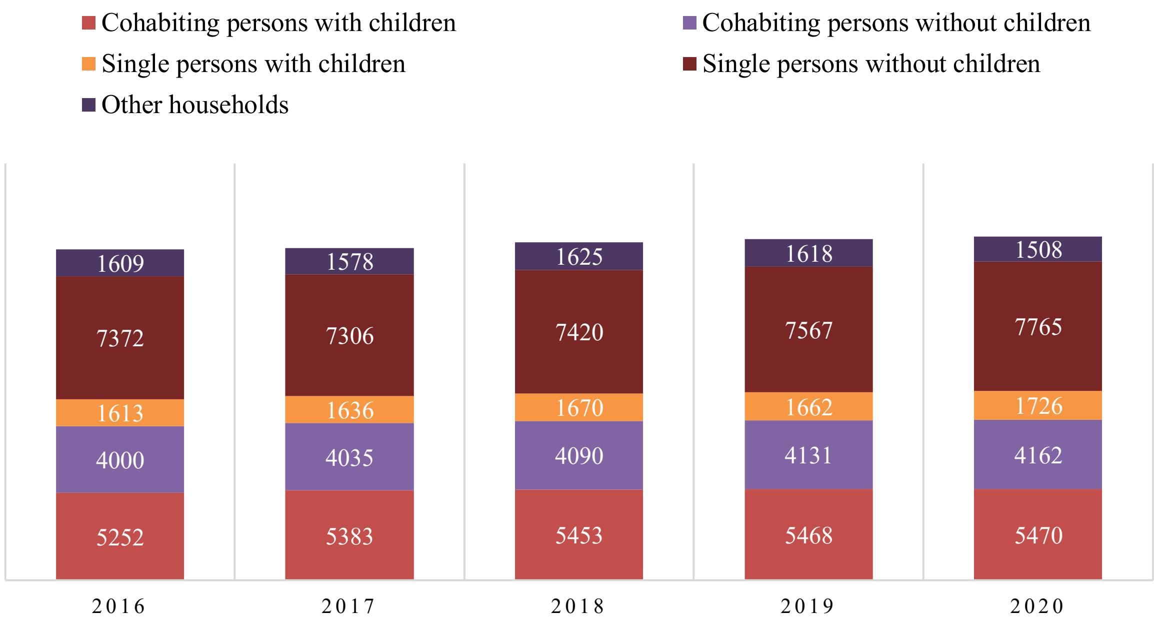

Figure 8 – Number and type of households for Lidingö – Dec 2020 [6].

A demographic study was conducted, analyzing the types of customers in the selected study areas. Local customers were classified as residential (either villa/radhus or lägenhet), commercial, fritidsboende, and others. The 'others' category included electric heating of apartments, street and road lighting, railways and trams, bus traffic, waterworks, and temporary connections. Residential customers made up 98% of the total customer base. However, despite the predominance of residential customers, some secondary substations were connected exclusively to commercial customers, which provided valuable insights for analyzing areas with varying customer compositions.

Additionally, data from a travel habits survey was gathered [8]. Figure 9 shows the start times for trips to and from work, business, school, and leisure activities. The data reveals two peak traffic periods: one in the morning and another in the afternoon, for trips related to work, business, and school. In contrast, leisure trips have a much more variable start time and are more evenly distributed throughout the day.

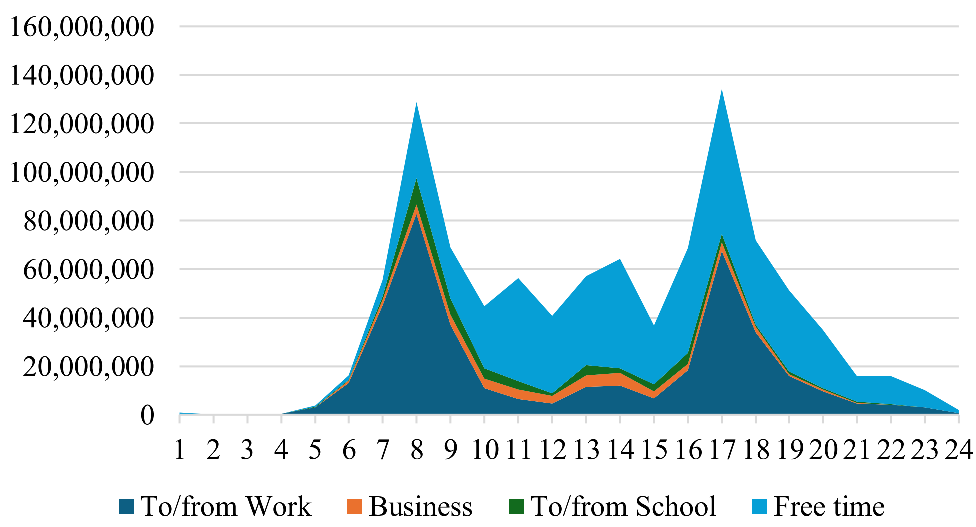

Figure 9 – Start times for trips with various errands [8].

