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Analysis of charging capacity for electric vehicles in soviet-era apartment districts from the perspective of substation power availability

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Abstract. This article analyses the potential for electric vehicle (EV) home charging in a Soviet-era apartment district powered by the Lammi substation in Tartu, Estonia. Using one year of hourly electricity consumption data from 360 apartments, the study evaluates three load management scenarios to determine how many EVs can be supported without overloading the existing transformer infrastructure. The analysis is based on a worst-case winter week, reflecting realistic household consumption patterns and typical EV charging behaviour, which does not require daily charging. Three load control strategies are compared: (1) dynamic load management limited by weekly peak load; (2) fixed nighttime charging within a capped substation load; and (3) full dynamic charging for all apartments. The results show that up to 96, 218, and 360 EVs could be supported under these respective scenarios. The findings highlight how the choice of charging strategy significantly affects infrastructure demands and demonstrate that coordinated load management can enable broader EV integration without immediate large-scale investment. The study contributes practical insight for energy planners and housing associations seeking to align smart charging systems with the technical limits of existing substations.

Key words: charging, electric vehicles, load management, residential charging, substation capacity.

INTRODUCTION

The main research question of this article is the following: How many electric vehicles (EVs) can realistically be charged at home in a Soviet-era apartment district under different load management strategies, without overloading the existing substation infrastructure? Specifically, the study evaluates whether the current capacity of the Lammi substation (serving 360 apartments) allows for meaningful EV integration and how this depends on the presence and type of Smart Charging Management Systems (SCMS).

Rather than setting an artificial threshold (such as 50% of households), this research formulates a more practical question: What is the maximum number of EVs that can be charged in a given week under various management scenarios? This approach reflects real-world needs, where energy planners and housing associations must determine what kind of smart charging setup (if any) can allow the widest possible EV adoption under infrastructure constraints.

A key insight driving this analysis is that EV owners do not typically need to recharge daily. With an average energy consumption of 20 kWh per 100 km and a typical daily driving distance of around 50 km, the average user only needs about 70 kWh of energy per week (EV Database, 2025). In practice, this means most EVs are charged once or twice per week - not every day. Accordingly, this study analyzes charging potential during the worst-case consumption week (8–14 January 2024), not a single day or hourly peak. This better reflects how SCMS systems can balance demand over time rather than being constrained to short peak periods.

Three different EV integration scenarios are analyzed:

1. Dynamic Load Management Based on Weekly Peak Power – showing that up to 96 EVs could be supported;
2. Fixed Nighttime Load Management (23:00–07:00) – allowing up to 218 EVs to be charged;
3. Dynamic Load Management for All Apartments (360 EVs) – requiring a calculated minimum capacity of 242 kVA to meet full weekly charging needs.

It is important to note that the 360 kVA limitation referenced in this study is not an imposed constraint of the analysis, but rather the realistic technical limit of the Lammi substation's transformer (90% of the transformer's rated 400 kVA), selected to reflect engineering safety margins used in practical network planning.

These scenarios illustrate the trade-offs and limits under real-world conditions, helping to define how SCMS should be configured. In essence, this article provides the energy consumption modeling needed to help set up SCMS to manage supply limitations effectively - one of the key challenges in older residential areas.

Greenhouse gas emissions from the transport sector are a key target of the European Union's climate policy (European Commission, 2024). A major element of this strategy is raising the use of electric vehicles (EVs), which decreases dependency on fossil fuels while also improving the environmental quality of urban areas. However, that creates some concerns about whether the electrical grid is up to the task, at least in older residential areas where the infrastructure may not be designed to accommodate today's level of demand.

This issue relates especially to Estonia where up to 70% of the population lives in apartment buildings (Estonian Human Development Report, 2020). Residential areas like Tartu's Annelinn already have considerable electrical grid loads and the integration of new types of intense loads like electric vehicles could have a significant impact on the stability of the network. Lammi substation in Annelinn provides power to several large apartment buildings, including using the first transformer output, 360 apartments.