The transition from passenger cars with internal combustion engines to PEVs shows that Lidingö has been faster in electrification compared to Sweden as a whole, though slightly slower than Stockholm County. As of December 2023, PEVs accounted for 11% of all passenger cars in Sweden; 22% in Stockholm County; and 18% in Lidingö. Additionally, the percentage of new passenger car registrations for PEVs by December 2023 was 58% in Sweden; 69% in Stockholm County; and 64% in Lidingö [9].

Furthermore, a total of 20 different PEV models were analyzed and considered in this project for modeling purposes, representing 60% of the market share in Stockholm County for 2023 (see Figure 10) [10].

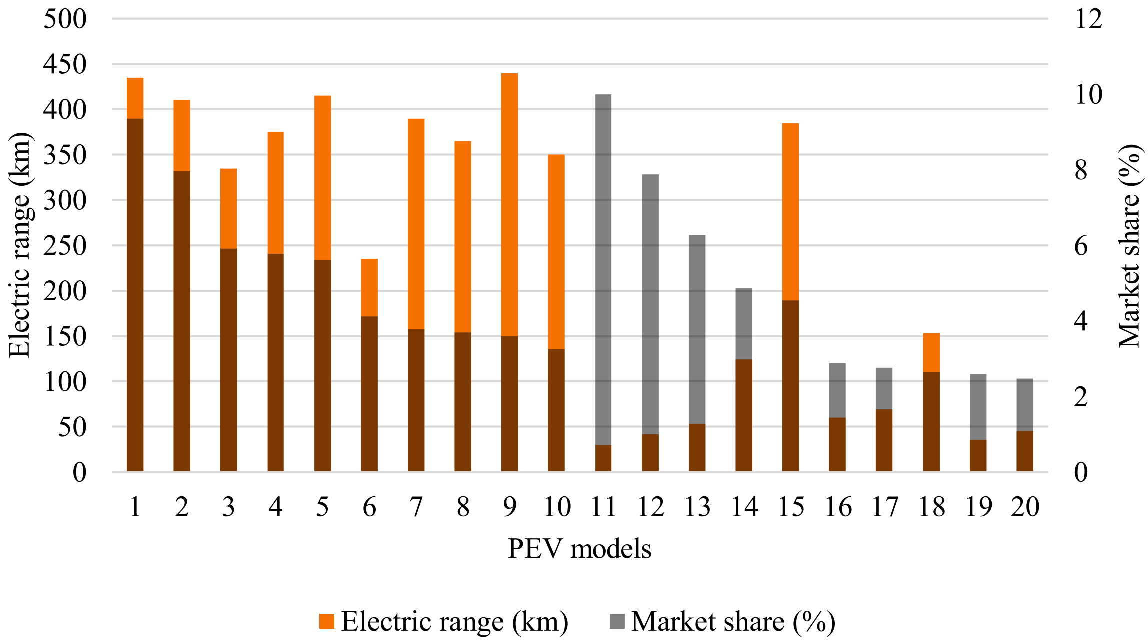

Figure 10 – PEV models used in the creation of the PEV charging load profiles classified by electric range in km and percentage of market share for 2023 [10].

In summary, based on the collected statistics on the population, existing and planned public charging stations within the municipality's development plans, parking slots, housing types, travel start and end times, and available PEV market models, the load profiles for PEVs were defined and used for the load flow analyses conducted in this project.

WP2: Low voltage (local) load flow analyses

The project conducted power flow analyses at different levels of the network, starting with specific secondary substations (low voltage) in this work package and moving up to primary substations (intermediate voltage) in work package 3.

Table 1 provides details on the characteristics of the electrical network used in the studies. The low voltage network includes 124 secondary substations from the three selected areas, ensuring a diverse mix of substations. This diversity was key to obtaining a broad range of results and ensuring the generalizability of findings.

Table 1 - Characteristics of the distribution system (DS).

Element name	Characteristics
Primary substations (FS)	3 units: GNG, KYR, TOR (each FS has 2 transformers of 25 MVA each)
Secondary substations (NS)	124 units: on average, transformers of 0.8 MVA, accounting for a total of 140 transformers
Connection points (CP)	4 782
Cable boxes	1 455
Medium Voltage (MV) lines	442
Low Voltage (LV) lines	8 949
Customers	15 782 (of which 3 are MV customers)

Five scenarios were developed to evaluate increasing PEV penetration levels, including a base case where the system was modeled without any additional PEVs. The customer consumption data, provided by Ellevio, is from 2022, when Lidingö had a PEV penetration level of 14%, which was used as the inbuilt penetration level for the base case. The other scenarios modeled penetration levels of 25%, 50%, 75%, and 100%. By December 2023, the island had 18,103 registered passenger cars, meaning a scenario with 100% penetration assumed that all 18,103 cars would be PEVs.

Power flow and hosting capacity analyses were conducted to determine the maximum allowable PEV penetration level and its impact on power quality and aggregated power ratios. In this project, the aggregated power ratios refer to the comparison between the combined peak power demand from multiple PEV charging loads at lower voltage levels and the actual peak power observed at higher voltage levels within the distribution system.

The results indicated that no overall hosting capacity limit was identified for the entire island. Instead, hosting capacities were determined for each secondary substation, with an average of 20% PEV hosting capacity. At penetration levels exceeding 20%, issues began to emerge, such as buses experiencing voltages below the 0.9 pu lower limit, lines being loaded beyond 80% of their capacity, and transformers operating above 100% of their nominal capacity.

Table 2 displays the 95th percentile (P95) of violations to the established power quality (PQ) limits, meaning the results have a 95% accuracy assumption. The table shows that up to a 25% penetration level, only a few elements experienced power quality violations. However, as the PEV penetration level increased, the number of violations also increased. Importantly, these power quality issues were not widespread across the entire electrical grid in Lidingö but were concentrated in specific secondary substations.

Table 2 – Summary of PQ violations in the DS.

Elements	Buses					Lines					Transformers				
Total elements in the system	8 862					9 391					146				
PQ limits	0.9 pu < Voltage < 1.1 pu					Loading < 80%					Loading < 100%				
P*l*	Base case	25%	50%	75%	100%	Base case	25%	50%	75%	100%	Base case	25%	50%	75%	100%
Number (% in relation to total)	119 (1.34%)	183 (2.07%)	236 (2.66%)	269 (3.03%)	377 (4.25%)	59 (0.63%)	84 (0.89%)	107 (1.14%)	142 (1.51%)	187 (1.99%)	8 (5.48%)	10 (6.85%)	11 (7.53%)	13 (8.90%)	17 (11.64%)

The aggregated charging power ratios resulting from PEV charging were calculated by considering differences in charging behaviors between residential and commercial customer types, as proposed in G2 for calculating the coincidence factors (CF). Figure 11 illustrates the maximum aggregated peak power for various penetration levels, while Table 3 presents the CF categorized by customer types. The findings indicate that the aggregated peak power increases slightly exponentially with higher PEV penetration levels, adding an extra 10 MW to the peak power from the base case to the scenario of 100% electrification.

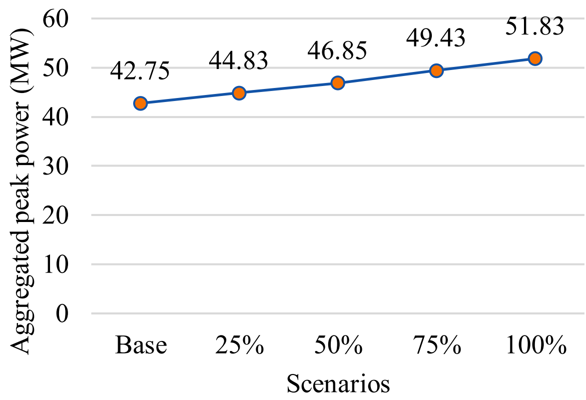

Figure 11 – Maximum aggregated peak power for different P*l* of PEVs for the whole DS.

Different coincidence factors were calculated for all analyzed scenarios, considering various types of secondary substations, such as residential and commercial. The impact of PEV integration on these factors was also analyzed. Coincidence factors measure the extent to which individual loads—such as homes, businesses, or PEV chargers—contribute to the grid's peak demand simultaneously.