Estonia has seen rapid growth in electric vehicle numbers. By the beginning of 2025, Estonia had registered nearly 8,400 battery electric vehicles, a significant increase from previous years (Ministry of Climate, 2025). According to a study commissioned by (Elering, 2022), approximately 250,000 electric cars and electric vans are forecasted in Estonia by the year 2040. This growth represents a heavy new demand, especially on residential low-voltage networks where home-based charging is generally favoured (Sica et al., 2025).

Hence, understanding the capacity of the existing grid and exploring how to enable EV adoption without jeopardizing the reliability of the network or requiring urgent, large-scale and expensive investments in infrastructure would need to be a requirement. A number of different studies have been performed in recent years in order to explore the effect that EV charging has on the power distribution system. A study titled 'Impact assessment of electric vehicle charging on distribution networks' analysed the influence of EV loads on low-voltage distribution systems under various charging strategies. It demonstrated that uncoordinated charging may lead to transformer overload and voltage drops, particularly during peak periods. The study also concluded that coordinated or smart charging significantly improves network stability and reduces energy losses (Khan et al., 2024). A different study, titled 'Impact of electric vehicle charging demand on power distribution systems', quantified the impacts of EVs on distribution systems, warning that without heavy investments in infrastructure, an increasing number of EVs could lead to network overloads affecting reliability (Li & Jenn, 2024). These findings underscore the importance of care in design and load management to successfully integrate EVs within existing distribution networks.

Smart charging has become an important strategy for minimising the adverse effects of EV charging on electrical networks. The study 'Impact of public and residential smart EV charging on distribution power grid equipped with storage' analysed if smart charging could be used as a tool for easing the impact of integration of EVs into the distribution systems, concluding that significant reduction in grid load during peak periods and better overall network performance could be observed (Khalid et al., 2024).

Recent studies emphasize the importance of smart charging and centralized Vehicle-to-Grid (V2G) management systems. Secchi et al. (2023) proposed an algorithm enabling smart EV charging integrated with centralized V2G capabilities to minimize grid load variability and enhance grid stability, particularly under conditions of increased penetration of photovoltaic (PV) systems and electric vehicles.

There are a few case studies that have looked at the impact of EV charging in particular areas. For example, the research 'Impact of Electric Vehicle Charging on Power Distribution Systems: A Case Study of the Grid in Western Kentucky' examined the effects of EV charging on the power distribution system in Kentucky (Roy et al., 2023), showing the possibility of overload and providing mitigation measures. This highlights the importance of regional analyses to better understand the effects of EV charging interaction with specific distribution systems.

The key takeaway is that the last five years of research shows charging electric vehicles has a big impact on electrical grids, but smart charging and new technologies can help meet the needs. It highlights the importance of continued research and investment to facilitate a smooth transition to electric transportation without compromising the reliability and efficiency of the power grid.

MATERIALS AND METHODS

The dataset of this study consists of hourly electricity consumption data from the first transformer output (T1) of Lammi substation from 9 December 2023 to 8 December 2024. The data are from control measurements of the distribution company with estimated values of active power (kW) and apparent power (kVA). To guarantee data quality, measurement errors were identified and excluded according to the Z-score method (±3 standard deviations). Also, outliers, had to be removed - since values below 20 kW(0.025 pu previously) and 20 kVA(0.025 pu from the max. apparent power) were considered unreliable. Thus, 90 data points were discarded from analysis out of a total of 8,784, and the final number of data points for analysis was 8,694.

Simulation Assumptions:

- The research based on the transformer output T1 load in the Lammi substation: The Lammi substation serves 360 apartments. This study was conducted on the Lammi substation, because it supplies only residential apartment buildings and no other consumers like commercial or educational buildings. This will enable the examination of EV charging effects on electricity consumption in an apartment building context without the influence of alternative patterns of consumption.
- In simulations, the apparent power (kVA) sent for electric vehicle charging is equal to the active power (kW). In reality, EV charging has also a certain reactive power component, however, this simplification is used in the present work in order to concentrate on the analysis of the active energy consumption impacts and avoid excessive complexity in the simulation model. Future studies should pay attention to reactive power in detail.
- The simulation assumes up to one electric vehicle for each apartment.
- Conventional daily energy consumption for electric vehicles is assumed to be 20 kWh per 100 km (EV Database, 2025), and average daily driving distance is 50 km (Solar On EV, 2024). That means around 10 kWh of charging needs per day or 70 kWh a week. These averages are consistent with numerous European studies and official data sources. In the real world, energy consumption and daily driving distance can differ greatly depending on the season, with energy consumption usually on the high side in winter and daily distance varying for holiday or work and school changes. Needless to say, such seasonal and usage-related variations merit distinct detailed scrutiny, which is not the focus of this article.
- The rated power for the transformer output is 400 kVA, but for ensuring grid reliability and safety, the maximum load used in simulations is limited to 90% of the rated power, namely a maximum of 360 kVA.
- Dynamic load management is used to manage electric vehicle charging:
  - Charging power is evenly distributed among chargers according to the maximum allowed total load (known as power sharing).
  - The maximum load can be limited either according to the weekly peak load or according to the substation's specified load limit (360 kVA).

Analysis of Electricity Consumption Data and Derivation of Models

To analyze electricity consumption, three separate trend functions were derived based on corrected measurement data.

Daily Load Profile (hourly-based)

The average hourly apparent power consumption per apartment, characterizing daily energy use, was modelled using a sixth-degree polynomial function (Eq. 1), fitted to the measured hourly data over the full year. This function allows approximation of typical daily load profiles in the absence of direct measurements:

$$f_{hour} = 1.64 \cdot 10^{-7} \cdot x^6 - 1.13 \cdot 10^{-5} \cdot x^5 + 2.89 \cdot 10^{-4} \cdot x^4 - 3.43 \cdot 10^{-3} \cdot x^3 + 1.90 \cdot 10^{-2} \cdot x^2 - 3.52 \cdot 10^{-2} \cdot x + 1.27 \cdot 10^{-1} \quad (1)$$

where x represents the hour of the day (0–23).

Fig. 1 shows the average hourly apparent power (kVA) consumption pattern per apartment derived from the hourly measurement data of Lammi substation. The solid line is the average hourly values, which illuminate the typical residential energy usage cycle over 24 hours. Nighttime has a particularly low consumption time frame, who start coming back on around 6:00 or so. Peak usage is between 16:00 and 20:00, which is in line with the average household schedule and evening energy-consuming activities. The dotted line shows the trendline of a 6-order polynomial fitted to the measured data points. The close match between the average consumption values and the polynomial trendline demonstrates a good mathematical fit for modeling purposes. However, this does not imply that each individual day follows this exact profile.

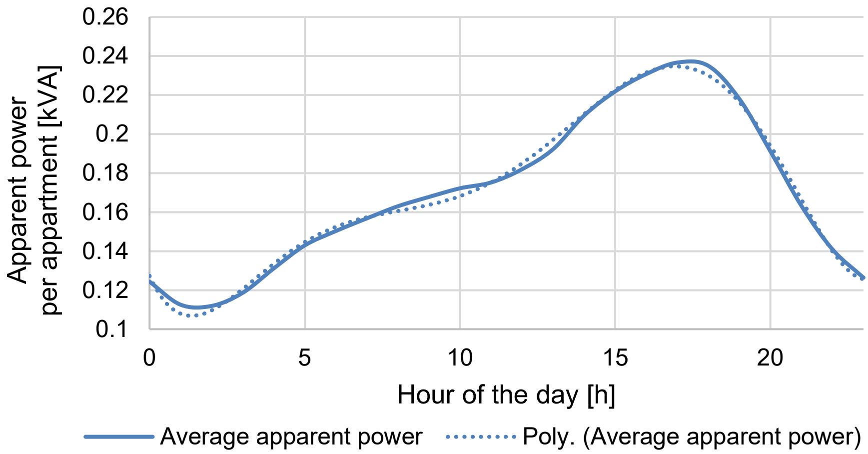

Figure 1. Average hourly apparent power consumption (kVA) per apartment over a typical day, based on one-year measurement data from Lammi substation. The solid line represents measured averages; the dotted line shows a 6th-degree polynomial approximation.