CF values close to 1 indicate highly coincident loads, while values farther from 1 suggest less coincidence. Overall, the results show that the CF decreases as PEV penetration increases, with a more significant impact observed in residential areas compared to commercial ones. This is largely due to Lidingö being a predominantly residential municipality, where only 2% of all customer units are used for commercial activities.

Table 3 – Coincidence factors (CF) grouped by categories in the low voltage side.

Scenarios/ CFs	Base case	P/25%	P/50%	P/75%	P/100 %	CF types	Number of Connection Points (CP)
CF1	0.9531	0.8028	0.7340	0.6778	0.6387	NSs type residential	-
CF2	0.9505	0.8927	0.8738	0.8482	0.8278	NSs type commercial	-
CF3	0.8429	0.8429	0.8429	0.8429	0.8429	CPs type 'Lokal'	3
CF4	1.0000	0.8240	0.5160	0.4792	0.4776	CPs type 'Lägenhet'	69
CF5	0.9510	0.8525	0.7696	0.7121	0.7254	CPs type 'Övrigt', 'Lägenhet', 'Lokal'	18
CF6	1.0000	1.0000	1.0000	0.9051	0.9176	CPs type 'Övrigt', 'Fritidsboende'	2
CF7	0.9955	0.8552	0.7756	0.6980	0.6341	CPs type 'Övrigt', 'Villa/Radhus'	202
CF8	1.0000	0.7984	0.7084	0.6161	0.5589	CPs type 'Villa/Radhus'	3 239
CF9	0.9781	0.8511	0.7815	0.7669	0.7520	CPs type 'Övrigt', 'Villa/Radhus', 'Lägenhet'	9
CF10	1.0000	1.0000	1.0000	1.0000	1.0000	CPs type 'Fritidsboende'	279
CF11	0.9658	0.9617	0.9377	0.9317	0.9272	CPs type 'Övrigt', 'Lokal'	14
CF12	1.0000	1.0000	1.0000	1.0000	1.0000	CPs type 'Villa/Radhus', 'Lokal'	1
CF13	0.9425	0.6676	0.5852	0.5474	0.5474	CPs type 'Övrigt', 'Lägenhet'	301
CF14	0.9544	0.9595	0.9291	0.8714	0.9272	CPs type 'Lägenhet', 'Lokal'	3
CF15	1.0000	0.7564	0.8920	0.7708	0.8007	CPs type 'Villa/Radhus', 'Lägenhet'	3
CF16	0.8308	0.7724	0.7565	0.7482	0.7098	CPs type 'Övrigt'	617

Load management strategies for PEV charging were evaluated, focusing on loss and cost optimization as outlined in G3, and their effects on the aggregated power ratios. The results (Figure 12) show that using only price signals for charging (orange curve) shifts the load to cheaper times but maintains the daily peak demand, reducing costs for PEV owners without easing the stress on the distribution system (DS). However, when a maximum peak demand constraint is added along with price signals (light blue curve), peak demand flattens, load valleys are filled, and grid balancing improves, while still offering lower charging costs to owners.

The results also highlight that implementing load management strategies reduces the coincidence factor (CF) compared to uncontrolled PEV charging. Uncontrolled PEV charging increases existing peaks, keeping individual loads coincident. When only price signals are applied, the peak is reduced by 15% as charging shifts to cheaper times, but CF decreases. Combining price signals with a maximum demand constraint cuts the peak by 68%, though CF remains nearly unchanged.

In summary, incorporating both price signals and demand constraints significantly reduces peak demand and benefits the grid without negatively impacting charging costs.