Note: The hourly, daily, and weekly trend functions presented here are not used directly in the simulation scenarios. Rather, they are developed to provide generalized approximations of residential consumption behavior. These trendlines can assist readers in future analyses or planning activities where measured data is unavailable, allowing them to simulate consumption with comparable accuracy based on fitted equations.

Weekly Load Profile (daily-based)

Weekly variations in average daily apparent power consumption per apartment were approximated using a sixth-degree polynomial regression function (Eq. 2). This captures general load patterns across weekdays and weekends, which can assist in week-based charging strategy planning:

$$f_{day} = -2.44 \cdot 10^{-5} \cdot y^6 + 3.45 \cdot 10^{-4} \cdot y^5 - 1.63 \cdot 10^{-3} \cdot y^4 + 2.72 \cdot 10^{-3} \cdot y^3 + 2.15 \cdot 10^{-4} \cdot y^2 - 3.85 \cdot 10^{-3} \cdot y + 1.68 \cdot 10^{-1} \quad (2)$$

where y denotes the day of the week (0 = Monday, ..., 6 = Sunday).

Fig. 2 presents the average weekly pattern of apparent power (kVA) consumption per apartment, calculated by aggregating daily measurement data over the entire week. The solid line shows the typical daily consumption from Monday (marked as day 0) through Sunday (day 6), illustrating how electricity usage varies throughout the weekdays. Consumption remains fairly consistent from Monday to Thursday but clearly rises beginning on Friday, reaching its highest point on Sunday, probably reflecting more household activities occurring during weekends. The dotted line shows a sixth-order polynomial trendline, which effectively summarizes the overall weekly pattern. While the polynomial provides a good fit to the average weekly consumption pattern, it should be interpreted strictly as a modeling tool. No statistical analysis was performed to confirm periodicity across all weeks, and further work is needed to determine the consistency of weekly load cycles.

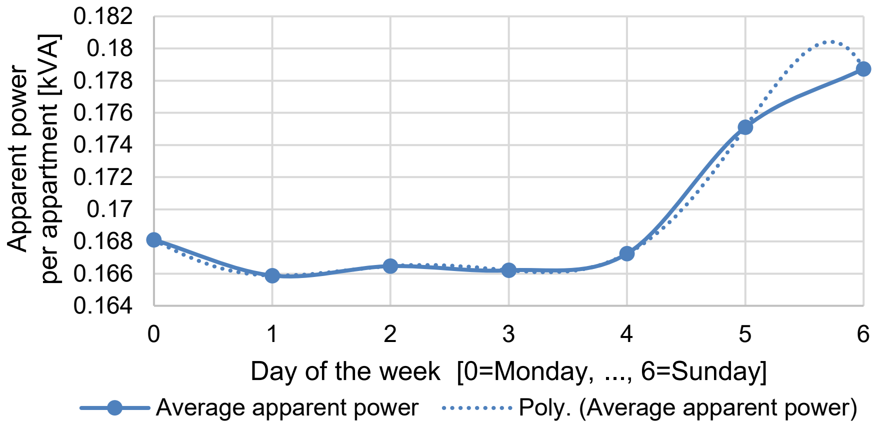

Figure 2. Average daily apparent power consumption (kVA) per apartment across days of the week. Values are based on aggregated yearly data. A 6th-degree polynomial approximation is shown as a dotted trendline.

Annual Load Profile (weekly-based)

Seasonal variation in apartment load was modelled using a sinusoidal approximation (Eq. 3), reflecting the impact of heating and lighting needs across different weeks of the year:

$$f_{week} = 2.586 \cdot 10^{-2} \cdot sin(8.855 \cdot 10^{-2} \cdot z + 2.280) + 1.779 \cdot 10^{-1} \quad (3)$$

where z represents the week number of the year (1–52).

Fig. 3 depicts the average weekly apparent power (kVA) consumption per apartment throughout a year, calculated from weekly aggregated measurement data. The figure clearly reveals seasonal patterns, showing higher electricity consumption in the colder winter months at the start and end of the year, while consumption noticeably drops during summertime. The lowest electricity usage appears roughly between weeks 20 and 30, corresponding to the summer period, when daylight hours are longest, and less energy is typically needed for heating and lighting. In contrast, the highest electricity consumption happens in winter, driven mainly by greater use of heating systems, lighting, and home appliances. These observations confirm how significantly weather and seasonal changes impact residential electricity usage.

Figure 3. Average weekly apparent power consumption (kVA) per apartment by week number (1–52), reflecting seasonal variations. The curve includes a sinusoidal approximation based on fitted historical data.

Charging scenarios

In this chapter, we discuss electric vehicle charging options available at the Lammi substation by applying different load management techniques and scenarios to assess the ability of the existing substation to meet EV charging demand. Note: The analysis is developed on the week of minimum yearly capacity reserve (08.01.2024–14.01.2024).

Scenario 1: Dynamic load management based on weekly peak power

In this case, dynamic load management was applied, since avoiding exceeding the maximum load of the substation when charging EVs during the week was needed, accounting for the peak power in the week of EV consumption. It was estimated that in this solution approx. 6,756 kWh can be used weekly to charge electric vehicles.

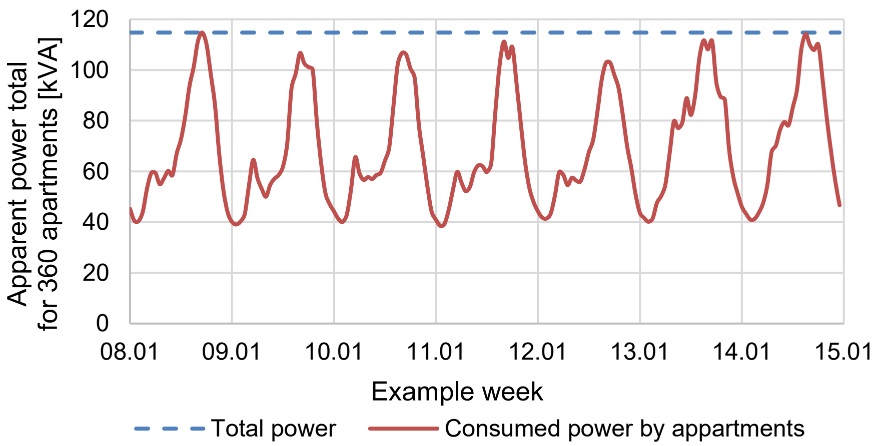

Figure 4. Hourly total apparent power consumption (kVA) for 360 apartments during the week of 8–14 January 2024. The dashed line represents the maximum available transformer capacity based on dynamic load management constrained by weekly peak consumption.

For reference, each electric vehicle needs about 70 kWh of energy per week on average, which means this solution would potentially accommodate the charging of nearly 96 electric vehicles. Fig. 4 illustrates the actual hourly apartment power consumption during the example week (8–14 January 2024), along with the maximum allowable load set according to the weekly peak power. The difference between the maximum allowed load and actual consumption clearly indicates the available power capacity for EV charging.

Scenario 2: Fixed nighttime load management

The second scenario used fixed load control at night (23:00–07:00). In this implementation, the substation load was constrained to 360 kVA, representing 90% of the rated capacity of the substation (400 kVA). Under this scenario, calculations showed that approximately 15,291 kWh of energy would be available weekly for electric vehicle charging. Assuming an average weekly energy requirement from the aforementioned source (70 kWh per vehicle per week), this method can sufficiently service for up to 218 electric vehicles per week. Fig. 5 illustrates hourly apartment consumption for the example week (8–14 January 2024), the total power capacity (blue dashed line), and the fixed maximum allowable load set at 360 kVA (green dashed line). The graph clearly shows the substantial available capacity during nighttime hours allocated for EV charging, highlighting the effectiveness of this load management approach.