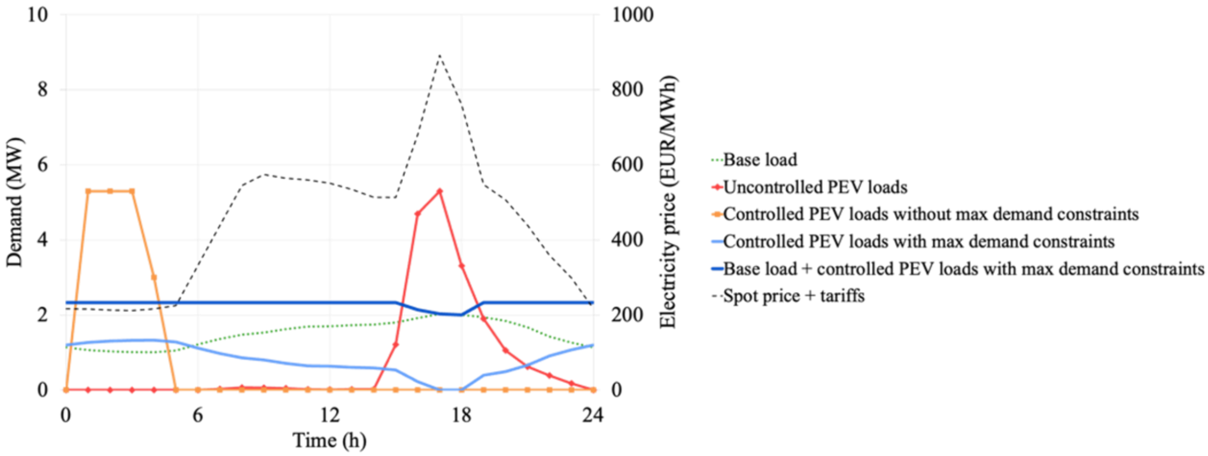

Figure 12 – All load scenarios (left axis) and the corresponding electricity prices for the analyzed period (right axis).

WP3: Intermediate voltage (district) load flow analyses

Table 4 presents the coincidence factors categorized by substation type and customer type shares to reflect their impact in the intermediate voltage. This classification was made to generalize and replicate the results across more secondary substations with similar characteristics. Overall, the loads become less coincident as the number of PEVs charging at a secondary substation increases, reaching a stable level before increasing again as penetration levels approach 100%. Residential substations, particularly those serving mainly apartment buildings, experienced the highest drop in the coincidence factor. This is because a greater number of PEVs are connected to the same point at different times, creating smaller, non-coincident peaks alongside the substation's base load.

Table 4 – Coincidence factors (CF) grouped by categories in the intermediate voltage side.

Scenarios /CFs	Base case	P*l*25%	P*l*50%	P*l*75%	P*l*100%	CF types
CF1	0.9805	0.9511	0.9062	0.8363	0.8578	NSs type 'Fritidsboende', 'Villa/Radhus'
CF2	0.9348	0.8544	0.8261	0.7885	0.7179	NSs type 'Övrigt', 'Fritidsboende', 'Villa/Radhus'
CF3	0.9034	0.7388	0.6894	0.6608	0.6663	NSs type 'Övrigt', 'Lägenhet', 'Lokal'
CF4	0.9220	0.7591	0.6553	0.6311	0.6481	NSs type 'Övrigt', 'Lägenhet'
CF5	0.9487	0.7898	0.7357	0.6957	0.6583	NSs type 'Övrigt', 'Villa/Radhus', 'Lägenhet', 'Lokal'
CF6	0.9457	0.7791	0.6992	0.6434	0.6019	NSs type 'Övrigt', 'Villa/Radhus', 'Lägenhet'
CF7	0.9419	0.8187	0.7768	0.7215	0.6574	NSs type 'Övrigt', 'Villa/Radhus', 'Lokal'
CF8	0.9684	0.8116	0.7460	0.6704	0.6186	NSs type 'Övrigt', 'Villa/Radhus'
CF9	0.9780	0.9633	0.9625	0.9430	0.9144	NSs type 'Övrigt'

In relation to G2, power flow analysis was performed on a smaller group of secondary substations connected to the same primary station. The fully implemented area comprises four different voltage levels, seven transformers, and 2,195 customer units. These customer units are classified as residential, commercial, and others, with residential units making up 98% of the total, following the trend of the distribution system across the whole island. Figure 13 illustrates the schematic diagram of the subsystem used to run load flow analyses for the intermediate voltage, showing the classification of customer units. Additionally, Figure 14 presents the aggregated load profile in the main transformers of the subsystem.

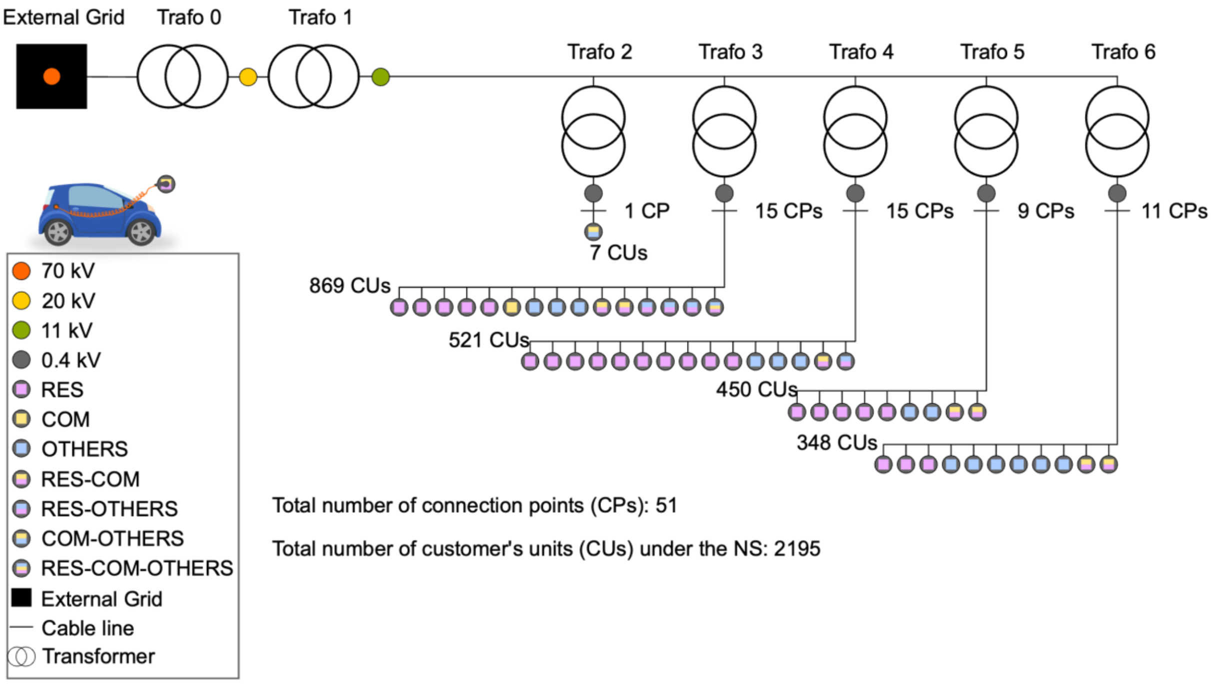

Figure 13 – Schematic diagram of the subsystem (RES = residential; COM = commercial).

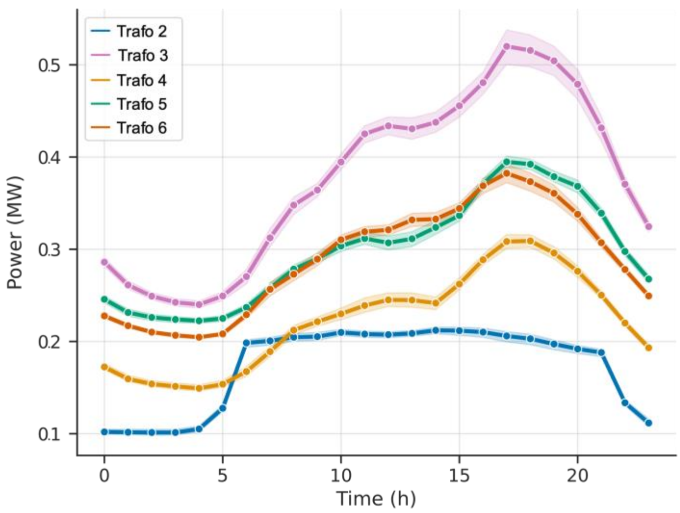

Figure 14 – Aggregated load profile for the distribution transformers of the subsystem.

Different penetration levels of PEVs were evaluated in this smaller distribution system. Figure 15 shows the maximum aggregated peak power for various PEV penetration levels, with a trendline plotted using the simulated results. It is expected that for PEV penetrations above 30%, the aggregated peak power will be at least double that of a grid without PEVs. Furthermore, at a penetration level of 100%, the peak is projected to be approximately 12 MW, representing a 512% increase compared to the system without PEVs.

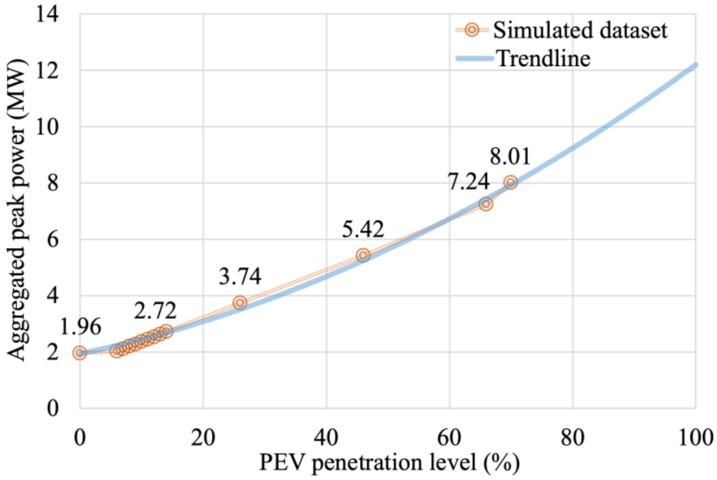

Figure 15 – Maximum aggregated peak power for different P*l* of PEV for a small region of 5 secondary substations connected to the same primary substation.