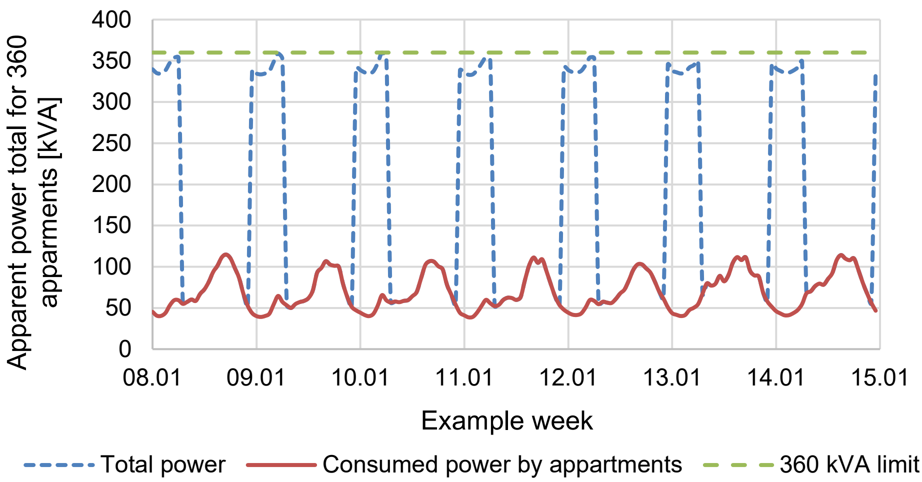

Figure 5. Hourly total apparent power consumption (kVA) for 360 apartments during 8–14 January 2024. The blue dashed line shows the total transformer capacity (400 kVA), and the green dashed line represents the 360 kVA limit applied during nighttime charging (23:00–07:00).

Scenario 3: Dynamic load management for 360 electric vehicles

The third case assumed the presence of one electric vehicle per apartment (360 vehicles in total). The analysis was conducted in order to find out the necessary required substation capacity to satisfy the weekly energy demand of all these EVs with respect to dynamic load management policy. The minimum total capacity of substation should be approximately 242 kVA, according to collected data and calculations.

With this capacity, enough charging could be provided for all of the 360 electric vehicles while considering the current energy consumption of the building as well. Fig. 6 presents hourly apartment apparent power consumption during the example week (8–14 January 2024), with the calculated total power capacity required to serve all apartments and associated EV charging.

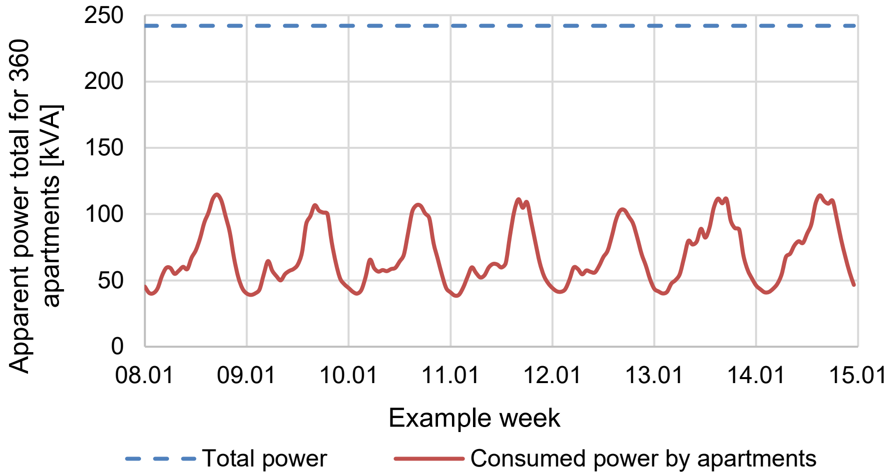

Figure 6. Hourly total apparent power consumption (kVA) during 8–14 January 2024. The dashed line shows the calculated minimum substation capacity (242 kVA) required to support charging for all 360 EVs through dynamic load management across the full week.

These three scenarios help evaluate the utility and capacity of the existing electrical grid and substation with widespread electric vehicle deployment. All scenarios give clues about the investments needed, allowing for grid operators and housing associations to better plan the rollout of electric infrastructure.

RESULTS AND DISCUSSION

In this chapter, we discuss how the scenarios presented in Chapter Materials and Methods could be used in practice for solutions for electric vehicle charging problems. This provides different opportunities and limitations for the usability of all scenarios in different contexts.