The scenarios simulated provided insight into the maximum level of penetration these vehicles could have in the chosen subsystem without experiencing power quality (PQ) violations. The hosting capacity of this smaller network is of 14% PEVs. Moreover, Table 5 presents an overall summary of the PQ results obtained. The table indicates that up to P*l* 40%, only a few elements experienced PQ violations. However, this number increased significantly to 52 buses, which represents 60% of all buses in this small DS, at P*l* 66%. Similarly, the share of violated lines and transformers at P*l* 60% amounted to 45% and 57%, respectively.

Table 5 – Summary of PQ violations in the subsystem

Element	Total elements	Pl	Max number of elements with PQ violations
Buses	86	26%	1
		46%	5
		66%	52
Lines	110	26%	3
		46%	25
		66%	50
Trafos	7	26%	4
		46%	4
		66%	4

The results show that the impact of PEV charging on the network is highly dependent on the area being studied and its intrinsic characteristics. However, the approach used can be applied to any grid to assess the impacts of PEVs and provide customized results for the chosen network.

Finally, Figure 16 illustrates the variation in coincidence factors (CF) for different PEV penetration levels (Pl) within the smaller distribution system analyzed in this work package. This figure shows the cumulative effect of PEV charging on the intermediate voltage network. Specifically: ‘CF1’ represents the ratio between the primary substation in Trafo 1 and the five secondary substations (Trafo 2, Trafo 3, Trafo 4, Trafo 5, Trafo 6), as shown in Figure 13; ‘CF2’, ‘CF3’, ‘CF4’, ‘CF5’, and ‘CF6’ represent the ratios between each secondary substation and their respective connection points; ‘CF7’ represents the ratio between the maximum peak experienced at the primary substation and all connection points of the analyzed subsystem.

The CF measures the ratio of the maximum values of the total load to the maximum values of the partial loads at a given grid element. In other words, it indicates how coincident the aggregated loads are, with a CF of 1 signifying that all loads peak simultaneously.

Results show that the CF drops as PEV penetration increases up to the network's hosting capacity level. After reaching the hosting capacity level, the CF starts to increase again, leading to more coincident peaks in power demand. Also, as the penetration level increases above the hosting capacity level of the network, the aggregated load becomes more stable. This reduction in stochastic behavior imposed by increased PEV charging on the distribution system emphasizes the importance of both time and space as critical variables when considering PEV charging impacts.

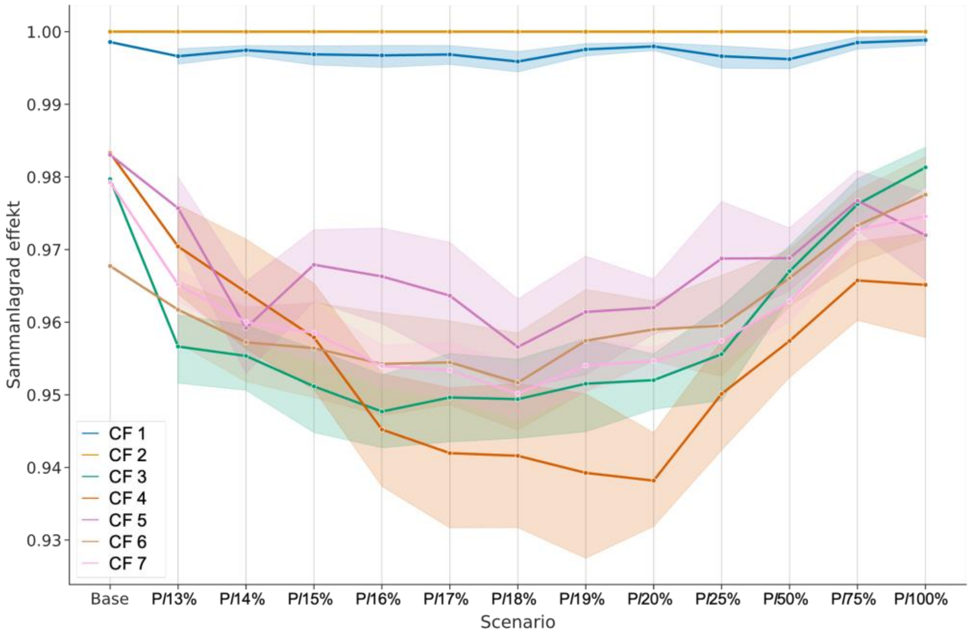

Figure 16 – Coincidence factors for different penetration levels for the subsystem.