Scenario 1: Dynamic load management based on weekly peak power – provides a suitable approach for housing associations wanting to autonomously manage the EV charging requirements of individual households. The main reason for this scenario is the flexibility of the system and the tight regulation of the load of the electrical grid in time and volume to avoid exceeding provided electrical infrastructure. However, this solution presupposes the availability of smart chargers combined with dynamic load management software from day one, which may involve higher up-front capital costs and increased technical complexity.

The second scenario: Fixed nighttime load management – is applicable in cases where EV penetration is low, and grid load can be unambiguously defined. Because charging restrictions are made in fixed time periods at a set maximum load level, the primary benefit to this methodology is that it eliminates the need to set up a complex dynamic load management scheme from the outset. However, this method is problematic: if there are many electric vehicles in a region, load ramps may happen heavily at the beginning and/or end of the charging times when using this method, which may lead to instability in the grid and the need for even more investments in the electricity networks.

The third scenario: Dynamic load management across the entire residential area, and it's an answer for local governments in the case of massive electric vehicle usage. The benefit to this scenario is that it has the potential to be deployed across broad regions all at once vs. each building or housing association having to spend on its own separate charging infrastructure. It also has the benefits of creating load levelling on the electrical grid and reducing the need for additional power investments. In this case, though, a full-fledged load management system would need to be developed and implemented, alongside coordination between network operators, local governments, and residents.

Comparable findings have been observed in related literature on residential grid capacity under EV charging scenarios. For instance, (Li & Jenn, 2024) found that uncontrolled EV charging could lead to transformer overload when EV penetration exceeded 30–40%, even in well-maintained U.S. suburban networks. In the present study, a dynamic load management approach accommodated up to 96 EVs (27% of households), while a fixed nighttime load window supported 218 EVs (over 60%). These results suggest that smart, time-based load shaping strategies can allow for significantly higher EV integration without overloading substations. Similarly, Khan et al. (2024) emphasized that coordinated charging can reduce transformer stress by up to 40% compared to unmanaged scenarios – aligning well with the substation efficiency improvements demonstrated here. These comparative insights reinforce that with proper load management, legacy infrastructure can reliably support a transition to widespread EV adoption.

In summary, the above examples highlight different solutions, and the choice of approach depends primarily on the existing load conditions and the potential for smart charging deployment. This study does not assess cost, pricing models, or detailed investment requirements. However, cost-benefit analysis and infrastructure upgrade cost modeling would be a valuable direction for future research to support implementation planning.

CONCLUSIONS

The affordability of electric vehicles (EVs) plays a critical role in the review of the Lammi substation and analysing the load management techniques. We analysed hourly electricity consumption data from 2023, employing a Z-score threshold to make sure that the data quality was high by removing insignificant errors in measurement.

The scenarios contemplated showed that the potential charging load of the existing substation can vary significantly depending on the selected load management strategy:

Dynamic load management – whereby power for charging EVs was limited to weekly peak power – allowed for the charging of up to 96 electric vehicles per week.

With applying fixed nighttime load management, limiting the charging load to 360 kVA (90% of the substation's rated capacity), the number of electric vehicles that could be charged weekly increased to about 218.

In the case of dynamic load management for all 360 apartments (one EV per apartment), the minimum required substation capacity was calculated at approximately 242 kVA, sufficient to ensure all electric vehicles were charged adequately.

It assists distribution network operators and housing associations to understand the interventions that need to be made in order to allow electric vehicles more widespread adoption and helps drive infrastructure developments in line with realistic load profiles and technical constraints of substations.

The findings provide useful insights into the number of EVs that can be supported under specific transformer capacity constraints and load management strategies. These results can serve as input for future planning and simulation studies by network operators and building associations considering smart charging adoption. While this study does not include a cost or infrastructure investment analysis, it establishes a foundational understanding of the technical conditions under which EV charging can be introduced in older residential grids.

It is important to emphasize that this study focuses on typical operating conditions based on realistic weekly consumption data. The modeling does not address rare boundary conditions or system failure scenarios, which would require a broader simulation scope and contingency analysis. Investigating such edge cases – including extreme peaks, system faults, or coinciding high-load events – would be a valuable extension for future research to complement the present findings.

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