WP4: Regional Capacity Analyses

Table 6 presents the coincidence factors for each primary substation of the chosen areas (WP1), highlighting their impact on the regional capacity.

Table 6 – Coincidence factors (CF) grouped by categories.

Scenarios/ CFs	Base case	P/25%	P/50%	P/75%	P/100%	CF types
CF1	0.9998	0.9972	0.9939	0.9941	0.9949	Peak all FSs / peak of each FS
CF2	0.9207	0.9104	0.8949	0.8957	0.8695	Peak FS GNG / peak of each NS under GNG
CF3	0.9389	0.9294	0.9126	0.8967	0.8926	Peak FS TOR / peak of each NS under TOR
CF4	0.9539	0.9353	0.9254	0.9176	0.9176	Peak FS KYR / peak of each NS under KYR
CF5	0.9390	0.9231	0.9063	0.8992	0.8901	Peak all FSs / peak of each NS
CF6	0.8886	0.7374	0.6613	0.6077	0.5690	Peak all FSs / peak of each CP
CF7	0.8770	0.7520	0.6761	0.6371	0.5919	Peak FS GNG / peak of each CP under GNG
CF8	0.8759	0.7158	0.6422	0.5921	0.5556	Peak FS TOR / peak of each CP under TOR
CF9	0.9071	0.7474	0.6741	0.6053	0.5685	Peak FS KYR / peak of each CP under KYR

As shown in Table 6, it was compared how different primary stations are loaded under normal conditions and at maximum PEV charging levels. This analysis assessed regional capacity in relation to G4. The findings highlight that Gångsätra, Torsvik, and Kyrkviken in Lidingö are priority investment areas due to network limitations and higher population density. Other regions with similar characteristics are expected to exhibit similar trends.

Overall, Lidingö was chosen for its controlled environment and its leading role in the electrification of transport. About 76% of its population has regular car access, making it a significant area for studying PEV integration. Across all analyzed regions, undervoltage was the most common issue related to PEV integration, becoming more prevalent than overloaded lines. When PEV penetration reaches 20-30%, power quality violations increase significantly. Therefore, expanding PEV charging infrastructure is crucial, but it must be balanced with grid capacity and renewable energy goals.

WP5

Two conference articles have been published and one Journal article is under review. One more Journal article will be submitted in Q3 2024.

Instead of a Licentiate, a mid-term seminar is planned for December 2024 as it is decided that the PhD student has the capacity to proceed towards a doctorate.

Publication list

In connection with G5, the publications related to this project during the reporting period include one journal article, two conference papers, and one MSc student report.

Journal Articles

Article under review at Elsevier journal Electric Power Systems Research, 2024: "*Plug-in Electric Vehicle Charging Patterns and Distribution System Integration: A Real Case Study in Stockholm County*".

Article to be submitted to Elsevier journal Electric Power Systems Research, 2024: "*Mitigation Strategies for Electric Vehicle Impact on Power Systems: A Comprehensive Statistical Method*".

Conference Articles¨

International Conference & Exhibition on Electricity Distribution – CIRED, 2023: "*Probabilistic Evaluation of Plug-in Electric Vehicles Impacts on the Steady-State Performance of a Distribution Network in Stockholm*".

International Conference on Power Engineering – ICOPE, 2023: "*Case Study on the Effects of Increasing Public Charging Infrastructure on a Distribution Network in Stockholm County*".

MSc Theses

Olle Hoffman Carlsson, "*Impact of Electric Vehicles on Equipment in a Local Electrical Distribution Grid*", MSc. Thesis, KTH Royal Institute of Technology, 2024.

Vicente Aires Roque da Costa Pereira, "Deve*loping and optimizing grid flexibility solutions including electric vehicles, batteries and PV for the municipality of Lidingö*", MSc. Thesis, KTH Royal Institute of Technology, 2024

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